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The Impact of the UK Government's Plan to Impose VAT on School Fees on Socio-Economic Mobility By YuHan Fu

Since January 1, 2025, the UK government has imposed a 20% Value Added Tax (VAT) on private school fees while abolishing their charitable tax relief. This move aims to raise approximately £1.6 billion annually to invest in public education, with a particular focus on improving resources for disadvantaged students. This policy stems from growing concerns about persistent educational inequalities in the UK, where private schools—attended by only 7% of students—have historically dominated access to elite universities and high-status careers.

Private school students make up over 40% of Oxbridge admissions, despite representing a small fraction of the overall student population. This highlights a cycle of privilege favoring wealthy families. Thus, the imposition of VAT will be a crucial step toward educational equity, and thus should be imposed.

The tax may raise private school fees, potentially pushing some middle-class families out of the market. However, the revenue could fund public education, such as hiring 6,500 new teachers or improving resources, key steps to reduce the attainment gap. While the exact impact is uncertain, the goal is clear: rebalance opportunities by redistributing advantages tied to wealth.³

Economists debate whether this VAT constitutes a progressive or regressive tax. While VAT is typically regressive, since a higher percentage of low-income budgets is allocated to consumption compared to higher budgets,²⁸ its application to private schooling—a service predominantly used by the top 10% income bracket²—may exhibit de facto progressivity. This means that the tax burden gradually increases in proportion to total income as income increases.

Her Majesty's Revenue and Customs data reveals that families earning over £150,000 bear 68% of the tax burden. With less burden from schools and middle- or low-income families, this tax might successfully transfer consumer surplus from high-income classes to subsidize and provide resources to the majority of students attending public schools. Private school students primarily come from high-income brackets, whose demand for private education remains relatively insensitive to price changes. For example, when Eton College, the most prestigious private school in the UK, increased tuition by 20% to around £63,000 per year in 2023, high-net-worth families were more likely to adjust other expenses or use savings to maintain their children's private education, with some relying on grandparents' financial support or prepaid fees.^{5,6} This insensitivity is rooted in the perceived long-term benefits of private schooling such as better university placements and social networks, and the fact that they earn a higher income.

Middle-class families might face some pressure: surveys show that 24% of parents who attend private schools may transfer their children to public schools due to the VAT.²⁹ The additional 20% tax (approximately £3,000) on top of an annual tuition of around £15,000 forces them to reassess their educational choices. For many middle-income households, private schooling accounts for a significant share of discretionary spending, often exceeding 20% of

their net income after housing costs.²⁹ VAT, as a consumption tax, directly increases the cost of services rather than reducing income through direct taxation.

In this context, the imposition of VAT alters the relative price of private versus public education, effectively increasing the marginal cost of paying for private schooling. Parents who were on the edge of affording private school before may now reconsider its worth, especially if public schools nearby have improved or if their results are comparable. The budget surplus has led to a sharp rise in students switching from private to public schools—over 5,000 in 2024 alone, a 270% increase compared to pre-policy averages of 1,200–1,800 (local council data; NFER 2023). This surge highlights the policy's immediate impact on middle-class school choices. This does not necessarily lead to a bad result: as mentioned earlier, 68% of the tax burden will be still carried by high-income classes, and extra tax revenue can compensate for the transfer of middle-class family choices.

While this influx could intensify competition for public school resources in the short term, the government estimates that the state system has sufficient capacity to absorb additional students due to projected demographic shifts, including declines in the UK school age population by 2030. Also, extra-revenue from VAT would, if properly attributed, increase education quality in public schools in the long term. Considering from a demographic point of view, public schools are still the optimal choice for the majority and enhancing the overall quality in public schools leads to a general increase in quality of education as a whole. Public schools might also have accessible laboratories, newly built exercise facilities just like private schools, and most importantly, extra classrooms and teachers to provide spaces and resources for additional student influx. In fact, The Observer noted that up to April 2025, 83% of London state schools received upgraded science labs using VAT funds. A YouGov survey even mentioned that some parents in Manchester stated: “My state school now has smaller classes than local private schools”. Therefore, VAT does indeed improve facilities and education qualities in multiple aspects.

Research shows that when middle-class families enroll in state schools, they often advocate for better resources—such as smaller classes or improved facilities—leading to policy changes. Their involvement can create a cycle of demand-driven school improvements. In the UK, a 2023 report by the Institute for Fiscal Studies (IFS) noted that areas with higher proportions of middle-class state school attendees had 15% more per-pupil funding and 20% lower teacher turnover rates, suggesting that parental engagement is correlated with tangible systemic improvements. Thus, the VAT policy may primarily affect wealthier households, but middle-class advocacy for better state schools could also improve equity in the long term.

For low-income households, private school fees already far exceed public education costs (£15,200 for private schools versus negligible expenses for public schools, in 2022–23).² Therefore, the VAT has a minimal impact on their choices, as their children mainly depend on the public education system. However, the policy indirectly benefits them through potential improvements in public school quality funded by the new tax revenue.

Notably, there might also be a group of people that might receive additional benefit from VAT. In some countries like UK or Israel, private religious schools resist state-mandated

secular curricula like LGBTQ+ inclusion and evolution. A VAT could incentivize enrollment in more inclusive public schools, aligning with progressive educational goals. To be more specific, the Charedi Jewish community in Israel, which comprises around 2.1-2.4 million people in 2024, with 81% of children attending private schools due to religious education requirements. A VAT could push 5–10% of families (21,000–48,000 children) toward state funded public schools,

Admittedly, the policy may have both positive and negative effects on educational resource distribution: the government plans to use new tax revenue to hire teachers and increase public school funding. If VAT is imposed, additional funds and budget will be made available to cover salaries for new teachers. The policy's side effects also exist—critics have highlighted a significant loophole in its design, whereby elite private schools like Eton can claim back VAT funds in the medium term, potentially undermining the revenue intended for public education. As reported by The Guardian in October 2024, this loophole allows schools to restructure as educational charities or access tax relief via investment schemes, effectively reducing the tax burden on the wealthiest institutions.²⁹

Positive externalities could emerge if tax-funded public education upgrades improve not only academic outcomes but also long-term workforce productivity and economic inclusion. Conversely, negative externalities are evident in the potential disruption to specialized services: many UK private schools provide specialized SEN (Special Educational Needs) programs to support students with autism or dyslexia. Data from the UK Department for Education (2023) shows that approximately 12% of SEN students in England attend private schools, where these programs are delivered with 30% fewer per-pupil costs than state systems.

Though negative effects and externalities seem to be evident, critics' concerns about talent cultivation overlook a fundamental truth: when 93% of students rely on public education—with private schools educating just 7% of the population³⁰—improving public quality through VAT redistribution yields greater societal returns than preserving elite enclaves. Nations with strong public systems (e.g., Finland) outperform UK private schools in Programme for International Student Assessment scores by an average of 12%, proving that equity and excellence can coexist.³ This shift might initially spark concerns about the development of high-skilled talent, but improved public education quality, funded by taxes, could offset this loss.

Compared to countries like Switzerland and Singapore, which impose low taxes on private education, the UK's policy may influence the decision of high-net-worth families to remain in the UK. However, the global reputation of UK private schools could still attract international students, partially mitigating the decline in domestic demand and thereby balancing the enrollment of students across different backgrounds. For example, while people might generally think that a price increase will lead to a decrease in quantity demanded, Eton College reports a 15% increase in applications from overseas families since the policy announcement, driven by its brand recognition despite higher costs.

In short, the UK government's VAT on private school fees represents a bold fiscal measure aimed at reducing educational inequality by redirecting resources to the public sector.

By channeling £1.6 billion annually from private to public education, the policy seeks to level the playing field and expand opportunities for students from less advantaged backgrounds. In the short term, the 20% tax is likely to reduce demand for private education among price-sensitive families, leading to greater social mixing in public schools. However, its long-term success depends on how well tax revenue translates into tangible improvements in educational quality and equity. Since it has strong benefits, hopefully its advantages will outweigh its disadvantages in the long term.

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How Does Peer Test Score Disclosure Relate to Motivation and Academic Performance Among High School and College Students? By Hersh Gandhi

Abstract

Student motivation has been a research focus over the past 20 years because it is linked to student engagement, classroom behavior, and academic performance. Student motivation is regarded as one of the most important factors in overall student well-being, as reported in previous studies. Peer test score disclosure, the practice of students' test scores being shared with classmates by the teacher or among students, may impact student motivation. While prior research has examined social comparisons in younger students, there has been very little research on how this practice affects high school and college students. This study employs a correlation design combined with a mixed-methods survey to investigate the relationship between peer test score disclosure and student motivation and academic performance.

The 24 participants completed a survey that asked questions based on their experience with peer test score disclosure. Although the focus was on students who experienced peer test score disclosure, students who did not experience it in their classes could still complete the survey, allowing me to compare the changes between students who had disclosure and those who did not. The survey included a variety of questions, including Likert-scale questions, self-reported test scores, and open-ended questions that asked them to describe how the disclosure affected their motivation and academic performance levels. The results suggested that students who experience test score disclosure score more consistently than those who do not, in both motivation levels and academic performance. I also found a differential relationship between disclosure and academic performance and motivation, where some students reported benefits, while others reported adverse effects.

My research suggests that test score disclosure impacts each student differently. However, those who did experience disclosure scored more consistently between the first and second tests. Schools should consider the possible benefits of test score disclosure, such as students scoring more consistently. They should also evaluate the potential harms, such as decreased motivation. Future research should use experimental designs to establish a cause-and-effect relationship and understand the effects of peer test score disclosure.

Introduction

The COVID-19 pandemic accelerated the switch from traditional public disclosure of test scores to online, privatized platforms, such as Canvas, Blackboard, and PowerSchool. According to Alford et al. (2021), the sudden shift to online teaching during the COVID-19 pandemic changed how educators assessed student learning. One significant change was the move toward less social comparison and more individualized feedback. As a result of COVID-19 and its consequences, peer comparisons, which were often triggered by the disclosure of peer test scores, declined. However, according to Landivar et al. (2023), most United States school districts have returned to in-person instruction. Although schools are returning to in-person

instruction, the COVID-19 pandemic has changed the environment for these students forever. As Gillis and Krull (2020) report, during the pandemic, “most students experienced barriers to learning...including distractions, increased anxiety, and feeling less motivated.” Many of these consequences still exist today. As Sokacz et al. (2021) confirm, “Survey data has indicated an increase in depression, anxiety, and thoughts of fear, worry, difficulty concentrating, and disrupted sleeping patterns.” These ongoing psychological effects may have changed how students respond to peer test score disclosure in the post-COVID-19 environment. If the impact of peer test score disclosure has changed for post-COVID-19 students and is now less common, it is necessary to explore these effects, as this will tell educators whether disclosing is still beneficial.

Peer test score disclosure, which allows students to see how they performed relative to their peers, has been linked to motivation theories, such as social comparison theory (Festinger, 1954). The social comparison theory says people evaluate their abilities by comparing themselves to others (Festinger, 1954). In schools, seeing peer test scores could impact a student’s motivation, either positively or negatively. Given that COVID-19 has left students in a more sensitive state than ever before, peer comparisons today might have completely different effects than they used to have. In younger students, research has shown that peers can have a significant impact in some cases (de Gendre & Salamanca, 2021; Sacerdote, 2014). However, very few studies have focused on college and high school students after the COVID-19 pandemic. Moreover, most studies have used data from a single classroom or institution, which limits the generalizability of the results.

Taking into account the impact of COVID-19 on students, it has become necessary to reevaluate the role of peer test score disclosure, mainly because students are currently in a sensitive state. This study examines the correlation between peer test score disclosure and academic performance and motivation among college and high school students. By focusing on post-COVID-19 high school and college students, this research addresses a gap in the literature that could help teachers choose whether to disclose peer test scores in their classrooms.

Literature Review

Knowing the relationship between score disclosure and motivation is important to understanding the current literature on peer test score disclosure. Festinger (1954), who initially suggested the social comparison theory, reported that people compare themselves to evaluate their abilities. Peer score disclosure provides a perfect opportunity for comparison, especially in tests, because students can quantitatively judge their performance compared to their peers. Recent studies have shown the outcomes of social comparison. As Suls et al. (2002) explain, “Comparing the self with others, either intentionally or unintentionally, is a pervasive social phenomenon. Perceptions of relative standing can influence many outcomes, including a person’s self-concept, level of aspiration, and feeling of well-being.” In other words, Suls et al. are saying that a student’s encouragement depends on how they interpret their standing in the class. For example, if a student looks at their peer’s higher scores and thinks they are obtainable,

they may get motivated through assimilation (Suls et al., 2002). On the other hand, if a student believes that their peer's higher scores are not achievable, they are likely to experience contrast and discouragement (Suls et al., 2002).

This foundational theory is important because it shows that social comparison and, in turn, peer test score disclosure do not always have a positive or negative effect on students; rather, it depends on how the students evaluate their standings. Past research has shown that there is no clear relationship between them. Simonsmeier et al. (2020) found that peers generally improve students' academic self-concept. However, they did not isolate the effects of peer comparison from regular feedback mechanisms. Hattie and Timperley (2007) further researched feedback and found that feedback from peers and teachers is only effective when combined with effective classroom instruction.

While there is a large body of literature on peer feedback, motivation, and social comparison, it does not explicitly address the effects of disclosing peer test scores alone. Moreover, the few studies that do exist focus on younger students. For example, de Gendre and Salamanca (2021) found that when students knew there were high achievers in their class, their test scores increased. Nevertheless, because de Gendre and Salamanca (2021) only studied Taiwanese middle school students, this research does not generalize to high school and college students because their environments differ significantly. Research by Albert et al. (2013) explains that adolescents, primarily high school and college students, are more sensitive to peer influence and comparison than any other age group. Specifically, their study found that the presence of peers alone activates the brain's socioemotional reward system, which makes adolescents more likely to make impulsive decisions (Albert et al., 2013). This increased level of peer sensitivity during adolescence means that peer test score disclosure could have strong motivational and academic effects.

The current body of literature does not account for school changes post-COVID-19. Alford et al. (2021) report that, due to COVID-19, many schools shifted to online platforms for instruction and grade reporting, a trend that was happening at a slower rate beforehand. These changes have made grading more privatized and less transparent between students. This privatization and increased use of online grade reporting mean peer score disclosure is happening less nowadays. Landivar et al. (2023) confirm that most schools have returned to in-person instruction. However, the everyday use of online grade reporting during remote learning has caused many schools to permanently adopt digital technologies, even after returning to in-person classrooms.

Additionally, Zarowski et al. (2024) say that even though schools have been returning to their everyday environments, students still face psychological consequences from the pandemic, such as "increased stress, anxiety, self-reported decreased well-being, [and] constant worrying." These psychological consequences may make students more vulnerable to the effects of social comparison when peer test scores are disclosed, especially since high school and college students are such a vulnerable group. For this reason, it is important to reevaluate the effects of peer test score disclosure, which will show us any benefits or harms associated with the technique.

Because only a minimal amount of research has been conducted to study the effects of peer test score disclosure after COVID-19, more effort needs to be made to understand these effects. Even if peer test score disclosure is becoming less common, it still occurs informally between students, for example, when one student shares their grade with another. Additionally, no study has examined whether the psychological consequences of COVID-19 have changed how students react to peer score disclosure. Studies like Zarowski et al. (2024) and Dworkin et al. (2022) point out that post-pandemic students have increased stress levels and more emotional sensitivity. However, these studies do not examine how peer factors play into these motivations and mental health declines. Without research that isolates peer test score disclosure to examine its effects on motivation and academic performance, teachers lack evidence on whether disclosure helps or hurts their students.

This gap is important because previous findings on peer test score disclosure may not apply to the post-COVID-19 environment of current high school and college students. Many previous studies have only examined the effects of test score disclosure on younger students. However, as Albert et al. (2013) report, adolescents are more sensitive to peer influence and comparison than any other age group.

In short, although the literature base has explored social comparison, motivation, and feedback, very little research has isolated the relationship between peer test score disclosure, motivation, and academic performance among high school and college students after the COVID-19 pandemic. The present study addresses this gap by focusing on high school and college students in the post-pandemic environment. Therefore, the question guiding my work was: How does peer test score disclosure relate to motivation and academic performance among high school and college students?

Hypothesis

I hypothesize that peer test score disclosure will be correlated with an increase in academic performance, similar to what students experienced in de Gendre and Salamanca's (2021) study. Secondly, I hypothesize that peer test score disclosure will also be correlated with increased overall student motivation.

Method

This study used a mixed-methods, correlation design to find the correlation between peer test score disclosure, motivation, and academic performance among high school and college students. A mixed-methods approach was proper because it allowed me to capture quantitative and qualitative data. Venkatesh et al. (2013) corroborate this by saying, "[A mixed-methods design] can help develop rich insights into vigorous phenomena of interest that cannot be fully understood using only a quantitative or a qualitative method." This helped offer a fuller understanding of the effects of test score disclosure. A correlational design was chosen instead of an experimental design because of the logistical barriers to manipulating peer score disclosure in real classrooms. Due to existing school policies at Olentangy High School, Ohio State

University, and Columbus State Community College, it was not possible to change disclosure conditions across classrooms. This made a proper experimental design infeasible, so I opted for a correlational design.

Participants

Participants were obtained from three different schools to make the sample diverse in terms of educational backgrounds: Olentangy High School, Ohio State University, and Columbus State Community College. Participants were obtained through voluntary response sampling, which means that the sample consisted of participants who volunteered to participate. This technique was used to maximize the number of survey respondents who met the eligibility criteria and to ensure a diverse sample. Studying this population was important for many reasons. As explained in the literature review, the effects of disclosing peer test scores have not been researched in high school and college students. The impacts of peer test score disclosure are particularly significant in adolescents due to the increased susceptibility to peer influence and comparison (Albert et al., 2013); thus, I chose this population. A total of 25 students completed the survey. However, one response had to be removed because it was incomplete. Eligibility criteria included enrollment as a high school or college student and having completed at least two tests in the course they chose to reflect on during the survey. Using respondents from multiple schools strengthened the validity of the findings by reducing the probability that the results were skewed and only represented one school environment.

Participation was voluntary, and participants could choose not to complete the survey at any time.

Instruments

A survey was administered using Google Forms (see Appendix A). The survey was designed to collect both qualitative and quantitative data and was divided into four sections. The first section was intended to separate participants based on whether they experienced peer test score disclosure. The first question asked students if their test scores were shared with their classmates after the first test, as shown in Figure 1. They responded with either “Yes” or “No.” This separation allowed for a comparison between the two groups.

Figure 1

Survey question used to create two groups for comparison: disclosure and non-disclosure.

...

In this class, were test scores disclosed to students? (This means that the educator shared the class's overall scores or individual scores among students. This includes average, high/low, and grade distributions.)

☐ Yes

☐ No

The second section of the survey was designed to assess the participants' initial level of motivation using the Situational Motivation Scale (SIMS). The SIMS is a validated questionnaire designed to help measure overall motivation for a particular situation (Guay et al., 2000). The SIMS scale was appropriate for this study because it provides a baseline measure of motivational levels for students before a specific event, such as studying for a test. This made it ideal because it would isolate how peer test score disclosure might relate to motivational changes. The SIMS uses a 7-point Likert scale, which was used to maintain the validated structure (see Figure 2).

Figure 2

Example of a survey question from the Situational Motivation Scale (SIMS).

1. Why did you engage in your first test? Because I think that this activity is interesting. *

	1	2	3	4	5	6	7	
corresponds not at all	☐	☐	☐	☐	☐	☐	☐	corresponds exactly

Sections three and four of the survey were questions that I crafted. These questions asked students additional questions about their motivation and effort before the first and second tests. Likert scales were appropriate for these questions because they allow participants to report the degree to which they experienced something, providing more specific data than simple yes/no answers. Additionally, Michalopoulou (2017) reports that Likert scales are extensively used in educational sample survey research.” Furthermore, the usage of 5-point Likert scales helped me to deliver a more straightforward response process for the respondents. To measure the effort and motivation of students in their learning and preparation for their second assessment, I used multiple-choice questions. Multiple-choice questions were the most effective here because they allowed me to categorize students by their effort and motivation levels before and after the first test. Open-ended questions were also used in the survey. These questions asked participants to reflect on how knowing (or not knowing) their peers’ scores affected them. Open-ended questions were included because they allow participants to explain their experiences, which would not have been captured through scales. This open-response format provided specific evidence on how students were affected by the disclosure of their test scores. Qualitative data

was needed to capture the participants' thinking and reflection on how they were impacted by the test score disclosure, things that are not easily quantifiable. Lastly, open-ended questions were used for participants to report their scores on their two tests. This format was chosen because it allowed for the collection of precise quantitative data, rather than general score ranges. Exact test scores made it possible to examine each participant's differences and compare them between those with and without disclosure.

Procedure

Students who met the eligibility criteria completed the Google Form survey. First, participants were asked if they experienced peer test score disclosure after their first test in whatever class they chose. Based on their answer here, participants were categorized into either a disclosure or a non-disclosure group. Next, all participants completed the SIMS motivational scale. Following the SIMS section, participants answered questions on a Likert scale, multiple-choice questions, and open-ended questions about their motivation and effort before their first and second tests. Then, participants responded to questions about how peer test score disclosure impacted their motivation. Lastly, they reported test scores for their first and second tests. The survey was designed to be completed in one sitting, and it took between 10 and 20 minutes to complete.

Data Analysis

The participants were split into two groups so that the changes between those who experienced peer test score disclosure and those who did not could be compared.

Quantitative data, such as test scores and Likert scale responses, were analyzed using descriptive statistical methods, including means and standard deviations. These measures were appropriate because they summarize the trend of the data and its variability, making it easy to view general patterns across the sample. This approach was proper because descriptive statistics can be used to show changes in performance between different groups, such as disclosure and non-disclosure groups.

For the Likert-scale responses about motivation, I calculated mean scores to compare the average levels of motivation before and after disclosure, as well as between the disclosure and non-disclosure groups. The use of averages was proper because it allowed me to view any general shifts in reported motivation across both groups. Inferential statistics were not used because of the small sample size. Correlational tests require a minimum sample size of 30; therefore, descriptive statistics were used.

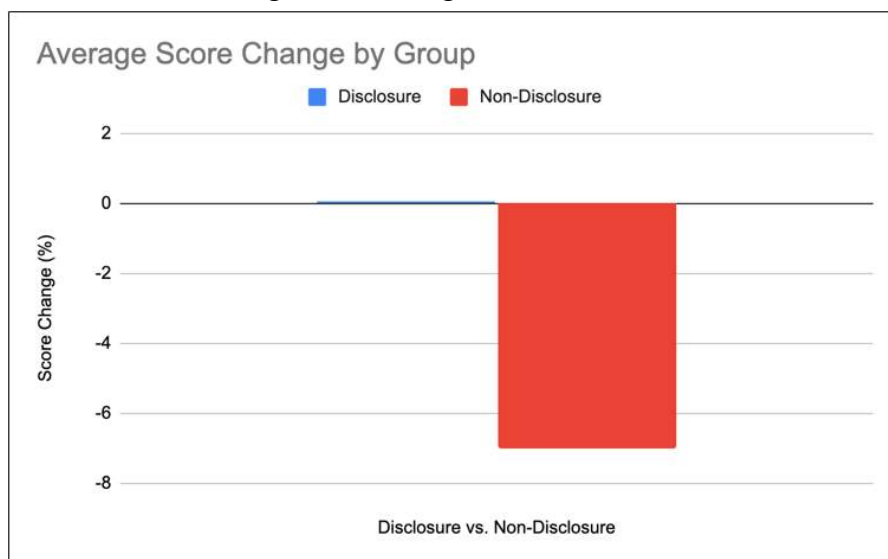
For the qualitative data from the open-ended responses, I grouped participants into two categories: those who reported that test score disclosure had a positive effect on their motivation, and those who reported no effect or an adverse effect. From this grouping, I saw the common perceptions among the participants.

Results, Discussion, and Analysis

Quantitative data showed that peer test score disclosure was correlated with greater stability of academic scores across two tests. Students who experienced peer test score disclosure had an average Test 1 score of 94.325% and an average Test 2 score of 94.4%, which shows a slight increase of 0.075%. In comparison, students who did not experience peer test score disclosure had an average Test 1 score of 96.5% and an average Test 2 score of 89.5%, which shows a sharp decrease of 7%. Additionally, the range of scores from the disclosed group is significantly lower than the range of the non-disclosed group.

Figure 3

Test 1 and Test 2 average score changes for Disclosure vs. Non-Disclosure groups.



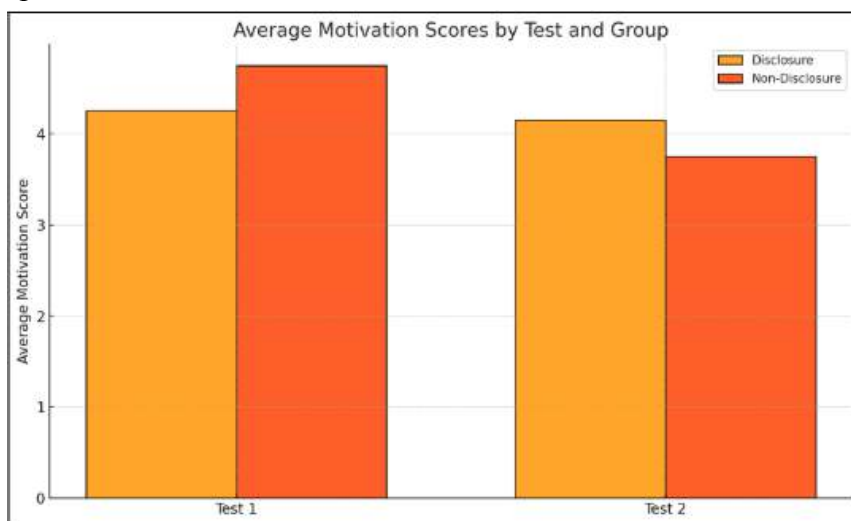
These findings partially support my initial hypothesis that the disclosure of peer test scores leads to better academic performance. While peer test score disclosure was not linked to any significant improvement in academic performance, it stabilized the scores. This is also supported by the fact that when peer test scores were not disclosed (for those who filled out the survey without experiencing disclosure in their class), there was a 7% decline in the average score. Accordingly, peer test score disclosure may not have been linked to the improvement I initially hypothesized; it may help keep scores consistent. These findings are partially in support of previous studies, such as Gendre and Salamanca (2021), which found that when students know there are high scorers in their class, they are likely to improve their performance. However, these results support the findings of Festinger (1954) and Suls et al. (2002), as they show that social comparison is indeed correlated with specific effects, which is evident when comparing the disclosure and non-disclosure groups.

The baseline level of motivation was very high, according to the SIMS scale, with most students reporting scores of 5, 6, and 7 on the 7-point Likert scale. This meant that, since we started with a highly motivated sample, any change in motivation we observed would have had to be significant. For students who experienced peer test score disclosure, the average motivation for Test 1 was 4.25 out of 5, and for Test 2, it was 4.15 out of 5. However, for students who did

not experience test score disclosure, the average motivation for Test 1 was a 4.75 out of 5, and for Test 2, it was a 3.75 out of 5. Again, we see that in the non-disclosure group, there are more sudden changes. This is visually evident in Figure 4.

Figure 4

Average motivation levels before Test 1 and Test 2 within the disclosure and non-disclosure groups.



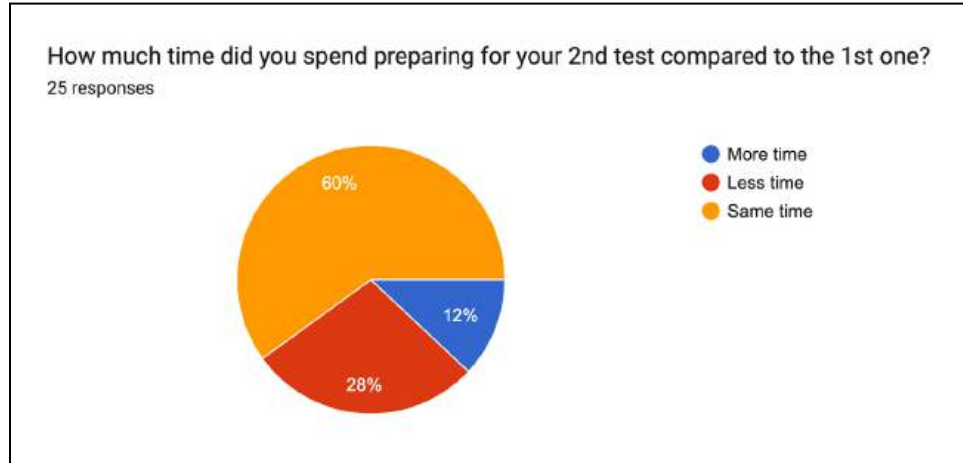
For the disclosure group, the average level of motivation decreased by 0.10 points. For the non-disclosure group, however, the average decreased by 1 point. This suggests that students who did not know their peers' test scores experienced a steeper decline in motivation between the two tests. On the other hand, students who did experience peer test score disclosure remained at relatively consistent levels of motivation (see Figure 4). This also matches the changes we experienced in our academic performance. For the disclosure group in academic performance, we saw consistent scores. However, for the non-disclosure group, we saw a sudden decline in academic performance. The same thing happened with motivation levels, which suggests that peer test score disclosure might be a way to preserve stable motivation levels and academic performance. Again, in my hypothesis, I thought that there would be an increase in overall motivation. My hypothesis was partially correct. Although motivation levels for both disclosure and non-disclosure students dropped, non-disclosure students' motivation levels dropped much more. This means that peer test disclosure is correlated with higher overall motivation compared to the group that does not disclose. However, the motivation for the disclosure group in Test 2 also decreased from that in Test 1, meaning that while peer test score disclosure can help maintain higher motivation compared to not disclosing it, it neither increases motivation nor fully protects it from decline.

In addition to the overall motivation declining for both groups, we can also see the behavioral effects this had on them. Students were asked to report how much time they spent studying for Test 1. Later in the survey, they were asked how much time they spent studying for

Test 2 compared to Test 1. Twenty-eight percent of survey respondents said that they spent less time preparing for their second test compared to their first (see Figure 5).

Figure 5

Time spent studying for Test 2 compared to Test 1.



This shows that not only did the overall motivation of students decline, but the decrease in motivation was also correlated with a reduction in preparation time, which can be referred to as effort. However, open-ended responses made things even more complicated (see Table 1).

Table 1

Table representing the responses to the open-ended question: “Explain how knowing your peers' scores affected your preparation for your 2nd test. If it had no effect, please explain why.”

Students who reported that disclosing peer scores increased their motivation.	13 students
Students who reported that disclosing peer scores did not affect their motivation.	5 students
Students who reported that disclosing peer scores decreased their motivation.	1 student

Although we saw that overall student motivation declined based on the Likert-scale responses, the majority of students reported that peer test score disclosure increased their motivation. Of the 24 total students, 13 reported that their motivation increased after test scores were disclosed (see Table 1). This illustrates that students may not be aware of their changes in motivation. This also highlights a limitation of this study, as self-reported survey data may be inaccurate or biased. Although students may feel that their motivation has increased, this does not always translate into a change on the motivational scales. The increase in motivation that the

disclosed students felt may have contributed to their consistent motivational levels, which we observed (see Figure 4).

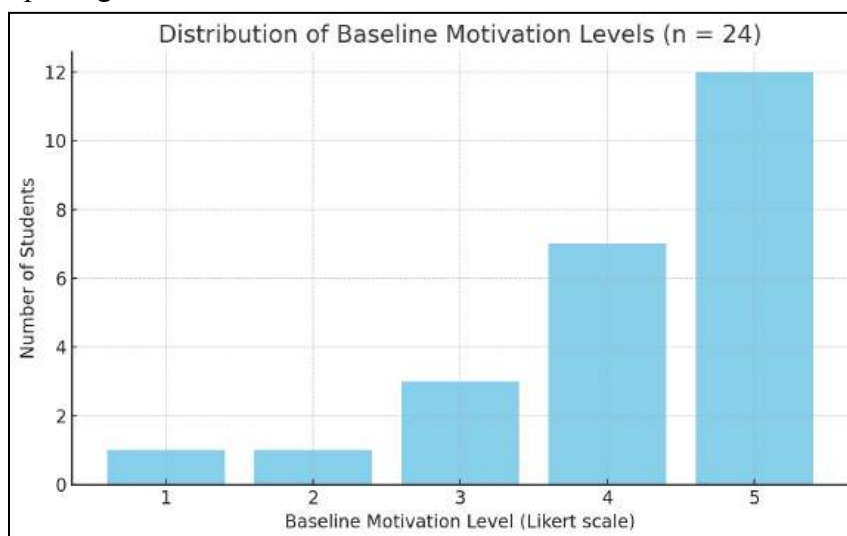
Conclusion, Limitations, Implications, and Future Directions

Before drawing any conclusions, it is essential that I acknowledge the potential limitations of this study. The small sample size ($n = 24$) prevents the generalizability of the findings. In this study, I analyzed the difference in average academic and motivation performance between the disclosure and non-disclosure groups. However, since the sample size was so small, the data variability might be higher than usual. This is because a large sample size is more resistant to outliers and change, while a small sample size is not. Therefore, the small sample size might have led to findings that overstate the impact of peer test score disclosure on motivation and academic performance levels.

Another limitation of this study is the response bias in self-reported data from participants. Due to the use of a survey design, most of the data collected was left to the participants to ensure accuracy and precision. However, at many times, participants do not meet this standard and might report inaccurate information in the survey. This was evident from the results in the open-ended questions. As seen in Table 1, 13 participants reported that disclosing peer test scores increased their motivation levels. However, this trend was not reflected in the Likert-scale questions or the effort questions. This could mean that participants either inaccurately reported their motivation levels on the Likert scale or the open-ended question. Because the participants in this study were self-selected, the sample might be biased towards a more motivated population. This is evident when we look at the baseline motivation levels. As shown in Figure 6, 19 out of 24 participants reported falling into the top two categories of motivation levels. This could be a more motivated sample, which would restrict the generalizability of the results.

Figure 6

Graph depicting baseline motivation levels.



Conclusion and Implications

The research question, “How does peer test score disclosure relate to motivation and academic performance among high school and college students?” can be answered by the trends seen in the data. This research found that while there was no significant increase in academic performance and motivation levels, those who experienced test score disclosure were able to maintain consistent performance and motivation throughout their two tests.

While my hypothesis, which expected the same result as deGendre and Salamanca’s study (2021), was proven incorrect, it still suggests a plausible benefit to disclosing peer test scores. This study presents multiple implications for teachers, especially those with highly motivated students. This study shows that disclosing peer test scores leads to consistency between students’ motivation and performance. Cohen et al. (2022) report that “students’ adaptive motivation to study tends to decrease over time.” Cohen et al. (202) show us that teachers struggle to keep students motivated throughout the academic year. One plausible way to maintain consistent motivation and performance levels throughout the school year could be to use peer test score disclosure. Score disclosure could enable favorable social comparison and lead to consistency in motivation and performance levels. These results align with Festinger’s theory (1954). Festinger (1954) found that social comparison leads students to think about their standing and evaluate their abilities, which, in turn, influences their behavior. These results suggest that there may be a behavior change, given the differences between the disclosure and non-disclosure groups. Although peer test score disclosure may lead to consistency in motivation and performance, teachers should still be cautious when applying score disclosure techniques in classrooms with lower motivation levels, as the effects may vary depending on the environment.

Future Directions

Future studies can be done to research the effects of peer test score disclosure. Future research can help address the limitations of this study. Future research should use experimental designs to examine the impact of peer test score disclosure. In this study, I was only able to see the association between disclosure and motivation and performance, not the actual effect. By utilizing an experimental design, future research can find the genuine cause-and-effect relationship between disclosure, motivation, and performance. Also, by using an experimental design, future research can remove biases that could be present in this study, such as response bias.

Additionally, future research should use larger samples and more effective sampling techniques. This study used voluntary participants, which may have biased the data. However, with the use of sampling techniques, future research can be sure to have more generalizable, bias-free results.

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Identity at the Ballot Box: Race, Ethnicity, and the Highland–Coast Divide in Peru’s 2021 Election

By Camila Angulo

Abstract

This paper examines how racial and ethnic identity shaped voting behavior in Peru’s 2021 presidential election, focusing on the divide between highland Indigenous regions and coastal urban centers. While prior analyses have emphasized class, populism, or party fragmentation, this study foregrounds the role of ethno-racial identity—drawing on theories of ethnic voting, colonial legacies, and representation. Using electoral and demographic data, as well as discourse analysis, it demonstrates how Pedro Castillo’s support in Indigenous-majority regions reflected not only socioeconomic protest but a form of political recognition and identity affirmation. The paper argues that colonial hierarchies continue to structure Peru’s electoral geography and that ethnic identity shaped how voters connected with candidates—both emotionally and as a shortcut for judging who would represent their interests. By centering race, ethnicity, and historical exclusion, this paper contributes to a growing reevaluation of Peru’s place within broader patterns of ethnic politics in Latin America.

Introduction

In 2021, Peru’s bitterly contested presidential election was framed around a powerful slogan: “¡No más pobres en un país rico!” (“No more poor people in a rich country”) (Sanborn). With this phrase, Pedro Castillo — a former rural schoolteacher and union leader from the Andean region of Cajamarca — launched one of the most polarizing campaigns in the country’s modern history. Wearing a traditional straw hat and promising to govern on behalf of the *Perú Profundo* — a term often used to describe the rural and Indigenous heartland of the country — Castillo positioned himself as the embodiment of the forgotten interior, pledging to rectify the “historical injustices” left by Spanish colonial rule (Guardado). His rise to national prominence was both rapid and unexpected, emerging from near anonymity amid a deeply fragmented political landscape (Axelsson).

In stark contrast stood Keiko Fujimori, daughter of authoritarian ex-president Alberto Fujimori, who represented the urban political establishment (Simauchi). A conservative congresswoman and three-time presidential candidate, Fujimori drew her support primarily from Lima — the coastal capital and longtime seat of political and economic power — as well as from the upper and middle classes, large business interests, and those nostalgic for her father’s hardline rule (Simauchi).

This contrast between Castillo and Fujimori — rural vs. urban, outsider vs. establishment, highlands vs. coast — captured the deep societal divides that marked Peru’s 2021 presidential election. In the first round held on April 11, a fragmented field of 18 candidates split the vote, with Pedro Castillo, representing the Marxist-oriented Perú Libre (Free Peru) party, receiving only 18.9%, and Keiko Fujimori, running under the right-wing Fuerza Popular (Popular Force), securing 13.4% (National Office of Electoral Processes). Despite these low margins, both

advanced to a runoff on June 6. In one of the closest elections in Peruvian history, Castillo narrowly defeated Fujimori by roughly 44,000 votes (National Office of Electoral Processes). Geographically, the split was clear: Castillo dominated the Andean highlands and the southern interior, while Fujimori won decisively in Lima and urban centers along the northern coast (National Public Radio). As political scientists Encinas and Fuentes observe, voters from the highland interior and those on the coastal plain moved in almost exactly opposite directions (272).

While many academic analyses of the 2021 election have focused on party collapse, class conflict, or regional polarization, these frameworks may overlook another fundamental dimension: race and ethnicity — a persistent, though often implicit, force in Peruvian political behavior. Muñoz, for instance, emphasizes the extreme weakness of Peru's parties and a growing crisis of representation, noting that this environment “intensified regional and socioeconomic fragmentation” (286). Other scholars frame the election as a clash between leftist populism and right-wing authoritarianism (Ilizarbe 360). Although racial and ethnic identity became a central theme in public discourse, media coverage, and political commentary during and after the election, academic treatments of these dynamics remain relatively scarce. This gap obscures a crucial dimension of the electoral divide: how enduring, racialized hierarchies — rooted in Peru's colonial past — may have shaped voter behavior.

Across Latin America, colonial legacies continue to structure contemporary politics. Indeed, Peruvian sociologist Aníbal Quijano argues that Spanish colonialism implanted a lasting racial-caste hierarchy that placed Europeans and their descendants at the top and Indigenous peoples at the bottom — a structure that has deeply shaped Peru's institutions, land tenure systems, and social imaginaries through education and language (Quijano).

In several Andean countries, such as Bolivia and Ecuador, these colonial legacies have given rise to explicitly ethnic political movements and parties (Yashar; Madrid). In Peru, however, racial and ethnic identity often operates more implicitly — shaping voter behavior without formal institutional representation. As Kelly notes, the absence of a nationally prominent Indigenous party in Peru has contributed to a scholarly tendency to treat the country as an exception, often excluding it from broader analyses of ethnic voting in Latin America.

This paper builds on a growing scholarly effort to challenge the notion that Peru is an exception in Latin America's ethnic politics. Building on Kelly's foundational work, and drawing on more recent research by Lau, which identifies emerging patterns of identity-based voting in Peru, it contributes to a field still in development — despite increasing evidence of ethnic voting behavior.

Drawing on Kelly and Wolfinger, this research understands ethnic voting as situations in which identifying with an ethnic or racial group functions as an “important independent variable in determining the vote” (Wolfinger 41). Furthermore, it argues that overlooking race and ethnicity obscures a crucial dimension of Peru's electoral geography. If the social order described by Quijano continues to shape Peruvian society, then the coastal–highlands electoral divide of 2021 may be its contemporary echo. Thus, this paper asks: How did racial and ethnic identity

influence voting behavior in Peru's 2021 presidential election, and how do historical inequalities shape this divide between highland Indigenous and coastal urban regions?

While acknowledging that other historically marginalized groups — such as Afro-Peruvians and Amazonian Indigenous peoples — also experience racial exclusion, this paper focuses specifically on the longstanding stratification between Indigenous Andean communities and the coastal mestizo and white elites. This focus reflects the electoral and regional polarization most visible in the 2021 presidential election, where the divide between these two segments of the population emerged as especially pronounced (Encinas and Fuentes; Lau). Rather than suggesting these are the only groups affected by structural racism, the aim here is to analyze a divide that, according to both voting patterns and existing scholarship, played a central role in shaping the election's outcome.

Indeed, understanding the significance of this divide requires a broader historical lens. This identity-based alignment cannot be understood in isolation: it must be situated within Peru's long history of institutionalized exclusion — a legacy that also shaped reactions to Castillo's unexpected rise and remains underexplored in the academic literature on the 2021 election.

By examining the 2021 presidential election through the lenses of ethnic voting and structural racism, this paper aims to reveal how colonial hierarchies continue to influence contemporary political behavior — particularly the divide between highland Indigenous voters and coastal mestizo and white populations. In doing so, it contributes to the broader literature on race and democracy in Latin America and challenges the notion that Peru is an exception to regional patterns of racialized voting.

Literature Review

1. What do race and ethnicity mean in the Peruvian context?

Unlike the biological definitions often assumed in popular discourse, scholars emphasize that race and ethnicity are socially constructed: race is typically linked to perceived physical traits—such as skin color or facial features—while ethnicity refers to shared cultural practices, language, and ancestry (Blakemore). However, these categories are not fixed; they are shaped by historical, political, and social processes.

Peruvian sociologist Aníbal Quijano describes race as a “mental category of modernity” that emerged with European colonization. Before the conquest of the Americas, the concept of race—as understood today—did not exist. Colonial authorities constructed racial classifications such as “Indians,” “Blacks,” and “Mestizos” to legitimize conquest and domination (Quijano 534). These categories gave rise to a racial-caste hierarchy that has persisted through institutions, educational systems, and power relations. Quijano refers to this as the *Coloniality of Power*—a framework that explains how colonial distinctions based on race, geography, and culture were not dismantled with independence, but instead embedded into the foundation of modern Latin American societies. In Peru, this means race functions not merely as a cultural identity but as a

marker of power, legitimacy, and political belonging—a dynamic that continues to shape social and political life, including voting behavior.

Ethnicity, by contrast, is typically defined by cultural markers such as language, tradition, or religion. For instance, Peter Wade notes that in Latin America, distinctions between “Indigenous” and *mestizo* populations have historically been treated as ethnic—based on dress, language, or rurality—rather than strictly racial (184). It is important to note that while race and ethnicity often intersect, they are not interchangeable. Ethnicity tends to reflect shared cultural heritage, as seen in communities such as Quechua-speaking highlanders or Amazonian tribes. Race, in Peru, has been more deeply influenced by colonial logics that associate physical appearance and ancestry with social status and power (Paredes). Out of this system, “mestizo”—broadly understood as individuals of mixed Indigenous and Spanish ancestry who are culturally assimilated—emerged as the dominant national archetype.

This Peruvian case reflects a broader Latin American pattern, where race and ethnicity are uniquely intertwined. Wade argues that Latin American racial thought is *sui generis*—shaped by colonial and postcolonial histories, yet still influenced by the global entanglement of nature and culture. A central example is *mestizaje*, the ideology of racial and cultural mixing. As Marisol de la Cadena explains, *mestizaje* in Peru blended colonial ideas of *limpieza de sangre* (purity of blood) with Enlightenment-era racial typologies (62). She calls this an “epistemological mixing”: a hybrid framework where racial categories were defined using both cultural and biological criteria. In practice, this meant race was often assessed less by fixed physical traits and more by cultural assimilation—such as Spanish fluency, Western dress, or Catholic faith. As a result, racial identity could be fluid, dependent more on behavior than phenotype or ancestry. Though *mestizaje* was promoted as a symbol of unity, it often masked persistent hierarchies that privileged urban, Spanish-speaking mestizos over Indigenous people (Paredes).

Peru’s social categories reflect this colonial legacy. “Indios” traditionally referred to rural, Quechua-speaking highlanders; “mestizos” to culturally assimilated individuals of mixed Indigenous–Spanish descent; and “criollos” to white, American-born Spaniards (Cánepa 15). These terms mapped a racialized social order: coastal *criollos* held power, while *indios* were viewed as backwards. Early 20th-century indigenist writers reinforced this by portraying rural Andeans as a deficient “race.” De la Cadena cites a 1922 Cuzco account describing Indians as having “intellectual impediment” (307), and shows how even supposed praise for mestizos positioned them above living Indigenous peoples (310).

By the late 20th century, cultural identity and ethnicity became more prominent in official discourse. Peru’s 1993 Constitution formally recognized “the ethnic and cultural diversity of the Nation” (Schmassman), naming Quechua, Aymara, and Amazonian cultures alongside the dominant coastal mestizo culture. Yet historical inequalities persist. Paredes notes that even after democratic reforms in 1980, the Peruvian state remained “Lima-centered and predominantly white and mestizo led” (4). National identity continued to be shaped in *criollo-mestizo* terms, marginalizing highland and Indigenous perspectives. This colonial legacy — of race as a caste

system and ethnicity as staged cultural difference — has deeply influenced Peru’s political landscape. In this system, individuals of European descent occupied the top tier, while those of Indigenous or African ancestry were placed lower — a hierarchy that persisted long after independence (Martínez and Iyer; Quijano).

Having outlined the social construction of race and ethnicity in Peru, this section turns to their historical entrenchment through colonial rule and how those structures have persisted into the Republic. Understanding this continuity is essential for analyzing how contemporary patterns of exclusion—such as the geographic polarization in the 2021 election—are rooted in long-standing racial and regional hierarchies.

2. Historical legacies and racial stratification in Peru

The social meanings of race and ethnicity in Peru cannot be fully understood without examining their historical origins in the colonial period. Scholars agree that Peru’s deep inequalities have roots in its colonial past. Beginning with the Spanish conquest, a rigid caste system placed European-born and creole elites at the top and subordinated Indigenous and African-descended peoples. In effect, colonial Peru was “a multiethnic, hierarchical society, where the indigenous populations are second-rate citizens” (Figueroa and Barrón 2). This system allocated economic and political power to the coastal criollo (white and mixed-race) elites and relegated Andean communities to a labor role. As economist Rosemary Thorp notes, geographic and institutional factors “marginalized the sierra (the Andean highlands), and with it, the indigenous population,” leaving the highlands outside mainstream development. After two centuries of exploitation under Spanish rule, the Andes did not modernize but served mainly as a labor reserve for coastal exports. These patterns of land use and labor helped concentrate political and economic power on the coast (Thorp and De los Ríos).

Even after independence, colonial hierarchies left a legacy of exclusion. The legal and social designation of *indio* in the Republic became almost synonymous with poverty (Thorp and De los Ríos). For instance, sociologist Guillermo Rochabrún observes that the *curaca* (Indigenous leader) class was dismantled early in republican Peru, so that by the late 1800s being called an *Indio* effectively meant being poor (Manrique). In practice, the republican state preserved many colonial-era inequalities. Anthropologists describe Peru’s society as remaining divided along “dividing lines...based on phenotypic traits” – that is, racialized social categories rooted in history (Manrique). Cultural analysts also highlight how racist ideologies such as *blanqueamiento* (‘whitening’—the aspiration to become socially and culturally whiter) persisted through the Republic, maintaining the colonial fantasy of a “white” nation that needed to distance itself from Indigenous roots (Vich; Thorpe and De los Ríos).

These racial and regional hierarchies—rooted in colonialism and reinforced throughout the Republic—continue to shape how populations relate to power and vote today. For example, regions with a history of more intensive colonial control showed significantly higher support for Castillo in 2021, linking centuries-old marginalization to contemporary identity-based voting (Guardado).

3. Ethnic voting in Peru

While much of the scholarly literature has focused on regional and socioeconomic disparities in explaining Peru's electoral outcomes, such approaches do not fully account for the patterns of support observed in the 2021 presidential election. To understand the geographic polarization between the coast and the highlands, it is necessary to consider how ethno-racial identity intersects with political preferences—a phenomenon widely recognized in the literature as “ethnic voting”.

As stated in the introduction, this paper understands ethnic voting as situations in which identifying with an ethnic or racial group functions as an “important independent variable in determining the vote” (Wolfinger 41). Sam Kelly, in his in-depth study of ethnic politics in the Andes, further refines this concept through the notion of “ethnic bias”—defined as a consistent pattern of electoral behavior that cannot be fully explained by socioeconomic status or ideological preferences (15). He identifies two main mechanisms: *expressive* ethnic bias, in which voters feel a psychological attachment to their ethnic group that predisposes them to support candidates perceived as ethnically proximate; and *heuristic* ethnic bias, in which ethnicity serves as an “informational shortcut” that allows voters to infer a candidate’s likely values, background, and policy orientation. In this view, ethnic cues—such as language, clothing, or origin—help voters evaluate which candidates are most likely to represent their interests, especially in contexts where formal party structures are weak or trust in institutions is low (15–17).

In the broader Latin American context, ethnic voting has become a central lens through which electoral behavior is analyzed, particularly in Andean countries where ethnic divisions frequently align with regional divides between highland and lowland populations (Madrid 271). Bolivia and Ecuador, for example, have developed nationally relevant Indigenous political parties such as Movement Toward Socialism (MAS) and Pachakutik, which have played prominent roles in shaping electoral landscapes. By contrast, Peru has not produced a nationally relevant Indigenous political party or movement capable of competing successfully in presidential elections (Kelly 165). This institutional absence has contributed to what Kelly describes as Peru’s “exceptionalism” in the academic literature: a tendency among scholars to treat Peru as an outlier in studies of ethnic voting, based on the mistaken assumption that ethnicity plays a weaker role in its electoral dynamics (Kelly 164–165).

Nonetheless, scholars have pointed to the existence of an “ethnic voting gap” in Peru, evidenced by consistent electoral differences between Indigenous-majority regions in the Andes and largely mestizo, coastal areas (Kelly; Madrid; Nureña et al.). This form of ethnic voting does not necessarily imply support for co-ethnic candidates. Rather, it refers to voters responding to cultural cues, symbolic representation, and perceived shared experiences. Candidates who perform cultural proximity to Indigenous or rural populations—through dress, discourse, or use of Indigenous languages—may be perceived as more representative of marginalized groups, even when they are not of Indigenous descent themselves.

Historical examples include Alejandro Toledo's emphasis on his Andean roots and Ollanta Humala's nationalist and anti-colonial rhetoric, which appealed to rural highland voters (Kelly 169). Pedro Castillo's 2021 campaign followed this pattern. A rural schoolteacher from Cajamarca, Castillo frequently wore a straw hat typical of the Sierra region and occasionally spoke Quechua in public appearances. These cultural signals, combined with his anti-elite rhetoric and the slogan "No más pobres en un país rico," helped position him as a candidate who embodied the lived experiences of Peru's most excluded populations (Al Jazeera; Ojo Público). According to data from Ojo Público, Castillo won in approximately 90% of districts containing officially recognized Indigenous communities, including Cusco, Puno, Apurímac, and Ayacucho.

Although Peru lacks a formal Indigenous political movement, these patterns suggest the emergence of an informal ethno-political cleavage. In previous decades, the Andean vote had been mobilized largely through class-based appeals, particularly by parties like APRA and Acción Popular. But since the 1980s, after the lifting of literacy requirements and the expansion of suffrage, candidates have increasingly drawn on ethnic and cultural imagery to mobilize rural constituencies (Madrid 270). Politicians such as Fujimori, Toledo, and Humala leveraged these appeals—without necessarily adopting ethnic platforms or addressing structural inequalities—yet they still achieved considerable electoral success in highland regions (Kelly; Madrid; Quiroz).

These patterns in the 2021 election reinforce the argument that Peru is not an outlier, but part of a broader Andean trend in which voters respond to cultural and ethnic cues in the absence of formal Indigenous institutions. Rather than relying solely on geographic or economic explanations, ethnic voting provides a more accurate framework for understanding the enduring influence of ethno-racial hierarchies on Peru's electoral landscape.

4. Dominant Explanations of the 2021 Election

Scholars analyzing Peru's 2021 presidential runoff have proposed multiple explanations—ranging from structural inequality to populist discourse—but few have addressed how race and indigeneity shaped electoral behavior. Thus, they often overlook the racial and cultural dimensions of voter behavior, as discussed below.

4.1 Class and Geography

Many scholars frame the election as a reflection of enduring class and regional divides. Muñoz argues that the 2021 election "reflects [...] the salience of preexisting regional and socioeconomic divides" (296). She describes a clear gulf between Lima and coastal areas, and Peru's poorer "peripheral zones": Castillo was "the candidate of those peripheral areas," while Fujimori drew her support chiefly from Lima and other more affluent coastal districts (Muñoz 4). Likewise, Guardado finds that Castillo's vote was strongest in the poorest rural regions (often with large Indigenous populations) and correlates with historical colonial-era burdens on those provinces (Guardado). In this framing, the election is interpreted as a structural backlash: a protest against the exclusionary nature of Peru's political and economic system. For example, Muñoz notes that disaffected voters turned to anti-system outsiders amid a weak party system

and crises, and that Fujimori ran a fear-based, nationalist campaign targeting middle and upper classes in Lima (291). Castillo's campaign, by contrast, successfully mobilized voters who were mostly poorer and rural by invoking his humble, Andean origins (297). While these accounts are valuable, they often treat race and ethnicity as peripheral concerns—an omission explored more fully below.

4.2 Populism and Political Style

Building on these socioeconomic analyses, many political scientists emphasize populist and ideological dynamics. Muñoz observes that Peruvian voters were “disaffected and discontented,” which led to a polarized runoff between a right-wing insider (Fujimori) defending the market order and a left-wing outsider (Castillo) promising radical change (301). Fujimori's campaign explicitly framed Castillo as a “communist,” mobilizing Lima's middle and upper classes around fears of instability (297). Meanwhile, Castillo positioned himself as the representative of the “Deep Peru” (the rural Andes and Amazon) and called for a new constitution to empower the marginalized (Guardado.). These accounts often portray the election as a clash of populisms rather than a referendum on race or indigeneity. However, these ideological cleavages also mirrored deeper cultural fault lines between Lima and the highlands. For instance, Castillo's rallies drew massive crowds in historically marginalized regions like Cusco and Puno (Asensio et al. 64–65), while Fujimori's support remained concentrated in coastal urban areas (Escárzaga).

4.3 Racism and Classism in Campaign Discourse

Beyond structural exclusion, the 2021 election also exposed how racism and classism manifested in public discourse. Escárzaga documents how Fujimori's supporters circulated hateful messages on social media, including calls to “destroy Ayacucho” and fantasies of violence against Quechua-speaking women (89). Her post-election fraud claims reflected racialized assumptions: that Indigenous highland voters were either incapable of voting properly or complicit in fraud. Villasante highlights how elite commentators routinely portrayed Castillo's base as ignorant, violent, or backwards. Even public intellectuals like Mario Vargas Llosa described Castillo's rise as a threat from the “barbaric” interior, reinforcing colonial binaries of civilization versus savagery (Escárzaga 81). These examples reveal how racial and class hierarchies were reinscribed through political language—often by those defending the status quo.

4.4 Ethnoracial Visibility as Political Assertion

While most explanations focus on class, populism, and geographic disparities, a smaller body of literature highlights the role of race and indigeneity more directly. Guardado shows that Castillo's strongest support came from “poor, rural, and Indigenous” areas, and that district vote shares correlated closely with the percentage of Indigenous-language speakers. Castillo publicly embraced and foregrounded his Indigenous Andean identity—crediting the Deep Peru for his victory and positioning himself as a rural schoolteacher from the highlands. Anthropologist

Fabiola Escárzaga interprets his win as a symbolic triumph for “plebeian, popular, [provincial]” sectors—an expression of ethnoracial recognition, not merely class revolt (89). From this perspective, the election was a moment in which Indigenous Andean populations asserted their cultural and political legitimacy in a system that has historically excluded them. The racialization of the vote, while rarely emphasized in mainstream political science, was visible in both campaign discourse and public reactions.

Gaps and Omissions in the Literature

Despite these patterns, most academic accounts underplay the role of race and indigeneity. Political scientists and pollsters tend to focus on ideology, class, and institutional decay, often describing Andean voters as “poor” or “peripheral” without identifying them as Indigenous. Muñoz, for instance, never uses the word “Indigenous,” and Guardado treats it largely as a demographic category without sustained analysis. Among the few exceptions, Sam Kelly remains the only scholar to systematically conceptualize ethnic voting in Peru as a behavioral mechanism—introducing frameworks such as expressive and heuristic ethnic bias to explain symbolic attachments and cultural proximity in electoral behavior. Meanwhile, Nureña et al. analyze long-term electoral patterns in the Southern Andes from 1980 to 2021, explicitly framing them through the lens of ethnic voting. However, because their focus is on historical continuity, their treatment of the 2021 election is brief and does not engage substantively with candidate positioning, campaign discourse, or symbolic cues. To date, no academic study has examined how ethnic or racial identity shaped voter behavior in the 2021 presidential election in behavioral and discursive terms. While anthropologists such as Escárzaga and Villasante do address race and indigeneity—particularly in relation to symbolic conflict and public discourse—their contributions remain rare and are not framed in terms of ethnic voting per se. As a result, the literature continues to overlook how colonial hierarchies shape not only identity but also electoral behavior. This paper builds on these critiques by analyzing how racialized narratives and ethnoracial hierarchies shaped voter perception, political legitimacy, and public discourse following the 2021 election.

Materials and Methods

This research is grounded in an approach that combines qualitative discourse analysis with quantitative electoral and demographic data interpretation. To explore how racial and ethnic identity influenced voting behavior in Peru’s 2021 presidential election—and how historical inequalities shaped the divide between highland Indigenous regions and coastal urban centers—this paper drew on official data, visual sources, and scholarly and journalistic interpretations.

First, electoral data published by the National Office of Electoral Processes (ONPE), Peru’s official electoral authority, served as the primary source for tracking second-round results disaggregated by department. This geographic data was cross-referenced with sociodemographic indicators to identify spatial voting patterns. An electoral map published by BBC News Mundo,

offering a visual breakdown of the vote distribution between Pedro Castillo and Keiko Fujimori, was especially useful in identifying regional trends.

To contextualize these voting patterns, demographic data from the National Institute of Statistics and Informatics (INEI) was examined, particularly census reports detailing the percentage of the population identifying as Indigenous and the prevalence of Indigenous language speakers (notably Quechua and Aymara). These figures were instrumental in correlating highland areas with strong Indigenous presence and their electoral behavior, as contrasted with urban and coastal regions.

A range of secondary sources complemented the quantitative data. These include the Bertelsmann Transformation Index (BTI), reports by Al Jazeera and the Washington Office on Latin America (WOLA), and academic studies analyzing the racial, spatial, and political polarization observed during the 2021 election. Such sources provided essential interpretive frameworks to understand long-standing patterns of exclusion, voter disenfranchisement, and structural marginalization.

Although the research does not involve primary fieldwork, it relies on publicly accessible, credible, and verifiable datasets and documents. The methodology centers on cross-referencing electoral maps, demographic statistics, and narrative sources to identify patterns that reflect the lived experiences of voters—particularly those in historically marginalized Andean communities.

Discussion

The 2021 Peruvian presidential election brought to light stark regional, ethnic, and socio-economic divides that have long structured the country's political landscape. Rather than reflecting a uniform national vote, electoral preferences followed consistent spatial patterns, closely aligned with demographic indicators such as language, ethnicity, and region. These trends are not new; however, their reemergence in such a polarized context underscores the persistent influence of structural inequalities on electoral behavior. This section examines the territorial distribution of the vote, highlighting the correlation between support for Pedro Castillo and regions with high proportions of Indigenous and Quechua-speaking populations—particularly in the rural highlands—as opposed to the stronger backing for Keiko Fujimori in coastal urban centers, especially Lima. By drawing on demographic data and voting outcomes, this analysis also engages with the theory of ethnic voting to explore how cultural and racial identity shaped political preferences in the 2021 runoff. It further considers how these patterns were reflected in voter mobilization and turnout, and how elite reactions to the election revealed persistent hierarchies of political legitimacy rooted in Peru's colonial legacy.

Regional Voting Patterns (2021 Runoff)

Building on this broader context, the territorial breakdown of the 2021 runoff reveals a pronounced electoral divide between Peru's rural highlands and its urban coastal centers.



Figure 1: Division of the Vote in Peru by Region in the 2021 Runoff

As illustrated in Figure 1, Pedro Castillo achieved decisive victories in 16 of the country's 25 departments, especially in the central and southern highlands, where historically underserved Indigenous communities predominate. In departments such as Puno (89.3%), Ayacucho (82.6%), and Cusco (83.2%), Castillo captured more than four-fifths of the vote (ONPE, 2021). These regions—marked by poverty, infrastructural neglect, and limited state presence—appeared to strongly identify with Castillo's message of anti-establishment renewal and his background as a rural schoolteacher from Cajamarca (Eschenbacher and Ponce).

In contrast, Keiko Fujimori won in Lima (65.7%), Callao, and other coastal regions such as La Libertad (60.0%), Lambayeque (58.2%), and Ica (52.5%)—departments with greater urbanization, stronger market integration, and less Indigenous visibility (ONPE; BTI). A May 2021 Ipsos poll similarly reported Castillo leading by 63.3% in rural Peru, compared to only 29.1% in Lima, indicating the extent to which geography intersected with class, identity, and access to services (Ipsos).

This territorial divide reflects more than just socio-economic polarization, it resonates with Peru's long history of centralism and exclusion. As Guardado has argued, provinces with more intense colonial-era extractive control tend to show higher contemporary support for anti-establishment candidates like Castillo, revealing how historical marginalization continues to structure political agency (Guardado). In this sense, the electoral map functions as a mirror of Peru's uneven development and the enduring salience of geographic hierarchies in shaping political allegiances.

Ethno-linguistic Identity and Voting Patterns

If territorial voting patterns were stark, the ethno-linguistic dimensions of the 2021 election were no less revealing. Census data show that language and cultural identity are closely linked to political behavior, particularly in Andean regions where Indigenous populations remain concentrated. According to the 2017 National Household Survey (ENAH0), the percentage of people self-identifying as Indigenous—whether Quechua, Aymara, or Amazonian—ranges from over 80% in Puno to less than 10% in coastal regions like Tumbes, Piura, and Lima.

This spatial concentration is visually evident in Figure 2, which maps self-identified Indigenous populations by region. The darker shades—indicating higher Indigenous self-identification—closely align with departments that overwhelmingly supported Pedro Castillo in the runoff. For example, Apurímac (86%), Huancavelica (80%), Puno (84%), and Cusco (72%) all report high percentages of Quechua-speaking or Indigenous-identified residents and simultaneously gave Castillo upwards of 80% of the vote (INEI; ONPE).

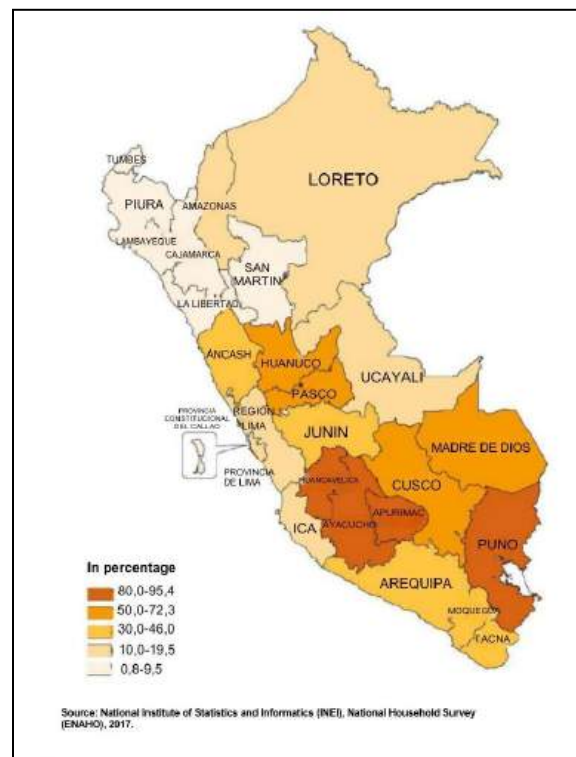


Figure 2: Self-identified Quechua, Aymara, and Amazonian Indigenous Population by Region, 2017

This relationship becomes even more striking when analyzed quantitatively. As shown in Figure 3, Castillo's regional vote share in 2021 correlates positively with the percentage of Indigenous language speakers, particularly Quechua. Drawing on data from the most recent national census conducted by INEI in 2017, the Center for Economic and Policy Research (CEPR) compared these figures with second-round vote shares and found a clear statistical association: regions with greater linguistic Indigenous density were also those where Castillo received his strongest support (CEPR).

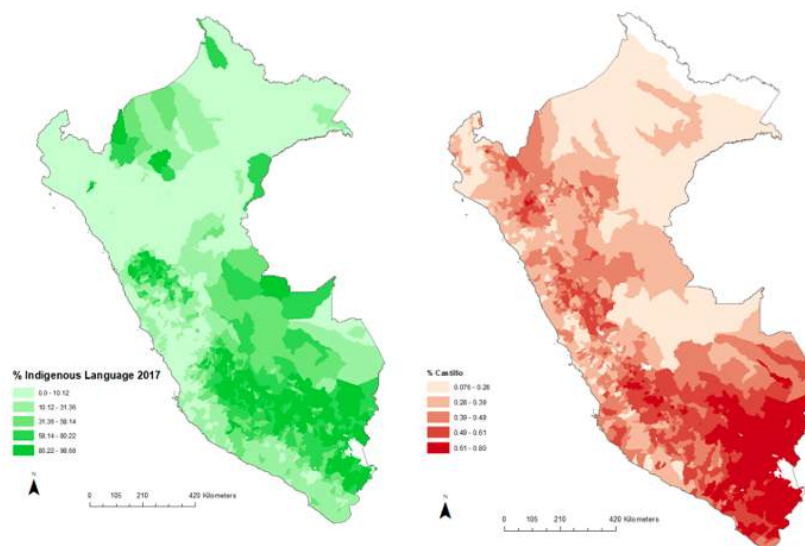


Figure 3: Percentage of Indigenous Language Speakers by District (2017) (L) and Support for Pedro Castillo in the 2021 Presidential Runoff (R)

These patterns suggest that Indigenous identity—both in terms of self-recognition and linguistic practice—played a decisive role in shaping political preferences. Crucially, this is not merely a demographic observation; it speaks to deeper political dynamics. Language and ethnicity in Peru function as markers of historical inclusion or exclusion. As theorized by Aníbal Quijano, the Peruvian state has been structured through the “coloniality of power,” whereby racial and cultural distinctions rooted in colonialism continue to determine access to legitimacy, visibility, and influence.

Thus, support for Castillo among Quechua-speaking and self-identified Indigenous communities cannot be reduced to economic protest alone. It should also be read as an act of symbolic and political affirmation—what the CEPR termed ethno-political mobilization. As Indigenous voters turned out in record numbers, particularly in highland departments, their votes expressed more than a partisan preference: they represented a long-silenced claim to national belonging.

Political Mobilization and Voter Turnout

While territorial and ethno-linguistic patterns defined electoral preferences in 2021, equally notable was the surge in political mobilization among historically marginalized communities. According to ONPE, national voter turnout rose from approximately 70% in the first round (April) to nearly 78% in the second round (June), with the most dramatic increases recorded in highland departments like Puno, Ayacucho, and Apurímac—regions where Castillo had already performed strongly (ONPE).

This increase was not evenly distributed. Urban centers like Lima and Callao exhibited minimal changes in turnout between rounds, while rural Sierra departments mobilized at even

higher rates than usual. This trend marked a departure from previous elections, where voter fatigue or logistical barriers often suppressed turnout in remote regions. In contrast, the 2021 election showed a new urgency: voters in Peru's "deep interior" saw their participation not just as a right but as a form of political assertion.

Importantly, this mobilization became most visible during the late stages of vote counting. As ballots from rural provinces trickled in, Castillo's national vote share steadily increased, overturning early leads held by Fujimori and bringing national attention to regions that are typically sidelined in Peruvian media and politics (EU Election Expert Mission to Peru). The Sierra's votes were decisive—not only in numerical terms but symbolically. Their weight in the outcome re-centered long-neglected populations within national political discourse, affirming that these communities were not passive recipients of politics but active agents in shaping Peru's democratic trajectory.

Political Exclusion and Electoral Legitimacy

However, the same regions that delivered Castillo his victory soon became the target of post-electoral scrutiny. Voters in rural, Quechua-speaking areas did not merely choose Castillo out of economic frustration—they cast ballots as an act of political inclusion and recognition. Yet parts of the political establishment treated their participation as suspect. Following the runoff, Keiko Fujimori's campaign filed legal challenges contesting tens of thousands of votes—almost all from highland departments like Cajamarca, Cusco, and Puno, where Castillo's support had been overwhelming (WOLA).

This legal offensive was unprecedented in scope and racially and geographically concentrated. According to WOLA, Fujimori's team attempted to nullify more than 200,000 votes, the majority from Quechua-speaking, rural areas. Observers such as the Organization of American States (OAS) and the EU Election Expert Mission declared these fraud claims baseless and affirmed the integrity of the election (EEAS). The U.S. State Department likewise stated that Peru's elections were "a model of democracy in the region."

Still, the implications of these challenges extended far beyond technical concerns. Headlines and elite commentaries did not simply question the legality of the vote—they implicitly cast doubt on whether ballots from Indigenous-majority regions should "count" the same. Discussions among elite opinion-makers sometimes suggested that rural Andean votes be "verified more closely," reflecting a persistent hierarchical view that the votes of Indigenous or poorer citizens are less informed or legitimate (Collins).

This racialized scrutiny of the electoral outcome underscores what Deborah Yashar has termed "differentiated citizenship," in which Indigenous populations are formally recognized but systematically subordinated in practice. The response to Castillo's victory—legal challenges, media narratives, and protests by retired military officers—revealed the endurance of this exclusionary logic. As Aquino reports, many right-wing protests in Lima echoed the sentiment that rural votes were inherently suspect, despite international observers confirming a clean and fair election.

Castillo himself alluded to this sentiment in his victory speech, thanking “those who defended the vote of the people of the deep Peru.” His words captured what the election symbolized for many Indigenous voters: a rare assertion of political voice within a system historically designed to exclude them. These developments illustrate that the act of voting in the Andes reawakens long-standing anxieties about national belonging, authority, and who gets to define Peru.

Ethnic Voting in Peru’s 2021 Presidential Election

This final section reframes the patterns previously examined—regional cleavages, ethno-linguistic correlations, turnout surges, and post-electoral contestation—through the lens of ethnic voting, particularly as conceptualized by Sam Kelly. Rather than viewing Castillo’s support as a purely economic protest or an anti-system backlash, this paper argues that ethno-racial identity operated as a core behavioral mechanism—a framework through which historically marginalized voters evaluated political options, asserted belonging, and exercised agency.

As outlined in the literature review, Sam Kelly defines ethnic voting as a pattern where an individual’s racial or ethnic group membership meaningfully influences their vote, even after controlling for other factors. Within this framework, Kelly distinguishes two mechanisms through which this influence can operate. The first is expressive ethnic bias, which refers to voting as a form of identification or symbolic affirmation—supporting a candidate not necessarily for material gains, but because they are perceived as reflecting the voter’s group identity or collective experience. The second mechanism is heuristic ethnic bias, in which voters use a candidate’s perceived ethno-cultural traits—such as origin, language, or appearance—as shortcuts to infer how that candidate might govern, especially in contexts where party labels are weak or uninformative.

Both dynamics were present in Pedro Castillo’s 2021 campaign. While he did not formally run as an ethnic candidate, his biography, aesthetic presentation, and rhetoric conveyed a sense of cultural proximity to rural Indigenous and Indigenous-mestizo populations. His Quechua-speaking background, his identification with the Perú profundo, and his use of symbolic markers like the wide-brimmed straw hat activated a range of affective and cognitive responses that fit the expressive and heuristic models described above. Voters could see themselves in him—and also project onto him an expectation that he would understand and defend their interests, even if they lacked detailed policy knowledge.

This does not mean that ethnicity operated alone or that voters made decisions purely on identity. Rather, as Kelly argues, ethnic cues become meaningful when they substitute for weak institutional signals, especially in countries like Peru where party systems are fragmented and trust in elites is low. In that sense, Castillo’s cultural proximity functioned as an interpretive tool for voters navigating uncertainty.

Moreover, the 2021 election also reflected what scholars have termed negative ethnic voting or “voto en contra”—a dynamic in which voters oppose candidates they associate with

exclusionary or historically dominant groups. According to Nureña et al., electoral patterns in the southern Andes across multiple election cycles show a consistent rejection of candidates linked to the criollo elite of Lima, a phenomenon especially pronounced in provinces with high Quechua and Aymara populations. In 2021, this dynamic reemerged sharply: for many rural and Indigenous voters, Fujimori symbolized a continuation of racialized elite rule, and the act of voting for Castillo was also a rejection of that symbolic order.

This form of voting against an “out-group” has precedent. As noted in Kelly’s comparative analysis of Bolivia and Peru, negative attitudes toward racially distinct elites often strengthen support for culturally proximate candidates, even in the absence of clear co-ethnic identification. It also echoes Madrid’s findings across the Andes, which suggest that symbolic and affective identification can substitute for institutional ethnic party structures. In Peru’s case, where no formal Indigenous party has emerged, symbolic resonance still generated strong electoral outcomes along ethno-regional lines.

Thus, ethnic voting in Peru should be understood as bidirectional: it involves both symbolic alignment with a candidate who reflects collective memory and a repudiation of those linked to exclusionary histories. Voters did not need to articulate this in explicitly ethnic terms for it to function as such. The affective, geographic, and cultural cues of the campaign sufficed to structure perceptions and expectations. Empirical patterns confirm this dynamic. From the concentration of Castillo’s support in highland departments, to the strong correlation between Indigenous language use and vote share, to the unprecedented voter turnout in rural Andean districts, the evidence consistently reflects a political alignment structured by ethno-regional identity.

Importantly, this challenges the idea—still dominant in some comparative literature—that Peru is an exception to Andean patterns of ethnic voting due to the weakness of ethnic parties. What 2021 revealed is that ethnic cleavages do not require institutional formalization to be electorally salient. Rather, symbolic cues, historical memory, and perceived legitimacy can generate what Kelly terms a “latent ethnic voting gap” that becomes politically decisive when activated. In this case, the absence of ethnic party infrastructure did not prevent ethno-political behavior; it simply relocated it into other registers—discursive, symbolic, and oppositional.

Conclusion

This paper has argued that the outcome of Peru’s 2021 presidential election cannot be adequately understood without centering the role of ethno-regional and ethno-linguistic identity, especially among rural Indigenous and Indigenous-mestizo populations. Drawing on theories of ethnic voting—particularly Sam Kelly’s framework of expressive and heuristic ethnic bias—this analysis has shown that the election served as a moment of ethno-political expression, in which the vote itself became a medium through which historically marginalized populations asserted identity, reclaimed visibility, and rejected exclusion.

Importantly, this politicization of identity did not emerge in a vacuum. Rather, it reflects the historical production of race and power in Peru—a social order structured by colonial hierarchies, linguistic marginalization, and the enduring logic of structural racism. As Aníbal Quijano has argued, the colonality of power continues to shape the very terms of political life in the region. Voters did not simply “choose” along ethnic lines; they acted within a system where race and geography have long defined who belongs, whose voice counts, and who is presumed legitimate.

This paper has not claimed that ethnicity alone explains the outcome. Indeed, many voters cast their ballots based on ideological commitments, economic anxieties, or strategic calculations. For instance, Keiko Fujimori’s polarizing candidacy—shaped by her association with her father’s authoritarian legacy—also influenced voter behavior, particularly among those who saw Castillo as a threat to economic stability. Some voters who supported other candidates in the first round chose Fujimori in the runoff out of ideological opposition to Castillo. However, what this paper insists on is that ethnic identity and historical experience must not be treated as residual or secondary variables. Rather, they intersect with political reasoning and are essential to understanding how and why certain electoral patterns emerge.

In this sense, the common analytical separation between “race” and “history” in mainstream Peruvian electoral analysis may overlook the ways these dimensions shape one another in practice. Rather than treating them as distinct or competing variables, this paper has shown that they are mutually constitutive. Racial identity in Peru is not merely cultural; it is the product of centuries of institutional exclusion, spatial inequality, and discursive erasure. Likewise, historical grievances are not just abstract memories; they are experienced through the bodies, languages, and everyday lives of racialized citizens. The 2021 election made this clear: the ballot became a site where voters could contest the normative boundaries of the nation itself.

Recognizing this dynamic is not only a matter of analytical accuracy—it has practical and political implications. If Peru is to move toward a more inclusive and legitimate democracy, it must reckon with the racialized foundations of its social and political order. Electoral behavior offers insight not just into preferences, but into demands for recognition, redistribution, and redefinition. Policies that ignore this will continue to reproduce exclusion. Scholarship that fails to see it will miss the deeper logic of democratic participation in Peru.

In short, the 2021 election was not just about Pedro Castillo or Keiko Fujimori. It was about whose Peru gets to speak—and how that speech is shaped by centuries of silencing. Ethnicity, history, geography, and power came together in a way that forces us to rethink what voting means in a country still grappling with the afterlives of colonialism.

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Relativistic Velocity Addition and the Computation of Political Ideological Differences

By Kayla Jian Cheong

Abstract

This paper models political perception using the relativistic velocity addition formula from special relativity. Political positions are represented on a one-dimensional axis, with the speed of light c set as the upper limit of ideological extremity, capturing perspective-dependent distortions. The model is applied to media coverage bias by treating news outlets and audiences as observers with ideological velocities, introducing resonance and distortion measures. This framework explains the polarisation amplification effect, where extreme outlets perceive centrist events as radical in the opposite direction, offering a mathematical basis for political polarisation.

Keywords Relativistic velocity addition, Political perception, Media bias

1. Introduction

The contemporary global political landscape has witnessed an unprecedented polarization of ideologies, manifesting in an increasingly pronounced schism between conservative and progressive paradigms. This polarization has led to the radicalization of political discourse, characterized by the extremist labeling of ideological adversaries. Progressive constituencies frequently invoke the designation "far-right" when referencing conservative positions, while conservative factions correspondingly employ "far-left" terminology to describe progressive ideologies. This linguistic phenomenon reflects a broader epistemological shift from substantive disagreement toward delegitimization and marginalization of opposing intellectual frameworks.

In this study, we aim to explore how the differences in political orientation between individuals can be quantified or modeled. Specifically, we propose the use of the relativistic velocity addition formula from special relativity as both a metaphorical and mathematical framework for analysing such differences. Our goal is to apply the concept of relative motion and perspective from physics to the ideological and rather abstract spectrum of political belief.

Our key insight stems from the constancy of the speed of light in special relativity. According to the theory, no matter how an observer is moving, the speed of light is always measured as the same constant value, c . Here, $c \approx 299,792,458\text{m/s}$. For example, whether we are moving to the right or the left, we will still observe a beam of light traveling to the right at the same speed c . This invariance echoes a familiar political intuition: no matter where we stand ideologically, someone who is extremely far to the left or right will always appear "extreme" to us. That is, just as the speed of light is constant for all observers, extremism in politics appears similarly absolute, regardless of one's own position.

From this perspective, the relativistic velocity addition formula provides a novel tool for modeling perceived differences in political ideology. It offers a nonlinear, observer-relative approach to measuring ideological distance, departing from traditional linear or absolute models. This paper is structured as follows: Section 2 introduces the basics of special relativity and the

mathematical form of the relativistic velocity addition formula. Section 3 develops a metaphorical model of political difference based on this formula and discusses how the two fundamental postulates of special relativity (the invariance of the speed of light and the equivalence of physical laws across inertial frames) can be interpreted in the context of political perception.

2. Special Relativity and Relative Velocity

To better understand how velocity is perceived differently depending on the observer's frame of reference, let us consider a simple example involving three people: A, B, and C.

Suppose person A is standing still in some fixed reference frame. From A's perspective, person B is moving to the right at speed v_B , and person C is moving to the right at speed v_C . In this case, since we are adopting A's frame as the reference, A's own velocity is 0.

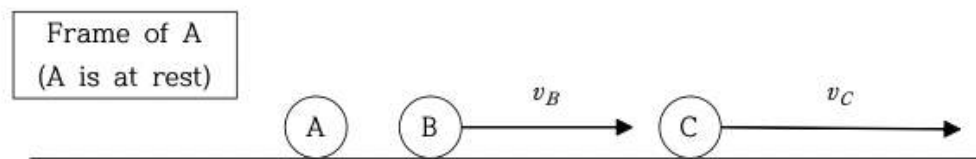


Figure 1 Two velocities of B and C measured by A.

Now, a natural question arises: from B's perspective, what is the velocity of C? In classical (non-relativistic) mechanics, the answer would simply be the difference in their velocities:

$$v_C - v_B.$$

This assumes that velocity is additive and relative in a linear way, which works well at low speeds. However, special relativity tells us that this is not accurate when the speeds involved approach the speed of light. The relativistic relative velocity formula is known as follows:

$$\frac{v-u}{1-\frac{uv}{c^2}},$$

where, u is the velocity of the observer, and v is the velocity of the person being observed. We referred to Section 37.5 of [1] for this relativistic relative velocity formula.

The term "relativistic relative velocity" may initially sound awkward due to the repetition of similar-sounding words. In this context, relativistic refers to quantities or effects derived from the theory of relativity, typically those that become significant when velocities approach the speed of light. On the other hand, relative simply indicates that the velocity is being measured

with respect to a moving frame, rather than an absolute reference. Thus, the phrase denotes the velocity of one object as observed from another moving object, calculated using the formulas of special relativity.

From this result, we can also express two velocities of A and C measured by B as the following figure.

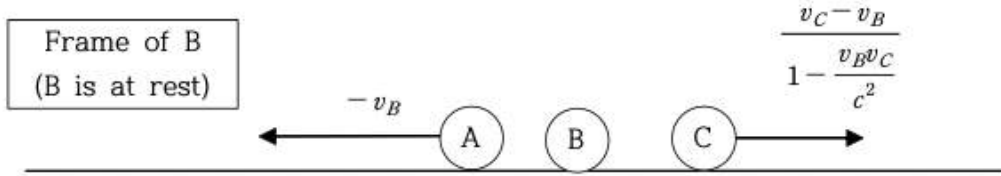


Figure 2 Two velocities of A and C measured by B.

We just substitute $v_A = 0$, v_B , and v_C into the formula properly. Now, we revisit the relativistic relative velocity formula:

$$\frac{v-u}{1-\frac{uv}{c^2}}.$$

This formula accounts for the nonlinear nature of velocity composition in special relativity. The denominator prevents the result from ever exceeding the speed of light c , regardless of the values of u and v (as long as their absolute values are less than c).

Examples.

(1) If $v = c$, then $\frac{c-u}{1-\frac{cu}{c^2}} = \frac{c-u}{1-\frac{u}{c}} = c$.

In this case, it means that regardless of the observer's velocity, if the observed object is moving at the speed of light, it will always be measured as moving at the speed of light.

(2) If $u = c$, then $\frac{v-c}{1-\frac{cv}{c^2}} = \frac{v-c}{1-\frac{v}{c}} = -c$.

In this case, regardless of the speed of the observed object, if the observer moves to the right at the speed of light, the observed object will appear to be moving to the left at the speed of light.

(3) If $|u|$ and $|v|$ are small enough compared to c , then $\frac{v-u}{1-\frac{uv}{c^2}} \simeq v - u$ and this

result is consistent with the formula for the classical relative velocity.

This formulation emphasizes that what one observer sees as a certain velocity, another observer moving at a different speed may perceive differently—and not in a simply subtractive way. The farther the velocities are from zero, the more significant the correction introduced by the denominator becomes.

In the next section, we will use this framework as a metaphor for political ideology. Just as velocity perception changes depending on one's frame of reference, so too may one's judgment of another person's political stance—especially when both hold strongly opposing views.

3. A Relativistic model of perceived political difference

Building on the velocity transformation framework introduced in the previous section, we now apply it metaphorically to the domain of political ideology. The central idea is that individuals perceive the political positions of others relative to their own, not with reference to any absolute ideological origin. Just as velocity in physics is frame dependent, so too is political judgment. One's perception of others is shaped by one's own ideological position.

In this model, we represent political ideology along a one dimensional axis, where the rightward (conservative) direction is treated as positive, and the leftward (progressive) direction as negative. Thus, a conservative stance corresponds to a positive velocity, while a progressive stance corresponds to a negative one. The magnitude of the velocity indicates the strength or intensity of one's political orientation. For example, $0.9c$ might represent a strong far right position, while $-0.3c$ would reflect a mild progressive stance. The constant c is a conceptual upper bound on ideological extremity, similar to the speed of light, representing the psychological limit beyond which positions are no longer meaningfully distinguishable as more extreme.

Now consider three individuals: A, B, and C. Person A acts as the observer and uses their own political stance as the frame of reference. From A's perspective, B is moving at velocity v_B , and C at velocity v_C on the ideological axis. A naturally concludes that C is further to the right or left than B. However, what we wish to understand is how extreme C appears to B.

In a classical model, the difference would be computed as $v_C - v_B$, assuming that perceived difference is linearly related to ideological distance. But this linear assumption fails to capture a key social and psychological reality. People tend to exaggerate how far others appear from them, especially when they themselves hold stronger views.

To address this, we propose using the relativistic velocity transformation as a model for perceived ideological difference. The formula is:

$$\frac{v_C - v_B}{1 - \frac{v_B v_C}{c^2}}$$

This expression gives the perceived political position of C from B's frame of reference,

incorporating a nonlinear distortion that becomes more pronounced as either v_B or v_C approaches c . Here, v_B is the observer's political orientation, v_C is the orientation of the person being observed, and c is the conceptual maximum of ideological extremity.

This model can explain the following situations:

[Situation 1] Perception is asymmetric. When B is already near the ideological extreme, they perceive C as even more extreme regardless of the actual difference. It can be explained by substituting $v_B = c$ into

$$\frac{v_C - v_B}{1 - \frac{v_B v_C}{c^2}} = \frac{v_C - c}{1 - \frac{v_B}{c}} = -c.$$

Therefore, if A observes B's political stance as $v_B = c$ (the extreme right), and C's stance as $v_C < c$ (not the extreme right), then according to the relativistic transformation, B will perceive C as being on the extreme left ($-c$).

[Situation 2] There is a saturation effect. As both v_B and v_C approach c , even small differences in belief are perceived as vast and radical.

For example, suppose A observes B and C's political stances as $v_B = 0.9c$ and $v_C = 0.99c$, respectively. From A's perspective, both B and C appear to be strongly right leaning, and the difference between them is only $0.09c$. However, if we apply the relativistic transformation to determine how B perceives C, we get:

$$\frac{v_C - v_B}{1 - \frac{v_B v_C}{c^2}} = \frac{0.99c - 0.9c}{1 - \frac{(0.9c)(0.99c)}{c^2}} = \frac{0.09c}{1 - 0.891} \approx 0.826c.$$

In other words, even though A sees only a small difference between B and C, B perceives C as having a significantly more extreme stance—approximately $0.826c$ to the right relative to themselves. This shows how the perception of political difference becomes nonlinearly inflated when both individuals are already near the ideological extreme. What seems like a minor disagreement to a third party (A) can feel like a dramatic ideological gap to someone (B) who is already strongly positioned.

This example highlights how the relativistic model reflects real world polarization dynamics. Even among individuals who appear politically aligned from an outside perspective, mutual perception may be sharply distorted depending on their respective positions.

This model also parallels the two foundational postulates of special relativity.

- (1) The constancy of the speed of light corresponds to the idea that ideological extremism is always perceived as extreme, no matter the observer's position.
- (2) The equivalence of physical laws across reference frames maps to the social fact that everyone tends to perceive themselves as moderate or reasonable, regardless of how others may view them.

4. Application: Media Coverage Bias as a Case Study

The political perception model described in the previous sections can also be applied to explain media coverage bias. News outlets, like individuals, possess their own ideological “velocity” which shapes how they interpret political events. If we let the actual ideological position of an event be v_{event} and the ideological velocity of the outlet be v_{outlet} , then the perceived position of the event by the outlet can be calculated as

$$v_{perceived} = \frac{v_{event} - v_{outlet}}{1 - \frac{v_{outlet} v_{event}}{c^2}}.$$

This perceived value affects the choice of words, the framing of the story, and the tone of the coverage. For example, Martin Luther King Jr.’s 1963 “I Have a Dream” speech can be modeled as $v_{event} = -0.4c$ (progressive). A conservative outlet with $v_{outlet} = 0.7c$ would perceive it as approximately $-0.86c$, viewing it as highly radical. A liberal outlet with $v_{outlet} = -0.3c$ would perceive it as about $-0.11c$, seeing it as a moderate reform. A centrist outlet with $v_{outlet} = 0.1c$ would perceive it as around $-0.48c$, closer to the actual position.

This framework also explains the relationship between media outlets and their audiences. Let $v_{audience}$ be the audience’s average ideological velocity. The event as perceived by the audience is given by the same relativistic transformation formula, replacing v_{outlet} with $v_{audience}$. Audience satisfaction tends to be highest when the outlet’s and the audience’s perceived values are nearly identical.

To quantify this alignment, we define Resonance as the normalized relativistic velocity difference between the outlet and the audience:

$$\text{Resonance} = 1 - \frac{1}{c} \left| \frac{v_{outlet} - v_{audience}}{1 - \frac{v_{outlet} v_{audience}}{c^2}} \right|.$$

We defined the resonance as the above due to the following properties.

- (1) The numerator inside the absolute value is the relative velocity between the outlet and the audience according to special relativity.
- (2) Dividing by c normalizes the value so it lies between 0 and 1.

(3) Resonance= 1 means the outlet and audience have identical ideological velocities (perfect alignment).

(4) Resonance= 0 means they differ by the maximum possible ideological distance c .

This definition directly incorporates the relativistic framework, ensuring that ideological alignment is measured consistently with the rest of the model.

When $v_{outlet} \simeq v_{audience}$, an echo chamber forms, where reporting and audience perception reinforce each other. This can amplify political polarization by filtering out opposing views. The degree of divergence between an event's actual position and an outlet's perceived position can be measured by the Distortion Factor:

$$\text{Distortion Factor} = \left| \frac{v_{event} - v_{outlet}}{1 - \frac{v_{event} v_{outlet}}{c^2}} - v_{event} \right|.$$

A larger value indicates greater distortion in coverage. Finally, the model predicts a polarization amplification effect: as $|v_{outlet}| \rightarrow c$, even moderate events appear as extreme in the opposite direction. For $v_{event} = 0.1c$:

$$(1) \text{ Far-right outlet } (v_{outlet} = 0.9c): v_{perceived} \simeq -0.88c$$

$$(2) \text{ Far-left outlet } (v_{outlet} = -0.9c): v_{perceived} \simeq 0.92c$$

In both cases, a centrist policy is perceived as highly radical in the opposite direction, deepening societal polarization.

This case study shows that the relativistic model of political perception can be extended beyond individual judgment to explain systemic patterns in media bias and audience engagement.

5. Conclusion

In this paper, we introduced a new way to think about how people see political differences. Our idea was based on a formula from special relativity in physics, which describes how the speed of one object looks different depending on how fast the observer is moving. We used this idea to model how people with different political views see each other.

We treated political views like velocities on a straight line. Moving to the right means more conservative, and to the left means more progressive. The further someone is from the center, the stronger their political opinion is. What we found is that when people have strong views, they tend to see others as much more extreme than they really are.

We used the following formula to model this:

$$\frac{v_C - v_B}{1 - \frac{v_B v_C}{c^2}}$$

This formula shows that even if the actual difference between two people is small, it can feel much bigger when both of them already hold strong positions.

One of the most interesting things our model explains is this: sometimes, a third person (A) may see both B and C as having very similar views, such as both being quite conservative. But B and C may still see each other as very different or even on opposite sides. Our model shows why this happens. When two people are both far from the center, their view of each other becomes more and more distorted, even if the difference between them is small.

This is not just about what people believe. It is also about where they are standing when they look at others. In physics, there is no one true viewpoint. Everything depends on the observer. In politics, it is the same. Everyone thinks they are the reasonable one, and that others have gone too far.

In the end, this model suggests that political conflicts are not just caused by differences in opinion, but also by the way we see those differences. If we understand this, we might be able to judge others more fairly and reduce some of the tension that comes from misunderstanding.

In addition, this framework can be extended to analyse media coverage bias by treating news outlets and audiences as observers with their own ideological velocities. Using the relativistic velocity addition formula, we can quantify alignment through a resonance measure and evaluate reporting accuracy with a distortion factor. This extension reveals a polarisation amplification effect, where extreme outlets perceive even centrist events as radical in the opposite direction, further deepening societal division.

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The Cognitive Biases Present in Marketing and How to Prevent Their Influence

By Clara Nicole Yao

According to studies, individuals make around 35,000 decisions within a day, which is around 2,000 decisions an hour. These decisions range from what to eat, who to talk to, what to watch, how much to spend, and many more. However, many of these decisions are actually influenced by cognitive biases and heuristics. This paper explores how businesses use cognitive biases in marketing to subtly influence consumer behaviour, focusing on examples grouped by their frequency and use together, as well as providing some tips and actions on how to prevent being influenced by these cognitive biases. This is done by analyzing previous research and case studies on how specific cognitive biases are able to influence the nature of our thinking in our everyday lives and examining how these influences may look in the modern world. This paper found that the cognitive biases mentioned are able to shift and change the perspectives and decisions of consumers just by changing advertisements and marketing tactics, such as prices and campaigns. Thus, by providing tips and actions, such as removing credit card information or taking time off online shopping before buying anything, allows consumers to be able to think rationally about whether they should purchase a good based on their own opinions and not by the influences of companies.

Cognitive biases are what influence individuals to act irrationally based on how an individual perceives reality. Furthermore, cognitive biases are also believed to have been created from mental shortcuts or heuristics. When faced with an abundance of information, these shortcuts allow the brain to automatically make shortcuts internally that promote problem-solving and judgment, leading to errors and biases without an individual realizing it.

Some cognitive biases are:

1. Social proof, wherein people are more trusting of products when they know other people who believe those products are valuable
2. Loss aversion, where people prefer to avoid loss, is such that they're willing to not make any gains, thus creating a sense of urgency or time-sensitive situations
3. Urgency and scarcity are where consumers place a higher value on items that appear to be limited, scarce, or hard to acquire
4. Reciprocity, where an item or company does something good for the consumer, and, in return, the consumer does something good for the company
5. Anchoring bias, where consumers often use the first item they see as the point from which they make their decisions
6. Information-gap theory, which states that a consumer has a gap of information about something of interest to them
7. The Pygmalion effect, wherein if you believe something about yourself, it will become the truth to the point that high expectations lead to improved performance and vice versa

8. Commitment, where businesses can make a customer commit to something small, and can then easily increase their ask to include bigger things
9. Consensus is when people are more likely to buy from businesses when there is proof that other people have made purchases and put trust in the company
10. Authority where people tend to pay more attention if they see that a company is an authority figure in the industry
11. Liking is when it's easier to get a consumer to buy from a company if they first like that company
12. Verbatim effect is where people tend to remember the gist of a given written or spoken topic rather than the information in its exact form
13. Unity is what encourages people to be a part of something

While there are many more, these cognitive biases are the most present within marketing and are used the most by businesses. In order for more clarity, each of the biases was grouped by how frequently or how well they were used together. The groups being:

1. Loss aversion, urgency, and scarcity
2. Unity, consensus, and social proof
3. Authority and commitment
4. Verbatim effect and information gap theory
5. Reciprocity and liking
6. Anchoring bias and the Pygmalion effect

Within marketing, these biases have been used by many companies in order to drive sales and influence consumer behaviour, usually seen in advertisements. These advertisements are used to subtly influence the decision-making of consumers in order to have them purchase products.

1. Loss Aversion and Urgency and Scarcity

These three cognitive biases are frequently used together in marketing to create a fear of missing out and drive immediate purchasing decisions.

In an experiment conducted by Worchel, Lee, and Adewole in 1975, the researchers used 200 female undergraduates and asked them to rate the value and attractiveness of cookies that were either in an abundant or scarce supply. For the participants exposed to the scarce condition, they were told that the cookies were either constantly scarce or they began in abundant supply and then decreased. Furthermore, participants with the scarce condition were told that the decrease in supply was either due to an accident or to a high demand for the cookies. Next, participants with the abundant cookies were told that the cookies were either constantly abundant or first scarce and then abundant. Similar to the participants in the scarce-supplied cookies, participants in the abundant-supplied cookies were told that the increase in supply was either due to an accident or to a lack of demand for the cookies. The results of the experiment showed that

cookies that were claimed to have a scarce supply were rated more desirable than cookies claimed to have an abundant supply, cookies were rated as more valuable when participants were told that the supply changed from abundant to scarce than when they were constantly scarce, and lastly, cookies that were said to be scarce because of high demand were rated higher than cookies that were scarce because of an accident.

This experiment, conducted by Worchel, Lee, and Adewole (1975), shows how urgency and scarcity of an item or product are believed to have an impact on the decisions made by consumers. Due to how scarce the cookies were presented to be, the consumers perceived it to be more valuable. While it was not tested in the experiment, it can be believed that due to the urgency and scarcity placed by the researchers on the cookies, participants may choose the scarce cookies more in order to avoid the loss and the possibility of gaining nothing.

In 1979, Kahneman and Tversky conducted the foundational study on loss aversion by trying to investigate how individuals make decisions with the presence of risk and uncertainty. To do this, researchers had asked participants—a range of university students and adults—to do a series of hypothetical situations and scenarios and had them decide between either a risky or certain choice involving gains or losses such as “a sure gain of \$240 or a 25% chance of \$1000 but a 75% chance of nothing” or “a sure loss of \$750 or a 75% chance of losing \$1000 or a 25% of losing nothing”. When the outcomes were framed as gains, participants preferred the confirmed option or the risk aversion. Conversely, when framed as a loss, participants preferred the risky option. The researchers concluded that individuals overreact to potential losses as the pain of losing is felt more strongly than the pleasure of gaining.

While these effects and influences can be seen in a controlled setting like the experiment, in the real world, this can be seen in many fast food chains, wherein they advertise their products to be seasonal and limited, giving a brief window of time for consumers to purchase those products before they disappear. This can be seen in fast food companies like McDonald's, Burger King, Domino's, Starbucks, etc, when they advertise limited edition or seasonal items like:

- The Shamrock Shake and the K-Burgers in McDonald's
- Pumpkin spice latte and seasonal mugs from Starbucks
- The Steakhouse Bacon Whopper, BK Melts, and the Halloween-themed Addams Family menu from Burger King



2. Unity, Consensus, and Social Proof

These three biases focus on the concept of following a group and having a homogeneous conclusion about a product. Consensus and social proof work together to allow consumers to be influenced by the evidence of other individuals and their experiences, thus creating a unity among a group of consumers.

As seen in an experiment conducted by Goldstein, Cialdini, and Griskevicius in 2008, wherein the researchers used the effectiveness of signs in hotel rooms that requested guests to participate in an environmental conservation program. One room used a sign with descriptive norms, or a sign which refers to what guests and individuals typically do, for example “the majority of guests reuse their towels”, and another room used a sign with provincial norms, or a sign that focuses on the norms of one specific setting, for example “the majority of guests in this room reuse their towels”. While the differences are subtle, there was a slight change in results for both conditions. Both conditions showed that participants are more likely to follow the behaviour based on the sign; however, the participants exposed to the descriptive norms are more likely to follow behaviors that they believe are common or typical in a given situation, whereas participants exposed to the provincial norms are more likely to follow behavior that is relevant and local to their immediate environment. Although participants exposed to both conditions showed results that both norms are more effective than a sign focused solely on environmental protection. The results showed that hotels should strive to have their guests feel and believe that their actions align and are similar to the actions of others who are in the same specific situation, rather than relying on environmental appeals

The experiment conducted by Goldstein, Cialdini, and Griskevicius (2008) shows that when there is a sign of unity and consensus by a group or society, other individuals are prone to following it, as that is what’s socially accepted. This also ties in with the concept of individuals not wanting to stand out or go against the social norm.

While these cognitive biases were proven to be present in these experiments, they can also be seen frequently in the real world, as seen in the advertisements and projects of Coca-Cola, Ben & Jerry's, TOMS Shoes, etc.

- First launched in Australia in 2011, Coca-Cola created the “Share a Coke campaign, wherein consumers could make personalized bottles with people's names to encourage consumers to find bottles with their names or names of friends to induce a social interaction within a community, thus creating a consensus of the idea of shared experiences.
- Typically, Ben & Jerry's is known for being a company that engages in social justice initiatives and environmental causes, such as advocating for racial justice and Black Lives Matter, supporting LGBTQ+ rights and marriage equality, engaging with grassroots organizations and community organizing, and many more. This type of advocacy promotes unity around shared values, invites customers to participate in activism, and fosters a sense of community among people with the same beliefs.

- In 2006, TOMS Shoes launched its “One for One” giving model, wherein for every pair of shoes bought from the company, TOMS donated a pair to a child in need. Over the past 14 years, TOMS has donated 95 million pairs of shoes worldwide and has now committed to donating $\frac{1}{3}$ of its profits to grassroots organizations focusing on mental health, ending gun violence, and increasing access to opportunity every year. This creates a sense of unity wherein consumers aren’t buying shoes for shopping; they’re also joining a global movement.



3. Authority and Commitment

While these cognitive biases could be grouped with others, the pair go well together—having a positive correlation—as when a large company is well established and known within an industry and has authority, it becomes easy for them to have consumers commit to something, whereas a smaller company may have a difficult time having their customers commit to a project or product.

In an investigation conducted by Bickman in 1974, the researcher aimed to find the degree and basis of social power of uniformed figures in 2 field experiments. In the first experiment, 153 adult participants were stopped on the street by a person dressed up as either a civilian, a milkman, or a guard. The participants were then asked by the disguised person to pick up a paper bag, give a dime to a stranger, or move away from a bus stop. The results showed that participants were more likely to listen when the person was dressed up as a guard rather than as a civilian or milkman. In experiment 2, the aim was to examine the basis of the authority of the guard, so 48 adult participants were asked to give a dime to a stranger under conditions of either surveillance or non-surveillance. The results showed that the guard's power was not affected by the surveillance manipulation. On further analysis, it was believed that the guard's power was based on legitimacy.

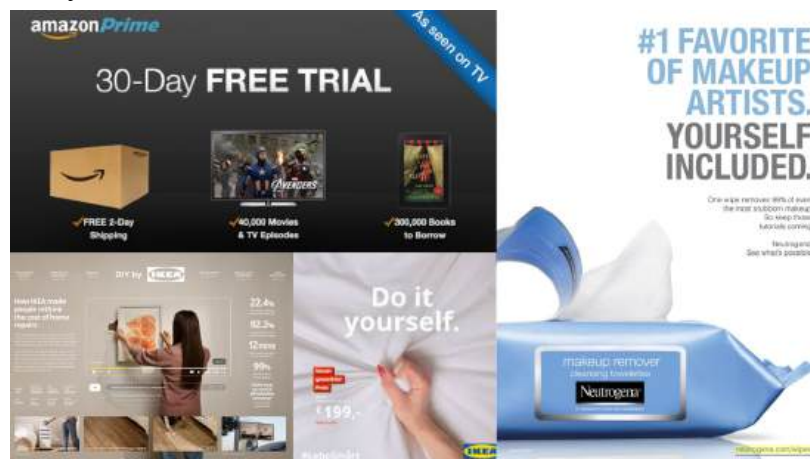
This experiment shows the concept of authority and how participants are more likely to comply when they see that the person or company, or in this case, the man wearing a guard outfit, has a perceived or symbolized authority. Regardless of whether the participants were

watched or not, they still listened and did what the guard asked, not due to fear of punishment, but respect and the belief that the guard had a legitimate authority.

In 1966, Freedman and Fraser experimented to see how agreeing to a small request could lead to agreeing to a much larger request later on. To do this, researchers split homeowners in a California suburb into 2 groups. One group was asked to place a small “Be a Safe Driver” sign in their window, and the other group wasn’t asked anything. After 2 weeks, a different researcher asked participants in both groups to put a huge “Drive Carefully” billboard outside in their front yard. The results showed that 76% of participants who were given a small request at the beginning agreed to put up the large billboard, while only 17% of participants who weren’t asked for any request at the beginning agreed. The experiment shows how people who commit to small requests are more likely to agree to a larger request later, as individuals want to behave consistently, thus showing how commitment influences consumer compliance.

In the real world, this pairing can be seen in some real-life products and marketing, such as:

- Neutrogena advertisements that say “9 out of 10 dermatologists recommend...”
- Free trial subscriptions to streaming services
- IKEA's “build it yourself” model



4. Verbatim Effect and Information Gap Theory

These two biases work well together as they focus on the information given to a consumer. When a consumer remembers the general summary of a product, companies can also promote the product as having a piece of information that was left out, thus the consumer will have to consider the product to get a better understanding of said product.

In 1972, Bransford and Johnson did a study wherein they wanted to test how important background information was when understanding and remembering passages. By using 102 high school students and 52 undergraduates, comprehension tests were administered wherein one group was given background information before listening to the passage, and the other group

after the passage. Researchers found that participants who were given the context beforehand understood the passage much better and remembered more details, thus having higher comprehension ratings than those of participants who were given the context after reading the passage.

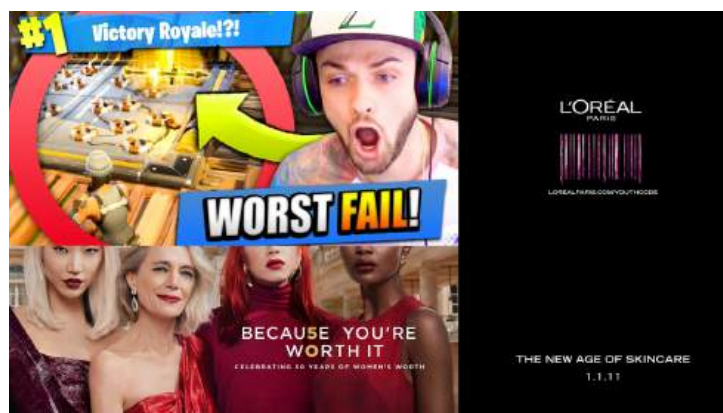
This experiment connects to the verbatim effect, as when students had context beforehand, they understood the overall idea, or the gist, of the passage, allowing it to be easier to recall the information, whereas students who had the context after listening to the passage couldn't understand the information as much as the other group did.

In 2009, Kang performed an investigation wherein they had participants connected to an fMRI scanner, or a functional magnetic resonance imaging machine that measures brain activity by changes in blood flow, while answering trivia questions. The results showed that when the participants were more curious about a question, the reward center in their brains, more specifically the caudate region, lit up, showing how being curious felt rewarding to the participants. In a separate test, researchers found that the more curious a participant was, the more likely they would be to “pay”, whether by tokens or by waiting longer, to get the right answer. Furthermore, results showed that when participants guessed wrong, their brains' memory centers became more active if they were more curious, meaning that curiosity helped participants remember surprising new information better.

According to the information gap theory proposed by Loewenstein in 1994, “curiosity happens when there's a gap between what you know and what you want to know”. This experiment shows that the trivia questions created an information gap where they didn't know the answer but they wanted to find out, and that the bigger the “gap,” the more motivated the participants were to act to close the “gap”, also showing how “closing the gap” was rewarding and allowed the information to be recalled better.

Other than in these experiments, this pairing can be seen commonly in some advertisements and products, such as:

- L'Oreál's slogan “Because You're Worth It” as consumers remember the emotional message rather than the scientific claims
- YouTube clickbait thumbnails or headlines
- Teaser advertisements



5. Reciprocity and Liking

This pair of biases works well together, as when a company reciprocates by doing something good for the customer, it can be very easy for the consumer to like the company back and thus are more likely to purchase their products as a result of this reciprocity.

In 1971, Dennis Regan did a study wherein participants believed they were there to evaluate paintings; however, in the room, there was also another man named Joe. The first thing Regan did was manipulate the way the participants perceived Joe by either having them overhear Joe being polite or rude over the phone. Next, Joe would either leave the room and bring back 2 Coca-Colas, one for him and one for the participant, or Joe would leave the room and come back with nothing. After the participants evaluated the painting, Joe was left alone with the participant and would then give the participant a note asking them to purchase some raffle tickets for him. The results of the experiment showed that in the condition where Joe didn't bring them a soda, the degree to which the participants liked Joe influenced how many tickets they would buy for him. By contrast, if Joe did give a soda to the participant, the participants bought twice as many tickets as the participants who didn't receive a soda, regardless of the degree they liked Joe. Not only that, but the results also showed that the participants who received a soda bought more raffle tickets than the price of the soda itself.

In 1984, Cialdini conducted an observational experiment wherein researchers aimed to see how liking influences compliance. To do this, researchers did a field observation as well as interviews with salespeople to gather data. The results showed that to be successful, salespeople often built relationships with consumers through similarities, physical attractiveness, and compliments. For example, a salesperson who had similar hobbies to the consumer was more likely to close a deal. This data from this experiment shows how people are more likely to purchase products from someone they like, even during high-cost situations, thus showing how liking can lead to consumer compliance.

Besides experiments, these cognitive biases can also be seen in different products and real-world examples, such as:

- Welcome discounts that create a sense of obligation
- Brands with relatable demeanors on social media, such as Wendy's Twitter/X posts
- Brand mascots such as Tony the Tiger or the Geico Gecko that create emotional attachment



6. Anchoring Bias and the Pygmalion Effect

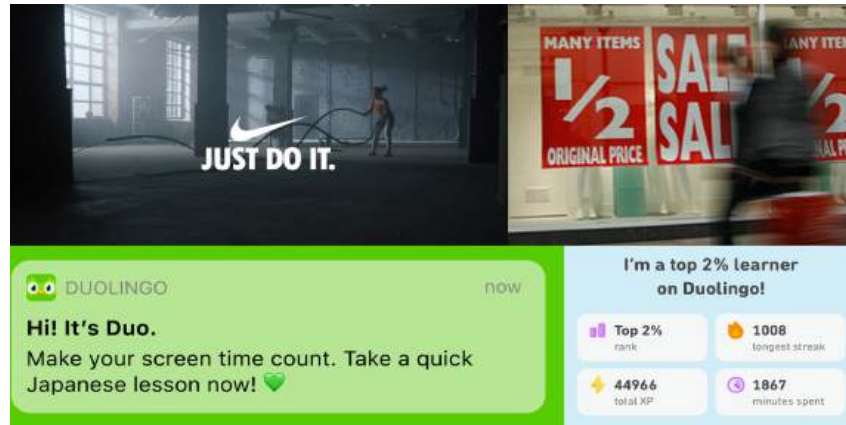
These two biases are somewhat similar, with the Pygmalion effect acting as a sort of subtopic for anchoring bias, as high expectations can act as the anchor and can be very easy for consumers and individuals to be “hung up” on these expectations, thus perceiving any following information through this anchor or expectation.

In 1971, researchers did a follow-up experiment on the experiment conducted by Rosenthal and Jacobson, wherein they found that a teacher’s beliefs can affect the performance of the students. In the follow-up experiment, they aimed to find how the teacher’s behavior may change as a result of the expectations of students they are told. For example, a teacher may believe a particular student is more gifted than others. The study used 26 female undergraduates and 104 6th-7th graders. The results of the experiment showed that the teachers didn’t differ in the amount of attention given to students who were deemed “gifted” and “nongifted”; however, the pattern of attention and praise, such as the positive feedback given to a student, was different. The results showed that teachers gave more positive feedback to the “gifted” students despite giving the same amount of attention to both types of students, suggesting that the expectations altered the type of feedback rather than the amount of attention given by teachers. The Pygmalion effect seen in the experiment is used in marketing, wherein marketers alter their advertisements in order to appeal to a certain demographic or economic group. For example, a luxury brand may use certain diction in order to appear more elegant and appealing to wealthier consumers, thus creating a perception of wealth and exclusivity.

In 1974, Kahneman and Tversky conducted a foundational study on anchoring bias wherein the researchers aimed to investigate whether people anchor their judgements on random, arbitrary numbers—to show that even random numbers may affect decision making and behaviours. To do this, researchers grouped the students and showed them a “wheel of fortune”. This wheel was rigged so that one group of participants would land on either 10—the low anchor—and the other 65—the high anchor—after spinning the wheel. After spinning the wheel, the students were then asked, “What percentage of African countries are members of the UN?” as well as asked to give their own numerical estimate. The results showed that participants who landed on the low anchor had a much lower average estimate of ~25% whereas participants who landed on the high anchor had a much higher average estimate of ~45% despite the fact that the anchors were irrelevant to the question. The experiment shows how people tend to anchor their judgements based on initial values, even if those values are irrelevant.

This pair of cognitive biases can be very common as a marketing tactic in the real world, such as:

- Retail pricing tactics such as “was \$199, now \$139” have consumers unintentionally use the original price as an anchor for the new perceived value
- Nike’s “Just Do It” creates expectations for consumers that they are an athlete
- Duolingo notification messages, such as “You’re in the top 10% of learners this week!” create expectations that boost commitment as consumers believe they’re high performers



While it may seem overwhelming once realising how consumers can be very susceptible to falling for these cognitive biases used in the real world by famous companies, it can also be easy to ensure a consumer doesn't fall for them as well.

In general, consumers should take time to understand what is going on in a situation, especially when shopping. Typically, an individual is shown 6,000-10,000 advertisements in a day, and they usually contain some form of cognitive bias to influence consumers into purchasing goods and services that they may not need. Thus, being able to stop and recognize that they are being influenced by these cognitive biases before purchasing anything can be very beneficial for consumers. Furthermore, being able to understand the signs or what the advertisement is trying to influence you to do is also very important and does require knowledge, time, and effort into doing so.

Secondly, in terms of the first group of cognitive biases of urgency, scarcity, and loss aversion—while it can be difficult—it's very important to limit screen time as now a days, companies are more frequently and commonly promote their products and services on social media, thus a break can provide some time for consumers to stop and think about their actions before purchasing anything. However, when that may be difficult to do, it's also possible to just try and skip the advertisements in videos when fully putting down technology becomes hard. Furthermore, it's also possible, when shopping online, to stop and wait for a few hours or days to see if a consumer truly wants the item or if they're only being influenced by the scarcity and urgency that the company presented to them. Lastly, while it may be annoying, consumers can also uninstall apps or remove banking information, as now, when a consumer wants to purchase something from a store, it becomes more tedious as there is now an extra step involved. Due to this, it requires consumers to think about the product as to whether they truly want to purchase it or not.

When it comes to the pairing of reciprocity and liking, while it may be very easy to fall for the glitz and glamour of what's being presented and offered to you, it's important to know when the company or firm is only showing the positive, more extravagant side and actions of the product.

For the last pair of anchoring bias and the Pygmalion effect, one way consumers can effectively not be influenced is to try and look for other substitutes or alternatives. By doing this, it allows

consumers to compare prices and quality rather than being influenced to like a certain item by companies and firms.

In conclusion, while cognitive biases are powerful tools used by marketers to influence purchasing decisions, consumers can take conscious steps to resist manipulation. By recognizing these psychological triggers and pausing before impulse purchases, individuals can reclaim control over their choices. With awareness and critical thinking, we can ensure that what we buy is based on genuine need—not subconscious persuasion.

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Behavioral, Physiological, and Morphological Adaptations of Marine Animals

By Sophia Kong

Behavioral adaptations are vital to marine animals' survival and reproduction (Selman, et al., 2013). The behavioral adaptations of basking to turtles are important for them to survive and reproduce (Selman, et al., 2013). Humans are causing the endangerment of sea turtles by habitat endangerment, pollution, bycatch, etc. (Selman, et al., 2013). Sea turtles have behavioral adaptations that they bask better without human distraction (Selman, et al. 2013). This behavioral adaptation helps sea turtles to survive because without basking, the sea turtles cannot live and will not be able to get out of the water whenever they need to. Basking is therefore important for sea turtles in order to survive and reproduce. The behavioral adaptation of nesting to turtles, are also important for them to survive and reproduce (Topping & Valenzuela, 2021). Turtles face a lot of different challenges during nesting (Topping & Valenzuela, 2021). When sea turtles choose a good place to nest, this is a behavioral adaptation. This behavioral adaptation helps sea turtles to survive because they need the nest and a good place to hide in order for the baby sea turtles not to get hunted (Topping & Valenzuela, 2021). If they do not have a good place to nest, and the baby sea turtles do not survive, the population of sea turtles will decrease (Topping & Valenzuela, 2021). So as a result, it is important for turtles to choose a good place for nesting in order to survive and reproduce.

For cetaceans, the behavioral adaptation of deep diving is important for them to survive and reproduce (Thomas, et al., 2017). Cetaceans have many different kinds of extreme adaptations. For instance, cetaceans have behavioral adaptations, such as deep diving behavior (Thomas, et al., 2017). Deep diving helps cetaceans to survive because it helps the cetaceans catch their prey that lives deeper in the ocean (Thomas, et al., 2017). For that reason, deep diving behavior is important for cetaceans to survive and reproduce. The behavioral adaptation of the arctic sea ice is another important adaptation for cetaceans to survive and reproduce (Alter, et al., 2010). Humans are also causing the endangerment of cetaceans, because the ice that cetaceans need is melting because of climate change (Alter, et al., 2010). Humans are making cetaceans lives harder by causing climate change. Climate change is making the arctic cetaceans not able to swim, because the weather is warming up, and all the ice is melting (Alter, et al., 2010). Cetaceans have the behavioral adaptation of breaking the arctic sea ice (Alter, et al., 2010). This behavioral adaptation helps cetaceans to survive because arctic cetaceans have the ability to break ice half a meter thick in order to breathe, and without it, arctic cetaceans can have acoustic disturbance, ship strikes, bycatch, and prey depletion (Alter, et al., 2010).

For deep diving pinnipeds, the behavioral adaptation of dark adaptation and visual sensitivity, is important for them to survive and reproduce (Levenson & Schusterman, 1999). Pinnipeds have behavioral adaptations such as dark adaptation and visual sensitivity (Levenson & Schusterman, 1999). This helps deep diving pinnipeds to survive, because they use visual sensitivity to help them locate prey, avoid predators, and navigate when they are diving

(Levenson & Schusterman, 1999). Therefore, dark adaptation and visual sensitivity is important to deep diving pinnipeds in order to survive and reproduce.

Moreover, in jellyfish, the behavioral adaptation of jellyfish blooms are important for them to survive and reproduce (Dawson & Hamner, 2019). Jellyfish's different adaptations evolved over time (Dawson & Hamner, 2019). Jellyfish have behavioral adaptations such as blooming, or swarming (Dawson & Hamner, 2019). These behavioral adaptations help jellyfish to survive and reproduce, because during a jellyfish bloom, prey can be more heavily consumed. Swarming also helps, because when the jellyfishes are in a large group, they are less likely to be attacked, since there are many eyes. Also, it confuses the predator, because it is harder to focus on one particular piece of prey in a large group (Dawson & Hamner, 2019). Due to these reasons, jellyfish blooms help jellyfish survive and reproduce in the wild. Jellyfish also have more behavioral adaptations, including swimming up in response to somatosensory stimulation, swimming down in response to low salinity, diving in response to turbulence, avoiding rock walls, and horizontal directional swimming (Dawson & Hamner, 2019). These behavioral adaptations help jellyfish to survive and reproduce, because jellyfish have typical behaviors involving sequences of movements that are adjusted in response to the requirements of the situation and that require sensory feedback when they are being hunted. (Dawson & Hamner, 2019). Therefore, jellyfishes need all these important behavioral adaptations to survive and reproduce.

This behavioral section answers the research question, “how do the behavioral, physiological, and morphological adaptations of different classes of marine animals, using cetaceans, turtles, jellyfish, and pinnipeds as examples, enable them to survive and reproduce in the marine environment?”, because each adaptation of the four animals (turtles, cetaceans, pinnipeds, jellyfish) explained why the adaptation helped that animal survive and reproduce. Jellyfish have behavioral adaptations such as blooming, or swarming (Dawson & Hamner, 2019). These behavioral adaptations help jellyfish to survive and reproduce, because during a jellyfish bloom, prey can be more heavily consumed. Swarming also helps, because when the jellyfishes are in a large group, they are less likely to be attacked, since there are many eyes. Also, it confuses the predator, because it is harder to focus on one particular piece of prey in a large group (Dawson & Hamner, 2019). This is answering our research question, because these adaptations (blooming, and swarming) are given to the jellyfish so they can survive and reproduce

Physiological adaptations of marine animals are also extremely important for them to survive and reproduce (Seymour, 1982). Firstly, the physiological adaptations of painted turtles are vital for them to survive and reproduce (Seymour, 1982). Painted turtles have physiological adaptations like the coordination depression of metabolism processes within the cells, and the exploitation of the extensive buffering capacity of the turtle's shell and skeleton (Jackson, 2002). This physiological adaptation helps painted turtles to survive because both the rate of substrate depletion and the rate of lactic acid production (when lactate accumulates in the turtle with a proton) becomes the production and are slowed greatly, and the turtle's shell and skeleton

neutralizes the large amount of lactic acid that eventually accumulates (Jackson, 2002). It is good that it is slow, because it drastically delays the depletion of stored substrate and slows the build-up of acid end products (Jackson, 2002). For that reason, all of these adaptations of the painted turtle are important in order for them to survive and reproduce. Adding on, sea turtles also have more physiological adaptations such as their slow metabolic rate (Bennett & Ruben, 1979). Turtles have this physiological adaptation for a good reason. This physiological adaptation helps them survive, because it allows them to stay submerged for long periods of time (Bennett & Ruben, 1979). Green sea turtles can stay under the water as long as five hours (Bennett & Ruben, 1979). Thus, slow metabolic rates of the turtle can help them to survive and reproduce.

In addition, for cetaceans, the physiological adaptations help them to survive and reproduce. The physiological adaptations of the cetaceans evolved over time (Thomas, et al., 2017). Cetaceans have physiological adaptations like modified nostrils (blowholes), extensive thermal insulation, though the most important is their way of taking in oxygen (Thomas, et al., 2017). This physiological adaptation helps cetaceans to survive because the more efficiently it is to take in breath, the easier it is to avoid predators and catch prey because they will have longer time underwater and more time to escape, or to catch (Thomas, et al., 2017). Hence, this is why these adaptations are important for cetaceans to survive and reproduce in the wild. Cetaceans have more adaptations such as deep diving adaptation of cetaceans (Cozzi, et al., 2010). Cetaceans have physiological adaptations like their telescopic modification of skulls (Cozzi, et al., 2010). This physiological adaptation helps cetaceans to survive because it makes space for the melon or the spermaceti organ located in the forehead of the cetacean and it improves hydrodynamics which is basically the study of water resistance and the impact on swim speed (Cozzi, et al., 2010). That being so, deep diving adaptations of the cetaceans are important for them to survive.

Moreover, for pinnipeds, the physiological adaptations of their systems help them to survive (Crocker & Champagne, 2018). Pinnipeds have physiological adaptations such as their sensory systems (Crocker & Champagne, 2018). These physiological adaptations help pinnipeds to survive and reproduce, because their sensory system enables them to successfully navigate, forage, and communicate in a variety of environments (Crocker & Champagne, 2018). That being the case, pinnipeds' sensory system keeps them alive so they can survive. Adding on, pinnipeds also have physiological adaptations that help them reproduce and survive (Crocker & Champagne, 2018). Pinnipeds have more physiological adaptations such as their central nervous system, and erythrocytes which transport gasses and nutrients throughout the body (Crocker & Champagne, 2018). This physiological adaptation helps pinnipeds to survive, because they need to provide carbohydrate to glucose-dependent tissues that include those adaptations listed above. (Crocker & Champagne, 2018). Due to the limited ability to store carbohydrate in the body, fasting pinnipeds are dependent on gluconeogenesis, the production of sugar by the liver and kidney, to provide fuel for these tissues (Crocker & Champagne, 2018). So therefore, the central nervous system, erythrocytes, and renal medulla all help the pinniped survive and reproduce.

Lastly, for jellyfish, they have physiological adaptations like their biomechanics (Megill, 2002). Jellyfish have physiological adaptations such as when they provide thrust, they eject a volume of water contained within their subumbrella cavities (Megill, 2002). This physiological adaptation helps jellyfish to survive because they provide thrust with it, and without providing thrust they cannot have locomotion, or the power to move (Megill, 2002). Thus, this is why when jellyfish provide thrust, they use this physiological adaptation to survive. Jellyfish have more physiological adaptations like jellyfishes' body plans that provide allometric advantages which are high water and low carbon (Pitt, et al., 2013). Jellyfish have physiological adaptations like rates of respiration, longevity, and swimming velocity of jellyfish. Rates of respiration is the number of breaths they take per minute, while longevity is the life span of the jellyfish, depending on which species are which. The swimming velocity of jellyfish on the other hand, is the speed the jellyfish is going at (Pitt, et al., 2013). These physiological adaptations help jellyfish to survive because they all have allometric relationships, which is the relation between the size of an organism, and after different creatures were taken into testing, the jellyfish were standardized for its carbon content (Pitt, et al., 2013). This helps them to survive, because jellyfish need to be fast in order to catch their prey, and escape their predators. Therefore, jellyfishes need these physiological adaptations in order to survive and reproduce on their own.

This physiological section answers our research question, "how do the behavioral, physiological, and morphological adaptations of different classes of marine animals, using cetaceans, turtles, jellyfish, and pinnipeds as examples, enable them to survive and reproduce in the marine environment?", because each adaptation of the 4 animals (turtles, cetaceans, pinnipeds, jellyfish) explained why the adaptation helped that animal survive and reproduce, for instance, sea turtles. Sea turtles also have more physiological adaptations such as their slow metabolic rate (Bennett & Ruben, 1979). Turtles have this physiological adaptation for a good reason. This physiological adaptation helps them survive, because it allows them to stay submerged for long periods of time (Bennett & Ruben, 1979). Green sea turtles can stay under the water as long as 5 hours (Bennett & Ruben, 1979). Thus, slow metabolic rates of the turtle can help them to survive and reproduce.

Morphological adaptations are crucial to marine animals if they survive and reproduce. First off, turtles have morphological adaptations to help them survive in the wild (Macip-Rios, et al., 2023). Aestivation, which is a long-term torpor in response to hot and dry periods, or in other words, hibernation, has evolved in turtles over the years (Macip-Rios, et al., 2023). Turtles have morphological adaptations such as aestivation. This morphological adaptation helps turtles to survive because aestivation is a multiday torpor in response to hot and dry periods. It helps the turtles survive in hot summers. For that reason, aestivation is vital for turtles to survive and reproduce. Turtles have more morphological adaptations, for instance, their strong armor, a carapace on top and the plastron beneath, long, stiff fore flippers, and hind flippers (Zardoya & Meyer, 2001). These morphological adaptations help turtles to survive, because they have strong armor so they can go against and protect themselves from predators (Zardoya & Meyer, 2001). The long, stiff fore flippers help them pull through the water, while the hind flippers help them

steer (Zardoya & Meyer, 2001). That being so, parts of the turtles' bodies can be used as morphological adaptations, which help them survive and reproduce.

Moreover, in cetaceans, there are morphological adaptations for them to survive and reproduce (Raven, 1942). Cetaceans have morphological adaptations such as their blubber, a thick layer of fat, which can also be called adipose tissue (Raven, 1942). This morphological adaptation helps cetaceans to survive because cetaceans use it to insulate the whale against the temperature of the water (Raven, 1942). The blubber is thus important for cetaceans for them to survive and reproduce.

Furthermore, pinnipeds have morphological adaptations to help them survive and reproduce (Loza, et al., 2019). They have the morphological function of southern pinnipeds' ears (Loza, et al., 2019). What's more is that they have two functions of ears; one used for land, and one used for water (Loza, et al., 2019). This morphological adaptation helps pinnipeds to survive, because the ears exhibit a high degree of sociability, mainly during the reproductive season, so mates can hear each other, or the mother/pup bond (Loza, et al., 2019). Adding on, several species of pinnipeds vocalize underwater, so they can also use their ears to communicate underwater (Loza, et al., 2019). Accordingly, the ears of the pinnipeds are morphological adaptations, which in this case can be used for them to survive and reproduce.

Additionally, the morphological adaptations of the jellyfish are used to help them survive and reproduce (LaPan, 2018). There are morphological adaptations in general about all kinds of jellyfish (LaPan, 2018). Diving deeper, jellyfish have morphological adaptations such as their tentacles (LaPan, 2018). This morphological adaptation helps jellyfish to survive, because these tentacles can help defend the jellyfish (LaPan, 2018). The stings of the jellyfish can be quite painful, as they are used for predators when they are too slow to get away. Aside from using the tentacles for predators, jellyfish often sting their prey in order to quickly stun it and keep it from escaping (LaPan, 2018). This can make feeding much easier and efficient for the jellyfish; and the tentacles can reach out and push food items toward the mouth of the jellyfish (LaPan, 2018). That being the case, the tentacles of the jellyfish are a morphological adaptation that helps them survive and reproduce on their own.

This morphological section answers our research question, "how do the behavioral, physiological, and morphological adaptations of different classes of marine animals, using cetaceans, turtles, jellyfish, and pinnipeds as examples, enable them to survive and reproduce in the marine environment?", because each adaptation of the four animals (turtles, cetaceans, pinnipeds, jellyfish) explained why the adaptation helped that animal survive and reproduce, for instance, cetaceans. As we have stated, cetaceans have morphological adaptations such as their blubber, a thick layer of fat, which can also be called adipose tissue (Raven, 1942). This morphological adaptation helps cetaceans to survive because cetaceans use it to insulate the whale against the temperature of the water (Raven, 1942). This is answering our research question, because the physiological adaptations of the cetaceans are enabling them to survive and reproduce.

To conclude, as it was stated in the introductory, understanding marine animal adaptations and how different animals are adapted to their style and habitats will allow us to understand how they have evolved such a diversity for animals. What the paper talked about marine animals' adaptations, is the research gap that needs to be filled. Starting with the behavioral section of turtles, basking is a behavioral adaptation and that turtles use basking to survive in order to change the temperature of their body. Also nesting. Nesting is an important behavioral adaptation, because turtles need their young to survive and so the adults can reproduce. Without nesting, sea turtles cannot survive.

As to cetaceans, first of all, cetaceans need deep diving to survive. They use it to catch prey that lives farther down the ocean. Second, cetaceans also have the adaptation of breaking the arctic sea ice. They need this adaptation to survive, because when it is cold, and the ice freezes over, they break the ice to form a small hole, in which they can breathe.

Going to pinnipeds, they have dark adaptation and visual sensitivity. They need this to survive, because they use the adaptations to avoid predators, catch prey, and navigate through the dark. Jellyfish have the adaptation of blooming, and swarming. They need blooming to survive, because prey can be more heavily consumed. They need swarming to survive, because in a large group, it is easier to escape from the predator and will also confuse the predator on which prey to pick.

After the behavioral section on adaptations, next is the physiological adaptation. Painted turtles have physiological adaptations like the metabolism processes within the cells, and the exploitation of the extensive buffering capacity of the turtle's shell and skeleton. This physiological adaptation helps painted turtles to survive because both the rate of substrate depletion and the rate of lactic acid production (when lactate accumulates in the turtle with a proton) becomes the production and are slowed greatly, and the turtle's shell and skeleton neutralizes the large amount of lactic acid that eventually accumulates. Also, sea turtles have physiological adaptations such as their slow metabolic rate and it allows them to stay submerged for long periods of time. For pinnipeds, they have their sensory systems as their physiological adaptation. Their sensory systems allow them to navigate, forage, and communicate in a variety of environments. Also, pinnipeds have their central nervous system. They need to provide carbohydrates to glucose-dependent tissues that include their central nervous system listed above. Moving on to jellyfish, they have the physiological adaptation of providing thrust. When they provide thrust, they eject a volume of water contained within their subumbrella cavities. This physiological adaptation helps jellyfish to survive because they provide thrust with it, and without providing thrust they cannot have locomotion, or the power to move.

Finally, the morphological adaptations. Sea turtles have morphological adaptations such as Aestivation. Aestivation is important for sea turtles to survive, because it helps them survive in hot summers. They also have strong armor as another adaptation, so they can go against and protect themselves from predators. Additionally, cetaceans. Cetaceans have the morphological adaptation of their blubber. This morphological adaptation helps cetaceans to survive because cetaceans use it to insulate the whale against the temperature of the water. Pinnipeds have the

morphological adaptation of their ears. This adaptation helps them survive, because the ears exhibit a high degree of sociability, mainly during the reproductive season, so mates can hear each other, or the mother/pup bond. Lastly, the jellyfish. They have the morphological adaptation of their tentacles. This morphological adaptation helps jellyfish to survive, because these tentacles can help defend the jellyfish. The stings of the jellyfish can be quite painful, as they are used for predators when they are too slow to get away. Aside from using the tentacles for predators, jellyfish often sting their prey in order to quickly stun it and keep it from escaping. This can make feeding much easier and efficient for the jellyfish; and the tentacles can reach out and push food items toward the mouth of the jellyfish.

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Traffic Density Prediction with Integrated Weather Data Using Machine Learning

By Onur Örnek

Abstract

Traffic congestion is a significant problem in Istanbul that affects commuters, pedestrians, residents and has implications on urban infrastructure. Predictive modeling forecasts traffic density can provide both short-term and long-term benefits. In the short term, these models allow commuters to visualize traffic patterns, allowing them to plan alternative routes and reduce traffic time. In the long term, urban planners can use these predictions to optimize infrastructure and implement traffic management strategies.

This research project uses traffic flow data to build predictive models for traffic congestion. The dataset includes temporal information, geographic location data, speed metrics, and vehicle counts, supplemented with weather conditions. Several models were implemented, including linear regression, decision tree, random forest, as well as deep learning architectures, including long short term memory and gated recurrent unit networks. Random forest models, both untuned and tuned, demonstrated superior predictive performance in terms of capturing relationships between the input variables and traffic density.

The research evidences the value of predictive modeling to support data-driven decision-making for urban mobility. By enabling real-time traffic management and facilitating long-term infrastructure planning, the work can help cities like İstanbul enhance transportation efficiency, reduce congestion, and improve the quality of urban life.

Introduction

Traffic congestion is a pervasive issue in major metropolitan areas, and in Istanbul - a city straddling two continents with over 15 million residents - it represents one of the most pressing urban challenges. The World Design Organization (WDO) identifies congestion not only as a daily inconvenience but as a major constraint on economic productivity, urban livability, and environmental sustainability.

While real-time traffic applications like Google Maps and Yandex utilize a mix of historical averages and live sensor data to provide short-term predictions, long-term forecasting remains underexplored. One critical and often overlooked determinant of traffic variability is weather. Rain, wind, temperature, and other atmospheric conditions exert profound influence on traffic flow: slowing vehicles, reducing visibility, and altering pedestrian and driver behavior.

The dependence of current traffic prediction models based on historical data poses especially relevant risks in the face of climate change. Weather is a significant variable of traffic, and historical averages are becoming less and less representative of present traffic patterns due to the difference in weather between now and then.

This study develops machine learning models that incorporate both traffic sensor and weather data to predict hourly traffic density in Istanbul. The integration of weather parameters not only enhances prediction accuracy but also offers a more nuanced understanding of traffic

dynamics for urban planners and policymakers. By identifying the most influential features, this study also guides future infrastructure and climate-resilient planning strategies.

Background

Traditional traffic prediction systems rely on two main data types: historical travel times and real-time sensor data. Google Maps, for instance, combines these to predict upcoming traffic, using machine learning to refine its estimated time of arrival (ETA) predictions. More recently, DeepMind has applied graph neural networks (GNNs) to represent city road systems as node-based networks, significantly enhancing spatial prediction accuracy.

However, most of these models are focused on short-term predictions for route planning, not on modeling underlying traffic density for long-term planning. Furthermore, the weather is rarely considered in these frameworks. This highlights a clear research gap: the need for traffic prediction systems that account for environmental conditions and can inform both immediate decisions and urban design strategies.

Machine learning, especially deep learning models like LSTM and GRU, has emerged as a powerful tool for capturing complex, nonlinear relationships in traffic data. A 2023 study in Nature Scientific Reports showed that such models could match or even surpass traditional microscopic traffic models in accuracy while being more efficient in real-time settings.

However, these models typically require extensive datasets and high-performance computing resources. This project addresses such limitations by preprocessing and consolidating open-source traffic and weather datasets to create a manageable input pipeline, suitable for both classical and deep models.

Modeling traffic with weather data introduces several challenges. Weather data must be spatially and temporally aligned with traffic data at hourly granularity. The influence of weather is not linear. For example, light rain may slow traffic, but heavy rain could stop it entirely. Geographic variables (e.g., latitude and infrastructure) may dominate the signal, masking subtle effects from weather. This study attempts to overcome these challenges through model tuning, feature importance analysis, and comparison across multiple architectures.

Data Collection

This research utilized two publicly available datasets to construct weather-informed traffic density prediction models for Istanbul. Traffic Dataset consists of hourly traffic records, and Weather Dataset consists of hourly weather records

Traffic Dataset

The primary dataset was obtained from the Istanbul Metropolitan Municipality Open Data Portal (*Hourly Traffic Density Data Set - Traffic Density Data for September 2023 - IMM*). It contains hourly traffic records across different road segments in Istanbul. Figure 1 illustrates the correlation among the attributes in the traffic dataset. The retained attributes were:

- Average Speed

- Minimum Speed and Maximum Speed
- Number of Vehicles
- Geospatial Indicators (Latitude, Longitude, and Geohash)
- Timestamp (hourly granularity)

Traffic density is a function of vehicle count and speed: it is directly proportional to the number of vehicles and inversely proportional to the average speed. In other words, more vehicles combined with slower speeds indicate higher congestion, whereas faster movement indicates lower congestion. Figure 2 illustrates the hourly average traffic density.

$$\text{Traffic Density} = \frac{\text{Number of Vehicles}}{\text{Average Speed}}$$

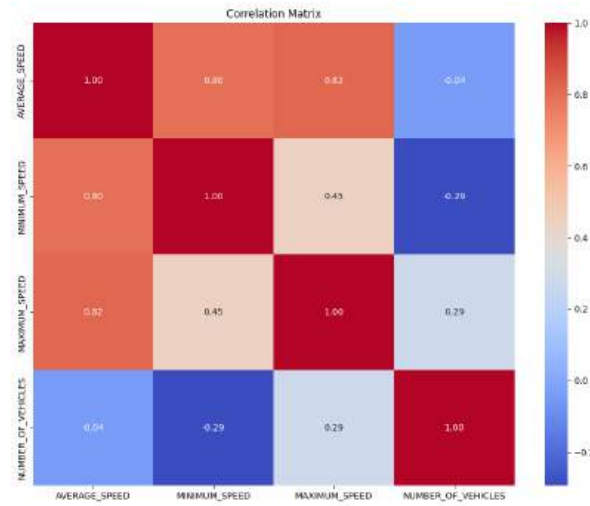


Fig.1 - Correlation matrix among the attributes in the traffic dataset

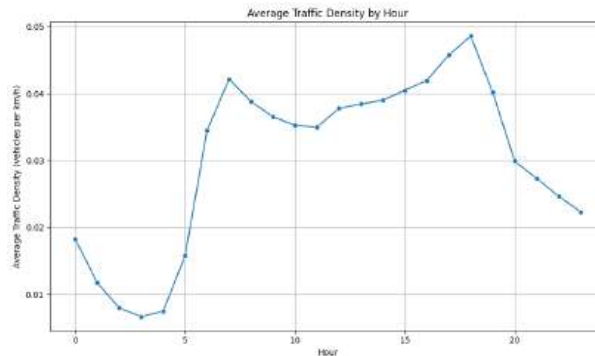


Fig. 2 – Hourly average traffic density

Weather Dataset

Hourly weather records were obtained from *Visual Crossing* for the months September 2023, December 2023, March 2024, and June 2024 (“Weather Query Builder”). The retained meteorological attributes included:

- Temperature (°C)
- Precipitation (mm)
- Wind Speed (km/h)
- Humidity (%)
- Atmospheric Pressure (hPa)
- Cloud Cover (%)
- Visibility (km)

Data Integration

For joint modeling, the traffic and weather datasets were combined along two dimensions; Temporal Alignment and Spatial Alignment. Both datasets provide time information by the hour, and temporal alignment was performed by matching the weather data with the traffic data using the same hourly timestamps. The traffic dataset shows road locations with geohash codes, and spatial alignment was achieved by decoding these into approximate latitude and longitude, then matching them with the area covered by the weather dataset. Since the weather data covers all of Istanbul, each road segment was given the related hourly weather information.

The resulting integrated dataset contained both traffic features (e.g., average speed, vehicle count) and weather features (e.g., precipitation, wind speed), with traffic density defined as the target variable. This structured input-output pipeline provided the foundation for developing and comparing classical and deep learning prediction models.

These values were aligned temporally and spatially with the traffic dataset using timestamp and approximate geolocation (via geohash decoding). Figure 3 illustrates how the traffic density output is obtained through data integration. Figure 4 presents the traffic density obtained after the integration of traffic and weather data in the form of a heatmap.

A series of preprocessing steps were applied to ensure data quality and consistency. Missing values were handled appropriately, and timestamps were standardized to hourly granularity. The traffic and weather datasets were then merged based on their shared timestamp values. Geospatial merging was facilitated using geohash codes, which were decoded into latitude and longitude coordinates to support spatial feature integration.

The target variable for the models, traffic density, was defined as the number of vehicles divided by the average speed. The resulting dataset included three categories of features: traffic-specific (e.g., average speed, number of vehicles), weather-related (e.g., temperature, wind speed), and spatial (latitude and longitude). These features served as the inputs for all subsequent models.

Model Development

Five distinct predictive models were developed and evaluated in this study: linear regression, decision tree regression, random forest regression, long short-term memory (LSTM) networks, and gated recurrent unit (GRU) networks. These models were selected to provide a comparative analysis between classical regression techniques and modern deep learning architecture.

The linear regression model, implemented using the `LinearRegression` class from the `scikit-learn` library, served as a baseline. Owing to its assumption of linearity between independent variables and the dependent variable, it was expected to perform sub optimally in the presence of complex, nonlinear interactions.

The decision tree model was constructed using the `DecisionTreeRegressor` class, which can capture non-linear dependencies through recursive binary splitting. While more flexible than linear regression, decision trees are susceptible to overfitting in the absence of pruning or depth constraints.

To mitigate the risk of overfitting and enhance generalization, an ensemble learning method was employed via the random forest algorithm. The `RandomForestRegressor` class was used to train multiple decision trees on different subsets of the data, and the predictions were aggregated to obtain the final output. This approach not only reduces variance but also improves robustness to noise.

Deep learning architectures were employed to model temporal dependencies in the data. Both LSTM and GRU networks were trained in sequential traffic and weather records. The input data for these models was reshaped into three-dimensional tensors to satisfy the architectural requirements of recurrent neural networks. The LSTM model was expected to capture long-term dependencies, while the GRU model, being a computationally efficient alternative, was expected to perform similarly with fewer parameters.

All models were trained using 80% of the dataset, with the remaining 20% reserved for testing. Temporal integrity was preserved during data splitting to avoid information leakage from future to past observations.

Hyperparameter Optimization

For the decision tree and random forest models, hyperparameter tuning was conducted using exhaustive grid search combined with five-fold cross-validation. Deep learning models were trained with default hyperparameters due to computational constraints. Both LSTM and GRU models used a single recurrent layer followed by a dense output layer. The models were trained using the Adam optimizer, a learning rate of 0.001, a batch size of 32, and a maximum of 50 epochs. Mean squared error was used as the loss function throughout.

Evaluation Metrics

The models were evaluated on two key performance metrics: Mean Squared Error (MSE) and the coefficient of determination (R^2 score). MSE quantifies the average squared difference between predicted and actual values, penalizing larger errors more severely. The R^2 score measures the proportion of variance in the dependent variable that is predictable from the independent variables. A higher R^2 score indicates a better fit between model predictions and observed values.

These metrics were calculated on the test set and used to compare the performance of each model across different experiments involving varying input configurations and temporal scopes.

Geospatial Feature Importance Mapping

In addition to global model performance metrics, the study also sought to understand how feature importance varied spatially across Istanbul. To achieve this, geohash-level feature importances were extracted from the trained random forest regressor. The random forest model provides intrinsic feature importance scores by measuring the average decrease in impurity across all trees resulting from splits on each feature.

A dictionary structure was created to store the feature importance values computed independently for each geohash region. These values represent how influential each feature (e.g., temperature, precipitation, wind speed) was in predicting traffic density within that geohash zone.

The resulting dictionary was converted into a structured DataFrame and merged with a geospatial reference table extracted from the original dataset. Since geohashes are area-based identifiers, the geometry associated with each geohash was approximated using the first recorded latitude-longitude pair in the dataset. These coordinates were then converted into geometric Point objects using the shapely library and passed into a GeoDataFrame.

To visualize the results, the GeoDataFrame was projected into the Web Mercator coordinate reference system (EPSG:3857) for compatibility with web-based mapping services. Using the geopandas and contextily libraries, a choropleth map was generated in which the intensity of color in each geohash region reflected the relative importance of a selected feature—in this case, cloud cover.

Missing values were imputed with zeros to maintain continuity in the visualization. The resulting map provides an interpretable spatial distribution of feature influence across Istanbul, highlighting, for instance, regions where cloud cover exhibited higher relevance in affecting traffic density.

This spatial decomposition of feature importance serves two purposes. First, it enables localized insights into traffic behavior, identifying which features dominate in specific regions. Second, it supports urban planners in tailoring interventions based on local environmental sensitivity. For example, areas where precipitation has high importance may benefit from adaptive road infrastructure or targeted traffic signaling during adverse weather.

Experiments

In this study, three experiments were conducted. The scope of these experiments and the results obtained are explained below.

In Experiment 1, which included Average Speed, Min–Max Speed, Number of Vehicles data for September 2023, the Decision Tree model outperformed Linear Regression for both geohash and latitude–longitude representations, achieving the lowest Mean Squared Error (MSE) and the highest R^2 values. The difference between geohash and latitude–longitude was minimal for the Decision Tree, and latitude–longitude proved to be easier and clearer to work with. However, a major limitation of this experiment was that the inputs included the outputs, allowing the model to directly learn their relationship and produce artificially high accuracy, reflected in the near-perfect R^2 value. As a result, the validity of these results is limited. Nonetheless, the experiment highlights the limitations of Linear Regression: even when provided with the outputs as inputs, its inability to capture nonlinear relationships leads to higher MSE values compared to the Decision Tree. Table 1 presents the MSE and R^2 values calculated in Experiment 1.

Table 1. MSE and R^2 values calculated in Experiment 1

Model	Location Parameter	MSE	R^2
Linear Regression	geohash	0.0430	0.970
	latitude longitude	0.1300	0.900
Decision Tree	geohash	0.0022	0.998
	latitude longitude	0.0023	0.998

Experiment 2 excluded those traffic-derived features, leaving weather and geospatial attributes. Linear Regression collapsed with negative R^2 , confirming its inability to model nonlinearities in heterogeneous urban data. Decision Tree, while more robust, achieved only moderate performance ($R^2 \approx 0.77$), indicating that single-tree structures can capture interactions but remain sensitive to noise and variance. Table 2 presents the MSE and R^2 values calculated in Experiment 2.

Table 2. MSE and R^2 values calculated in Experiment 2

Model	MSE	R^2
Linear Regression	5095501940	-8546320616372.097
Decision Tree	0.00013	0.7741830656182732

In Experiment 3, the same four parameters excluded in Experiment 2 (Average Speed, Minimum Speed, Maximum Speed, and Number of Vehicles) were again omitted, while the dataset was expanded to include September 2023, December 2023, March 2024, and June 2024. Relying on data from only a single month proved limiting; incorporating weather data across different seasons introduced greater variability, allowing the models to capture more distinct patterns. Incorporating data from additional months boosted the performance of all models, while further tuning led to even greater predictive accuracy. Importantly, in no case did a tuned model perform worse than its untuned counterpart. Here, a clear performance hierarchy emerged: Random Forest achieved the best accuracy ($R^2 \approx 0.91$), outperforming Decision Tree ($R^2 \approx 0.83$) by leveraging ensemble averaging to reduce variance. Random Forest also demonstrated stable performance across both tuned and untuned configurations, reflecting its resilience to overfitting. Table 3 presents the MSE and R^2 values calculated in Experiment 3.

Table 3. MSE and R^2 values calculated in Experiment 3

Model	Tuned/Untuned	MSE	R^2
Linear Regression	Untuned	3.5e-4	0.11
Decision Tree	Untuned	7.0e-5	0.82
	Tuned	6.5e-5	0.83
Random Forest	Untuned	3.5e-5	0.91
	Tuned	3.5e-5	0.91
LSTM	Untuned	3.3e-3	0.48
GRU	Untuned	3.5e-3	0.47

The deep learning models (LSTM and GRU) delivered mixed results. Despite being well-suited to sequential data, they underperformed compared to tree-based ensembles ($R^2 \approx 0.47$ – 0.48). This can be attributed to two factors: (i) the dataset’s relatively short temporal span, limiting the ability of recurrent models to exploit long-term dependencies, and (ii) computational constraints that restrict hyperparameter tuning and deeper architectures. With richer datasets and optimized architectures, LSTM and GRU could potentially rival or surpass Random Forest.

Taken together, these results show that classical models like Linear Regression are inadequate for traffic prediction tasks involving spatial and weather-related complexities.

Decision Trees capture nonlinearity but risk overfitting. Random Forest, by contrast, consistently emerged as the most balanced and accurate approach. Deep learning architecture, while currently less effective, remains promising candidates for future work when more extensive datasets are available.

Feature Importances

The analysis of feature importances revealed that the most influential predictors were longitude and latitude, which was expected given that variations in road infrastructure have a greater impact on overall traffic flow than weather conditions. This result aligns with the reality of Istanbul, where the capacity of road infrastructure to accommodate traffic differs significantly across neighborhoods, leading to localized bottlenecks and non-optimized traffic flow. Interestingly, precipitation was found to have the lowest importance among the variables, suggesting that rainfall exerts a weaker effect on traffic density compared to spatial and structural factors. Other weather attributes, such as temperature, wind speed, and humidity, exhibited moderate levels of importance, indicating that while atmospheric conditions influence traffic flow, their effects are secondary to the spatial configuration of the road network. Table 4 presents the relative importance values of the features along with corresponding comments, while Figure 5 provides a graphical representation of the feature importances.

Table 4. Feature Relative Importances and Comments

Feature	Relative Importance	Comment
Longitude	Highest	Geospatial variables dominate since infrastructure strongly affects traffic capacity.
Latitude	Highest	Geospatial variables dominate since infrastructure strongly affects traffic capacity.
Temperature	Moderate	Weather variable with some effect, linked to seasonal travel behavior.
Wind Speed	Moderate	Moderate effect, as strong winds may reduce speed and increase caution.
Humidity	Moderate	Moderate effect, influencing driver comfort and road conditions slightly.
Pressure	Moderate	Moderate effect, linked to air density and visibility but less direct impact.
Cloud Cover	Moderate	Moderate influence, cloud cover may affect visibility but not traffic flow directly.
Visibility	Moderate	Moderate effect, reduced visibility can impact driving but context-dependent.
Precipitation	Lowest	Lowest importance; rainfall in Istanbul seems less decisive than infrastructure factors.

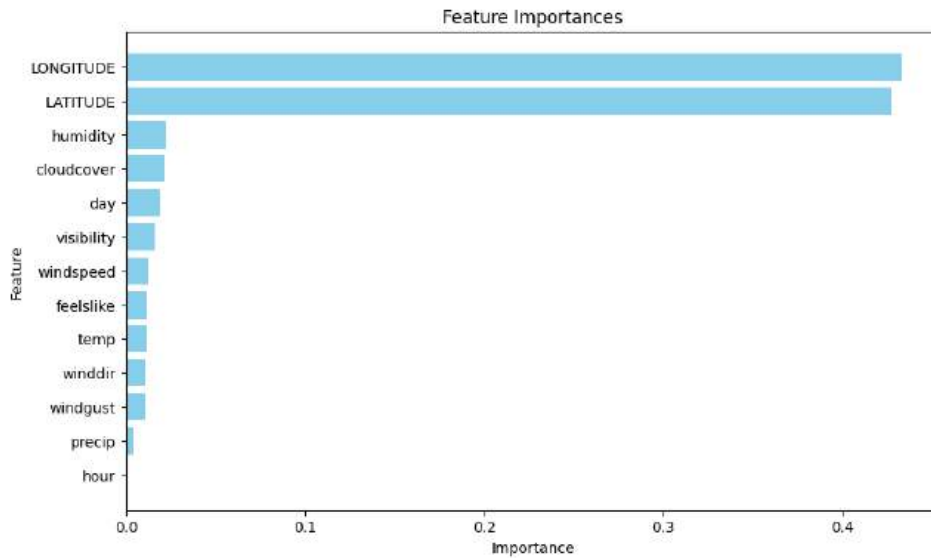


Fig. 5 - Graphical Representation of the Feature Importances

Regional Variability in Feature Importance

The study found that spatial variables exerted a stronger influence on predictive performance than weather-related variables. Building on this insight, a feature analysis approach was applied to identify the most influential predictors within individual geohash regions. This enables the detection of region-specific traffic challenges that may warrant targeted improvements or interventions. Figure 6 illustrates the spatial distribution of the humidity feature across geohash areas and highlights how the impact of certain variables can vary substantially depending on location.

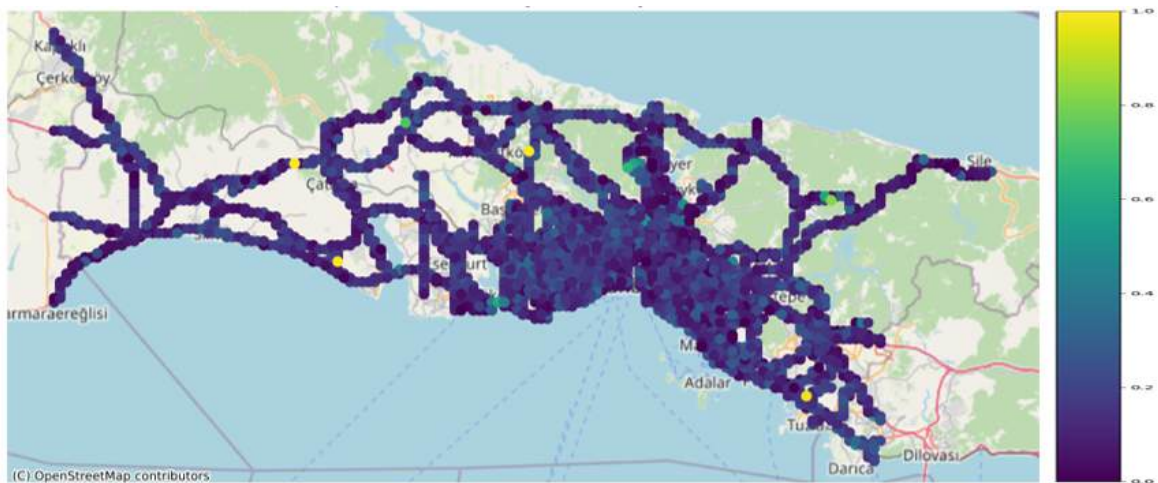


Fig. 6 – Importance of “humidity” Feature by Geohash

Discussion

Traffic prediction tasks involve complex and nonlinear relationships between variables such as vehicle counts, speed, and weather conditions. The models tested in this study demonstrated distinct strengths and weaknesses in handling these complexities.

Linear Regression served as a baseline but struggled across all experiments. Its strict assumption of linearity meant that it consistently failed to capture the nonlinear interactions present in urban traffic data. This was evident in Experiment 2, where it collapsed with negative R^2 values.

Decision Trees performed considerably better, thanks to their ability to capture nonlinear thresholds and variable interactions. However, their tendency to overfit limited their generalizability, particularly when the dataset became more heterogeneous.

Random Forest achieved the best overall performance. By aggregating multiple decision trees, it reduced variance and improved robustness against noise. Both tuned and untuned configurations produced high R^2 scores, with tuned Random Forests showing only marginal improvement, reflecting the algorithm's natural stability.

Deep learning models (LSTM and GRU) provided mixed results. While well-suited to sequential data, their predictive accuracy in this study was lower than Random Forest and even Decision Tree in some cases. LSTM achieved slightly higher accuracy than GRU, indicating its greater ability to model long-term dependencies. However, both models were constrained by the relatively short dataset and limited hyperparameter optimization. With larger datasets covering more extensive temporal patterns, recurrent neural networks could achieve superior results.

In summary, Random Forest emerged as the most effective model for this dataset, offering the best balance of accuracy and robustness. Decision Trees were useful but less stable, Linear Regression proved inadequate, and recurrent deep learning models remain promising but underdeveloped given the current data constraints.

Conclusion

This study demonstrated that integrating weather and traffic data improves the accuracy and interpretability of traffic density predictions for Istanbul. Among all models evaluated, Random Forest consistently delivered the strongest results, offering the most effective balance between bias and variance. Decision Tree followed, effective but prone to instability when data noise increases. Linear Regression proved unsuitable for this domain, unable to capture the nonlinear and interaction-heavy structure of urban traffic dynamics.

Although LSTM and GRU underperformed relative to tree-based methods in this study, their architecture remains valuable for problems with richer sequential structures. Their moderate results suggest that with longer datasets, enhanced hyperparameter optimization, and computational resources, deep learning could complement or surpass ensemble methods in traffic prediction.

An important finding was that spatial variables (latitude and longitude) dominated predictive power, overshadowing weather features. Still, weather attributes introduced seasonal

variability that improved generalization, supporting the argument that climate change will make weather-informed models increasingly necessary.

Future studies should investigate hybrid strategies that integrate ensemble tree models with optimized deep learning architectures, while also expanding the dataset to cover at least a full year. Such improvements could unlock higher accuracy and real-time applicability in intelligent transportation systems.

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Reducing Plastic Pollution Through Technological Advancements in Recycling Systems & Materials: A Policy Brief By Ashley Du & Jeff Li

Plastic pollution is a global issue that has devastating effects on humans, animals, and the environment. Compounds that are often found in our plastic bottles can leach into the water, causing serious health issues like hormone changes, insulin resistance, and cancer (Geneva Environment Network 2022). These microplastics are ubiquitous in our food, largely because they are found in the soil and groundwater in which our plants grow. Plastics in landfills can break down over decades and seep into the soil and the groundwater. When our plants grow using the plastic-filled groundwater and soil, microplastics enter their cells and, subsequently, when we eat them, enter our bodies (Gerresten 2023)

The harms of plastic pollution do not just affect humans. Over 1 million marine organisms like turtles and seals are trapped in large pieces of plastic per year, causing difficulty breathing and eventually death (Sea Turtle Conservatory 2002). Losing marine biodiversity impacts the whole ecosystem, which means if this magnitude of plastic pollution continues, the whole marine ecosystem will suffer greatly. Both recycling and utilizing alternative materials can help alleviate the devastating effects of this issue and help rejuvenate Earth.

Starting with recycling, the standard single-stream recycling process has existed since the 1990s, and it is what most of the world uses today. The 4 step process, including collecting, transporting, sorting, and recycling the plastics, has not been effective in the past and will not be in the future. Over 26% of recyclable materials end up in landfills because of clumsy sorting issues or the intolerance of the recycling plant for mixed materials (Burrows 2022). For instance, many recycling plants cannot process straws or bags because they clog up machinery. Recyclable materials disposed of in a household trash bag often get sent straight to the landfills because it is inefficient for workers to unwrap and sort the trash (Burrows 2022).

The core problem of these ineffective recycling systems is the highly manual and outdated machinery the plants use. This is partially because the federal and state governments do not allocate enough funds for recycling technology development. Large companies also do not want to switch to other materials because of the cheap cost of plastic. To solve these issues, new recycling system prototypes have been proposed to truly make these processes effective. Bio-engineered enzymes, AI-integrated systems, and the Exxon-Mobil advanced recycling system will be discussed in this brief as solutions to the current recycling problem.

The second way to alleviate the harms of plastic pollution is to target the plastic itself. It is important to note that even though plastic alternatives are likely to be more expensive than plastic, they must be considered because of the devastating trajectory the world is headed toward if we keep using plastic. Plastics that humans use every day are not biodegradable, which means that the material will stay in the environment for over 1000 years (Kayla 2023). These plastics do not just remain present in the environment; they interfere with the natural course of life, killing animals by suffocation and ruining soil. The front runner in plastics, PET has over 10,000 chemicals involved in its production, and 24% of them are harmful to humans and the

environment (Lim 2021). Thankfully, scientists have developed many alternatives to plastics that are biodegradable including bioplastics, mushroom mycelium, and casein plastics, which will be discussed in this brief.

Plastic pollution is devastating and has already been stated by many to be unsolvable or irreversible. In fact, by 2050, the number of plastics in the ocean will quadruple (WWF 2022). However, there is still hope of alleviating the effects if humans unite and decide seriously to act on this issue as soon as possible. This brief will close with policy recommendations to reduce plastic pollution, thereby protecting human and ecosystem health.

Overview of the Current Recycling System

Recycling systems vary from one country to another, but the standard single-stream recycling system includes four different steps. First, the consumers throw their trash into separate bins in colors that correspond to the trash type. Next, the trash bins are transported to a recycling facility. The facility will clean, sort, and prepare recyclables. Lots of unwanted materials get mixed in with the recyclables, so some trash will take additional work to sort. Unwanted trash gets sent to landfills. Finally, the recyclables are made into new products at other facilities like plastic bottle factories or paper mill facilities (USEPA 2019).

Countries like Switzerland use innovative ways to deal with unwanted trash, such as incinerating it to extract a proportional amount of energy from the heat released (Duong 2021). Innovative recycling systems are crucial for alleviating plastic pollution because of the lack of reliability other methods provide. For instance, convincing the general public to start reducing their plastic consumption is difficult as most do not understand the harms of the issue. Recycling systems provide a tangible solution to already-created plastic by reusing plastic to reduce the demand for natural resources to produce new plastic. However, current recycling systems have shown flaws in terms of effectiveness and efficiency. Over 26% of recyclable materials end up in landfills because of clumsy sorting issues or the tolerance of the recycling plant. Many recycling plants cannot process straws or bags because they clog up machinery. Recyclable materials wrapped in a household trash bag could get sent straight to the landfills because it is inefficient for workers to unwrap and sort the trash (Burrows 2022). The core problem of these ineffective recycling systems is, thus, the highly manual and outdated machinery the plants use. To solve these issues, new recycling system prototypes have been proposed to truly make these processes effective.

Bio-Engineered Enzymes

As bio-engineering continues to advance, enzyme technology subsequently has improved. New enzymes, called PETase, have been developed that can break down the chemical bonds of PET, the most common type of polyester, by reducing it to mono-terephthalic acid. This acid can then be further decomposed by MHETase, another enzyme, into glycol and ethylene, which are good carbon sources for bacteria (Burgins 2024). With this new enzyme, plastics can be bio-degraded with no emissions. PETase can replace the heavy machinery that is currently

employed to break down plastic. However, the PETase enzyme does take a bit of time to decompose plastic, lasting days or even weeks. Furthermore, the temperature needs to be at exactly 40 degrees Celsius for optimal performance. Temperature control is hard to monitor outside the lab, making optimal performance infeasible. It is worth noting that PETase is relatively inexpensive, costing only around 116 USD per ton (Chen 2023). Each ton of enzymes can break down many more tons of plastics. Even with its cheap cost, the main issue with this method is the versatility of the enzyme. PETase can only break down PET plastics, which means that other types of plastic would require different enzymes. Scientists have not yet developed a panacea enzyme to break down all types of plastic. This process could be effective in the future when all lab testing is complete and results are satisfactory. But right now, it is not commercially viable and is too complicated to integrate into our system.

Integrated Recycling Systems

The second solution takes advantage of the increasingly prominent artificial intelligence technology and integrates it into traditional recycling systems. In this process, the standard single-stream recycling system is still used, but this time each step is modified to use AI to make things easier and more effective. At the first level, normal recycling bins are replaced with smart bins with sensors to detect the material thrown into them so that they can automatically filter recyclable materials into a separate compartment from non-recyclable materials. This process helps to solve a major issue faced by current recycling systems, as human workers and outdated machinery have low accuracy.

In addition to smart bins placed in the home, AI can further increase accuracy by using sensors to accurately filter out trash on-site at the recycling plant. For instance, the robot arm developed by Everest Labs utilizes AI to detect non-recyclable trash and remove it from the conveyor belt. They use their own AI system, EverestOS to help with evaluating the quality of the materials and detecting contaminants in the recycle stream. This eliminates human error and improves efficiency so that the recycled materials are more pure and last longer. The downside to this process is the huge cost that comes with these robots. Each robot could cost up to 300,000 dollars, and multiple are needed in each facility (Everest Labs n.d.). In addition, smart bins would be hard to implement because no consumer would be willing to pay more than \$100 just for a trash can. The government would need to allocate significant funds to recycling and create a plan for distributing new machinery and bins around the country. As AI matures, this process will likely become increasingly feasible as costs decrease. At this point, however, it is not possible due to the high cost and labor-intensive process of introducing AI to the general recycling system.

Exxon Mobil Advanced Recycling

The advanced recycling system developed by Exxon Mobil includes four different steps, just like a normal single-stream recycling system. However, each part of the process is modified slightly to create a more effective system. First, Exxon Mobil is collecting not only plastics like

bottles and bags but also hard-to-recycle plastics like gas containers and hard plastics. Next, those hard-to-recycle plastics that would normally end up in the landfill are sorted and sent to the advanced recycling facilities. Normal plastics are sent down the stream to mechanical recyclers. Then, the hard plastics are shredded and processed to fit the specifications of the advanced recycler. Lastly, the plastics are broken down into liquid and gas molecules by the advanced recycler so they can later be rebuilt into raw materials (Exxon Mobil n.d.).

Though both the aforementioned advanced recycler and the enzyme break down the plastic, Exxon Mobil has produced tangible results and the system is already in motion. Their facility in Baytown, Texas, has been running since 2022 and has an annual processing capacity of 80 million pounds of plastics per year (Exxon Mobil n.d.). They also have plans to expand their facilities around the globe and introduce 1 billion pounds of capacity by 2027 (Exxon Mobil n.d.). It is important to note that there could be bias in the literature because the company is writing about itself. There is also a lack of discussion around the costs of this system. Despite that, this recycling system is the most feasible because it already exists and is working. In addition, they also have plans to expand into other continents, showing that this recycling system could stand the test of time (Exxon Mobil n.d.). Having an actual facility and statistics to back it up makes this the most plausible and effective system of the three discussed so far.

Materials

Plastic is a widely used material, with 400.3 million metric tons of plastic produced in 2022 (Statista Research Department 2024). In 1988, the Society of Plastic Industry divided plastics into seven categories (Almack 2023). Polyethylene Terephthalate (PET) is the number one most used plastic. It is lightweight, strong, transparent, normally used in food packaging, and widely recyclable. Number 2, High-Density Polyethylene (HDPE), is extremely resistant, as it can be subjected to high temperatures and used in grocery bags, milk jugs, and playground equipment. It is accepted at most recycling centers. Number 3, Polyvinyl Chloride (PVC), is the world's third-most widely produced synthetic plastic polymer used in the building and construction industry and is now replacing traditional building materials. However, PVC is hardly recyclable. The rest of the plastic materials we use are Low-Density Polyethylene (LDPE), Polypropylene (PP), Polystyrene (PS), and other plastics, which are all nearly non-recyclable except for Polypropylene (Plastic Oceans International 2021).

Of the various types of plastics used, most are non-recyclable. Only 9% of the plastic ever produced has been recycled, and 19% has been incinerated, as recycling is an energy-intensive process that is extremely costly (Main 2023). Yet, a big reason is the lack of capacity to recycle various plastics. With 19-23 million tons of plastic waste leaking into aquatic ecosystems, polluting the environment, and harming the ecosystem, more environmentally friendly and sustainable materials are worth investing in (UNEP n.d.). In order to increase the recyclability of our waste, new materials should be explored and invested in.

Bioplastics

Bioplastics are manufactured from bio-based polymers derived from renewable or recycled raw materials. These natural polymers are often from agricultural, cellulose potato, and corn starch waste. Bioplastics made from these raw materials are 100% degradable and are equally resistant and versatile as plastic (Sustainability for All n.d.). However, bioplastics made from petroleum and GMOs are nondegradable (Sustainability for All n.d.). Bioplastics are already used in agriculture, medicine, the textile industry, and packaging markets (Rosenboom et al. 2022). They are popular in cities in the United States and Europe, as they can be produced by fermenting raw materials with bacterial strains, resulting in bioplastic. Within ten years, bioplastics are expected to cover ten percent of European plastics market needs (Sustainability for All n.d.). Bioplastics can reduce our carbon footprint, save production energy, and reduce waste (Rosenboom et al. 2022). However, they increase competition with food production and have unclear end-of-life management. Furthermore, the cost of bioplastics is between twenty and fifty percent higher than traditional plastics, making them infeasible in many markets (Elytus n.d.).

Mushroom Mycelium

Mushroom Mycelium can also be used as an alternative to plastics. Mycelium is the root network of a fungus, usually found below the ground. It is a natural material that's renewable and cheap to produce (SourceGreen 2023). It is also easy to grow and has an excellent end-of-life performance, as it is home-compostable (SourceGreen 2023). Mycelium is not only strong but can also be molded into different shapes. It can be used for protective packaging using agricultural byproducts such as woodchips and straw to create rigid shapes. As Mycelium is incredibly versatile, it is also used to make skincare sponges, cruelty-free leather, and alternative protein substitutes (SourceGreen 2023). Mycelium-based products are cheaper to produce than most plastics. It costs around fifty USD to produce one square foot of Mycelia (Straits Research n.d.). However, it is a living material sensitive to environmental conditions. It is also susceptible to contamination if not properly sterilized. Mushroom mycelium is not produced at scale yet due to the early stages of technology and the lack of funding to support the cost of production, which as said, is way more expensive than traditional plastics. Additionally, as mushroom mycelium is derived from the roots of mushrooms, scaling up production puts stress on mushroom plantations. However, with an increase in funding to support technological advancement and production fees, mushroom mycelium could be an alternative to traditional plastics.

Casein Plastic

Casein plastics can be another alternative material. Milk contains many molecules of casein, which is a protein. Each casein molecule is a monomer, and a chain of casein monomers is a polymer. The polymer can be molded and made into casein plastic (Scientific American 2024). It can be used as food wrap, and it is 500 times better at sealing off food from oxygen than petroleum-based plastics (Scientific Discoveries n.d.). Milk protein is made up of eighty percent casein and twenty percent whey protein. Whey and casein can be used on their own or

combined to develop edible food coatings and edible films applied on fruit and vegetable surfaces (Chaudhary et al. 2022). However, casein plastic is generally more expensive than traditional plastic. It costs around \$3,000 to \$4,500 a tonne, and its uses are generally limited to food packaging, as it is brittle and not very durable (Oils 2021).

Policy Recommendations

On June 8, 2022, the Secretary of the Interior issued an order outlining a “Department-Wide Approach to Reducing Plastic Pollution,” which stems from President Biden’s Executive Order on “Catalyzing Clean Energy Industries and Jobs Through Federal Sustainability” (SO 3407, U.S. Department of the Interior 2022). This increased attention and action at the federal level aims to reduce the sale and distribution of plastic products and packaging on department-managed lands by 2032 (U.S. Department of the Interior 2022). Single-use plastic products and packaging include plastic and polystyrene food and beverage containers like bottles, straws, cups, cutlery, and disposable plastic bags intended to be used once. The U.S. Department of the Interior collects solid waste and recycling information to track progress toward achieving diversion rates for waste and demolition debris of at least fifty percent by 2025 and seventy-five percent by 2030 (U.S. Department of the Interior 2022). While the executive branch is increasingly focused on reducing plastic pollution, there are no nationwide laws requiring states to recycle. Each state has its own recycling law that slightly differs but is mainly focused on either recycling goals or landfill bans. The lack of a clear nationwide law to instruct different states causes a gap in efficient recycling for different states. As recycling is not demanded, many individuals may choose not to recycle for convenience, and states may choose to implement a sub-optimal recycling system in order to preserve public funds.

Increased Funding

The lack of comprehensive recycling policies contributes to severe environmental issues. In order to address these growing issues, the United States should implement funding programs to increase the budget for research, development, and implementation of new recycling processes that increase efficiency and decrease cost, thereby increasing public trust in recycling and decreasing barriers to state policy. Funds could come from taxes, donations, and extra fees for purchasing plastic products collected from states. Funds could be deployed strategically by awarding organizations that are making progress in sustainable materials research, which would help to create competition and spur innovation. Funds could also be used to support local factories to advance production efficiency, lower costs, and reduce carbon emissions from shipping. This will make eco-friendly materials such as mushroom mycelium and casein plastics more affordable to the public, allowing them to be introduced across different states.

There are some challenges to implementing these policies. It would be hard to get appropriate funding, as the amount of money distribution across branches cannot be easily increased. Therefore, purely relying on the government, taxes, and donations will not work. It is more important to include extra charges for plastic products in the funding.

Consumer Oriented Partnerships and Marketing

People often don't view climate change as an issue that affects them personally or their community. Therefore, they don't feel motivated to shift to more sustainable methods, such as using eco-friendly products and properly recycling their trash. The government could fund departments to use social media to introduce these materials, allowing more individuals to view them as a decent replacement for plastic products. This would spark consumer interest which in turn could increase economic growth and open new markets. As more business opportunities are created, more organizations would turn to the production and use of sustainable materials.

In order to further incentivize the creation of business opportunities, the United States could form a partnership with companies engaged in the recycling industry, such as Exxon Mobil. Partnerships expand access to recycling systems not only for common plastics but also for hard-to-recycle plastics, reducing pollution. For instance, Exxon Mobil's recycling facility in Baytown, Texas processes 80 million pounds of plastic waste per year, supporting the circular economy. With the implementation of this system, every state in the nation would recycle billions or even trillions of plastics that otherwise would have ended up in landfills.

Despite the array of challenges associated with these proposed recommendations, there are many benefits once these policies are implemented. The shift towards sustainable materials and recycling processes will help reduce plastic waste and pollution. It also reduces carbon emissions and harmful toxins released from landfills where plastic products are buried. A more sustainable lifestyle will protect our environment, reduce natural disasters, and alleviate climate-caused health problems. Ultimately, these policies help preserve the environment to protect biodiversity and the home of generations.

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Comparative Analysis of Deep Learning and Machine Learning Models for Stock Price Prediction By Ethan Fahy¹, Odyssea Drosis²

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Abstract

This project investigates the effectiveness of machine learning models in predicting stock prices and supporting investment decisions. Using five years of historical data from Apple, Tesla, HP, CVS Health, and Chevron Corp, we trained and tested six models: Linear Regression, Decision Trees (with depths of 7, 10, and 20), Random Forest Regression (with maximum depths of 5 and 10), Multilayer Perceptron (MLP), and K-Nearest Neighbors (KNN, with neighbors of 2 and 3). We split the data into training and testing sets to ensure unbiased performance evaluation and applied techniques such as dropout and regularization to reduce overfitting in complex models. Prediction performance was measured using Mean Squared Error (MSE), while the practical financial value of each model was evaluated using a simulated buy/sell trading strategy. Our findings show that MLP consistently outperformed other models in both prediction accuracy and investment returns, particularly for volatile stocks like Tesla, while Linear Regression performed well for more stable stocks such as HP. Random Forest models, despite occasional overfitting, captured actionable patterns in trading simulations, and KNN delivered moderate results. These results suggest that deep learning approaches, combined with proper evaluation strategies and trading simulations, can provide powerful tools for stock price prediction and investment decision support.

Introduction

The stock market is the network of exchanges, brokerages, and venues where investors buy and sell shares of publicly held companies. The history of the stock market dates back to the 17th century, where the Amsterdam stock exchange, widely considered the world's first stock exchange, traded shares of the Dutch East India Company. The London Stock Exchange and New York Stock Exchange became major financial centers when markets began their global expansion during the 18th and 19th centuries. These institutions enabled companies to obtain funding while managing risks and promoting economic development. The stock market has shown both fast growth and major market collapses throughout history, including the Great Depression of 1929 and the 2008 financial crisis, which demonstrated its unpredictable nature and sensitivity to worldwide occurrences. Financial research faces a perpetual challenge to achieve accurate prediction because of the extensive historical development of the stock market.

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Predicting stock market prices is one of the most complex and thoroughly studied challenges in financial forecasting. Stock prices are affected by many factors, including economic indicators, company performance, global events, and public sentiment, which makes prediction tough. Recently, the use of Artificial Intelligence (AI) and Deep Learning (DL) models has shown significant promise in addressing this complexity because they can reveal non-linear relationships and learn from large amounts of historical data.

Traditional statistical models, while helpful, often fail to capture the changing and time-dependent nature of financial data. In contrast, deep learning models such as Long Short-Term Memory (LSTM) networks, Multilayer Perceptrons (MLPs), and ensemble methods like Random Forest Regressors have become powerful tools for predicting time series. According to Cao (2024), LSTM outperforms standard RNNs and CNNs in financial forecasting because it can retain information across long sequences. Other research, such as that by Abunasser et al. (2023), has compared machine learning algorithms and found that deep models consistently provide better performance on unstable financial datasets.

In this research, we applied and compared six machine learning techniques: Linear Regression, Decision Trees, Random Forest Regressors, Multilayer Perceptrons (MLPs), and K-Nearest Neighbors (KNN) to predict stock prices for Apple, Tesla, and HP. We trained the models on a five-year historical dataset using features like stock prices and open/close values. We also evaluated model performance using Mean Squared Error (MSE) on both training and testing data to find the most effective approach. A simulated trading strategy was used to evaluate potential financial gains based on model predictions.

The main hypothesis of this study is that deep learning models, such as MLPs and Random Forest Regressors, will exceed the performance of traditional models like Linear Regression and Decision Trees in predicting stock prices and maximizing returns. To test this, we analyzed prediction accuracy and investment performance across different models. We also set up a basic trading algorithm to simulate gains using model predictions as buy/sell signals.

Our findings support the hypothesis: MLP consistently performed better than other models in both prediction accuracy, especially for Apple and Tesla, and in simulated investment returns. Interestingly, while Random Forest Regressors showed signs of overfitting in some cases, it still produced strong financial results for certain stocks. In contrast, Decision Trees struggled due to overfitting, and KNN delivered moderate results. These outcomes align with prior research (e.g., Zheng & Jin, 2017), suggesting that combining AI models with proper preprocessing and evaluation strategies can create effective stock forecasting systems.

Materials and Methods

The dataset used in this study included five years of historical stock data for Apple, Tesla, HP, CVS Health, and Chevron Corp. Each dataset featured Open (the stock price at the beginning of the opening day), Close (the stock price at the end of the trading day), Volume (how many shares were traded), and Adjusted Close prices (the closing price accounting factors like dividends or stock splits, resembling a more accurate measure of value over time). These

variables were chosen because they represent key market signals, capturing both day-to-day fluctuations and broader stock performance trends.

To evaluate model performance clearly, we split the data into training and testing sets with an 80/20 ratio. This method helps the models learn from past patterns while testing them on unseen data to avoid overfitting. The separation between training and testing ensured that the results reflected how well each model could generalize, not just memorize, historical price movements.

A recurring issue when deploying modern predictive models is overfitting. This phenomenon occurs when a model achieves near-perfect accuracy on its training set yet fails on testing data. The underlying cause is that the model catalogues idiosyncratic noise or minuscule fluctuations within the training subset, skewing itself to the training but failing the more robust generalization task. To counter this, practitioners routinely resort to regularization methods that dampen the contribution of marginal features, thereby curbing the excessive signal that noise would otherwise provide. Within deep learning, dropout has emerged as a staple remedy; by randomly disabling a fraction of neurons at each training step, the architecture is compelled to scatter learned information across multiple pathways rather than fixate on a narrowly defined set. By combining explicit regularization and dropout, practitioners guide the model toward a judicious trade-off between training accuracy and generalization capability, a necessity, especially in financial forecasting. Given the pervasive noise and volatility that characterize financial time series, such measures have transitioned from best practices to essential routines.

We employed six different models

Linear Regression is a simple model that identifies the best-fit line through the data by minimizing the squared difference between actual and predicted values.

Decision Trees divide data into branches based on feature thresholds, ultimately reaching leaf nodes that represent predictions. They are highly interpretable and can capture non-linear relationships, but they often overfit when trained deeply, memorizing patterns rather than generalizing them. While effective for smaller datasets or clear patterns, their performance declines on volatile stock data, where randomness and noise dominate.

Random Forest Regression builds upon Decision Trees by constructing an ensemble of them and aggregating their predictions, usually through averaging. This process reduces the high variance of individual trees, making the model more stable and less prone to overfitting. By considering multiple trees trained on different data subsets and features, Random Forest often captures meaningful signals while balancing bias and variance. However, it can still struggle with highly unpredictable markets where noise overwhelms consistent patterns.

Multilayer Perceptron (MLP) is a deep learning model composed of multiple interconnected layers of neurons, including hidden layers that enable it to capture complex, non-linear dependencies. MLPs are particularly powerful for financial time series because they can uncover subtle relationships that simpler models overlook. To prevent overfitting, techniques such as dropout and regularization were used, forcing the network to distribute learning across

many nodes rather than memorizing narrow patterns. Despite being computationally intensive, MLP consistently provided the most accurate predictions in this study.

K-Nearest Neighbors (KNN) predicts values by examining the outcomes of the most similar data points in the feature space, determined by a distance metric such as Euclidean distance. Its strength lies in its simplicity and adaptability, as it makes no assumptions about the underlying data distribution. However, KNN can be computationally expensive on large datasets and sensitive to irrelevant features, since predictions rely heavily on the local neighborhood. In financial forecasting, where volatility creates frequent shifts, KNN's reliance on past "neighbors" can be both a strength and a limitation.

We measured model accuracy using Mean Squared Error (MSE). This metric calculates the average squared difference between predicted and actual prices, penalizing larger errors more severely. A lower MSE indicates higher predictive accuracy.

For the trading strategy, the system simulated buying a stock when the model predicted a price increase and selling it when a decrease was expected. These guidelines connected predictive accuracy to potential investment outcomes, bridging the gap between theoretical performance and real world applicability. We began with initial investments of \$1000, \$2000, and \$5000 to evaluate adaptability across different investment sizes. No external factors such as investment costs or slippage were included, ensuring that results were showcasing only the model's raw predictive capability. By applying this strategy across different predictive models, the study provided a consistent way to assess how well predictions could translate into financial returns.

Results

$$\text{MSE} = \frac{1}{n} \sum_{i=1}^n (y_i - \tilde{y}_i)^2$$

Experiment 1: Stock Price Prediction

The goal of this experiment was to evaluate how well various models generalized to unseen data when applied to stocks across three sectors: technology (Apple, Tesla, HP), healthcare (CVS Health), and energy (Chevron).

This table shows how well each model performed on unseen data, where lower values indicate stronger predictive accuracy.

Test MSE	Linear model	MLP	Decision tree depth = 7	Decision tree depth = 10	Decision tree depth = 20	Random forest Max depth = 10	Random forest max depth = 5	Knn Neighbors = 2	Knn Neighbors=3

Apple [Tech]	9.50	12.72	16.43	17.92	21.19	213.73	14.02	14.04	17.71
Tesla [Tech]	106.80	107.85	171.39	201.19	202.40	138.37	111.68	173.80	141.11
HP [Tech]	0.32	0.35	0.03	0.03	0.03	0.37	0.02	0.44	0.02
CVS Health [Health care]	1.33	1.50	2.34	2.74	3.33	1.64	1.98	2.34	2.37
Chevron Corp [Energy]	4.26	5.31	6.97	7.24	10.00	5.42	4.97	7.59	6.79

This table shows model performance on training data, highlighting cases of overfitting where training error is near zero but test error is high.

Train MSE	Linear model	MLP	Decision tree Max depth = 7	Decision tree Max depth = 10	Decision tree max depth = 20	Random forest Max depth = 10	Random forest Max depth = 5	Knn Neighbors = 2	Knn neighbors=3
Apple [Tech]	10.62	14.17	4.50	1.18	0	134.57	7.57	5.19	6.37
Tesla [Tech]	105.54	107.79	51.99	13.06	0	23.93	83.71	58.21	78.60
HP [Tech]	0.35	0.37	0.01	0	0	0.08	0.01	0.16	0.01
CVS Health [Healthcare]	1.73	1.86	0.94	0.27	0	0.43	1.31	0.95	1.13
Chevron Corp [Energy]	4.81	5.68	2.88	0.98	0	1.26	3.90	2.43	3.40

Experiment 2: Simulated Trading Returns

The second experiment tested whether predictions could be translated into profitable trades. A simple trading strategy was applied: buy if the model predicted a price increase, and sell otherwise.

This table shows simulated profits for investments of \$1,000, \$2,000, and \$5,000 using the models that included trading logic (MLP, Random Forest, KNN). Higher values indicate more profitable strategies.

Final amount	1000	2000	5000
Apple [Tech]	3271.81	9444.68	9376.94
Tesla [Tech]	3051.01	19465.91	13108.17
HP [Tech]	637.12	1552.27	2466.06
CVS Health [Health care]	4332.28	5090.33	11668.19
Chevron Corp [Energy]	2278.55	5920.64	16716.55

Interpretation of Experiment 1

Linear Regression and MLP consistently performed well across all sectors, particularly on stable stocks like HP (Tech) and CVS (Healthcare). Volatile stocks such as Tesla (Tech) produced much higher errors, especially for Decision Trees, which overfit the training data. Energy stocks like Chevron displayed more variability in accuracy, reflecting the commodity-driven influences on price. Overall, MLP offered the best balance of accuracy and generalization across industries.

Findings (see the MSE tables)

Apple: Linear Regression (9.50) and MLP (12.72) achieved the lowest test errors, with KNN close behind. Decision Trees and Random Forests displayed substantially higher MSEs, reflecting overfitting.

Tesla: Errors were larger across all models due to high volatility. Linear Regression (106.80) and MLP (107.85) again led in test accuracy, while Decision Trees generalized poorly (> 200 MSE).

HP: As the most stable stock, all models performed well. Linear Regression (0.32) and MLP (0.35) were nearly identical in accuracy, with KNN also close.

CVS Health: Results followed the same trend: Linear Regression (1.33) and MLP (1.50) were most accurate, while tree-based models suffered from higher variance.

Chevron Corp: Accuracy was moderate overall, with Linear Regression (4.26) and MLP (5.31) again outperforming more complex models.

The consistent preprocessing and train/test splits ensured fair comparisons. Overall, Linear Regression and MLP provided the best balance of accuracy and stability across different stock types, while Decision Trees often overfit the training data.

Interpretation of Experiment 2

Technology stocks like Apple and Tesla yielded the highest simulated returns, but with greater volatility and risk. Healthcare (CVS) produced more stable gains, showing the benefit of steady price movement for trading models. The energy sector (Chevron) showed strong but less predictable results, depending on commodity-driven swings. Across all sectors, MLP delivered the strongest trading outcomes, reinforcing its effectiveness for both prediction and financial performance.

Findings (see the profit table)

Apple: MLP achieved the best returns, growing \$5,000 to over \$23,000. Random Forest and KNN also produced gains, though less significant.

Tesla: High volatility led to large profits for MLP (\$13,108.17 from \$5,000), while KNN and Random Forest underperformed.

HP: Gains were smaller due to stability, but MLP still outperformed, turning \$5,000 into about \$2,468.

CVS Health: Performance was strong, with MLP converting \$5,000 into over \$11,600, demonstrating that healthcare sector stocks also benefited from machine learning predictions.

Chevron Corp: Energy sector volatility drove high returns, with MLP boosting \$5,000 to over \$16,700, making it the second-strongest performer after Apple.

Linear Regression and Decision Trees were excluded since trading logic was not implemented for them. This comparison highlights how different models translate predictive accuracy into practical investment outcomes.

Conclusions from Experimental Data

From both experiments, we can draw the following conclusions:

MLP consistently showed the best performance in predictive accuracy (low MSE) and practical profitability (high simulated returns).

Random Forest Regression models, despite weaker test MSE scores, performed reasonably in trading, suggesting they captured some exploitable signals.

KNN performed moderately well in both experiments but never surpassed MLP.

Decision Trees, while achieving zero training error, failed to generalize, confirming issues related to overfitting.

Linear Regression remained strong for accuracy, particularly with stable stocks like HP and CVS Health, though it was not tested in trading.

These findings support the idea that deep learning models like MLP are more effective for predicting stock prices and guiding investment strategies across diverse industries, from technology to healthcare and energy.

Discussion

This research looked at using machine learning models to predict stock prices and simulate investment strategies using historical data from Apple, Tesla, HP, CVS Health, and Chevron Corp. These companies were chosen not only for their market presence but also for their diversity across sectors: technology (Apple, Tesla, HP), healthcare (CVS), and energy (Chevron). Testing across these industries allowed us to evaluate whether model performance trends were consistent in markets with different volatility profiles and economic drivers.

The results showed that MLP consistently provided the best balance between prediction accuracy and simulated returns, regardless of sector. For highly volatile technology stocks like Tesla, MLP captured complex patterns that simpler models missed. For stable stocks such as HP and CVS, Linear Regression and MLP both performed well, demonstrating that simpler models can still be effective when price fluctuations are limited. In the energy sector, Chevron's data revealed that MLP could also handle commodity-driven volatility, producing strong trading returns even when predictive accuracy was moderate.

Our trading strategy executed buy and sell actions based on predicted price direction. While this simple approach worked well across sectors, especially for MLP, it highlighted the different risk–reward dynamics inherent in each industry. For instance, technology stocks offered the largest growth potential but also carried greater prediction error, while healthcare and energy stocks yielded steadier, sector-specific gains.

While this system is promising, several improvements could make it stronger. For example, adding real-time political events, earnings reports, or economic indicators might boost predictive power. Integrating sentiment analysis from social media platforms like Twitter could give early warning signals about changes in market mood, as previous research has shown. A significant future direction is adapting the system to operate on a per-second basis, allowing for high-frequency trading. This would need both real-time data feeds and enhanced computing power, but it could potentially maximize returns in fast-moving markets.

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Assessing Drivers and Impacts of Wildfires in Colorado: A Geospatial and Climate-Informed Approach to Risk Mitigation

By Olivia Fang and Saiee Brunda Devireddy

Abstract

Wildfires are becoming increasingly destructive in the Western United States, with Colorado facing heightened risk due to climate change, human development, and limited emergency resources. This study investigates the contributing factors such as anthropogenic activity, climate-induced environmental stressors, and naturally flammable vegetation and consequences of wildfires which include degraded air and water quality, ecosystem imbalances, infrastructure damage, and public health risks.

With the guidance of experts' collaboration, geospatial mapping, and scientific literature, we analyzed the relationship between anthropogenic activity, vapor pressure deficit (VPD), fuel aridity, and land development in high-risk zones such as the Wildland-Urban Interface (WUI). Our team used QGIS to create original hazard and resource maps developed for Highlands Ranch, Colorado, and identified regions where emergency services are limited or unevenly distributed. We analyzed air, soil, water, and vegetation data to assess the impact wildfires have on both the environment and humans. Our findings show that climate change, in particular, is a prominent factor that intensifies wildlife conditions.

Some of the possible solutions to minimize wildfire occurrence that are identified here are engaging in prescribed burning, building public awareness, and using remote sensing technologies like LiDAR. Without intervention, wildfires in Colorado and similar regions are projected to grow in frequency, intensity, and scale.

Introduction

Wildfires are a growing environmental and public health threat across the Western United States, especially in Colorado. In 2023 alone, over 220,000 acres burned in the state, endangering communities, ecosystems, and infrastructure [4]. This study explores the increasing severity of wildfires, with a focus on the role of human ignition, climate change, and community vulnerability in Colorado.

According to National Geographic, forest fires are “uncontrolled fires that burn vegetation in forests” [23]. Over the past forty years, forest fires have become more frequent, largely due to rising carbon dioxide levels and the warming of global temperatures [19]. This dries out vegetation, making forests more susceptible to fires.

Wildfires in Colorado impact communities by damaging ecosystems, degrading soil and water quality, threatening structures, and posing health risks from smoke exposure [28]. Health risks arise from soot and particulate matter produced by the smoke people inhale [26]. Structures like homes or buildings get destroyed, requiring costly reconstruction [22]. As forest fires become more common, it becomes necessary for individuals to build awareness of these dangers and learn ways to protect themselves. Those who live in hazardous areas need to be able to

access evacuation routes to direct themselves away from the danger in the event of a wildfire [6]. Environmentally, fires degrade soil quality and pollute water sources [28]. Chemicals from smoke can coat plants with a temporary film that reduces water permeability [26]. As a result, rainfall that occurs after fires washes debris and smoke particles into water sources, making it unsafe for animals and the land [26].

One of the most concerning effects is the risk to human health. Based on the increase in air pollution produced by particulate matter from wildfires and the 22% increase in fire-related deaths over the last decade [27], it is clear that wildfires have a direct impact on individuals.

According to Dr. Jennifer K. Balch, a professor of Geography and director of the Earth Lab at the University of Colorado Boulder, 85% of wildfires are caused by human activity. Although many are accidental—such as a car striking a rock, sparking flames, or the heat from a vehicle igniting dry vegetation [24]—these seemingly small accidents are magnified by today’s fragile ecosystem. While lightning still contributes to wildfires, human-ignited fires occur more frequently, are more destructive, and cost more to suppress [3]. Box-and-whisker plots comparing suppression costs and homes threatened clearly show that human-caused fires, especially in the Wildland Urban Interface (WUI), pose greater risks to communities [22].

Additionally, vapor pressure deficit (VPD), a measure of how much moisture is in the air, is a factor that needs to be considered. A high VPD indicates dry air, while a low VPD indicates dense air and high moisture [1]. Vapor pressure anomalies can explain the increasing frequency of wildfires in the region [1]. This correlates with increased fuel aridity, which can cause fires to ignite and spread quickly [1].

To understand how wildfires in Colorado have become more destructive, we analyzed both immediate ignition sources and long-term environmental contributors. The following sections explore these causes in depth.

Methods

To better understand wildfire risks in Colorado, our team began by conducting background research and consulting with experts in the field. We reached out to postdoctoral associates and researchers at the University of Colorado Boulder, including professionals at the Earth Lab, whose work focuses on wildfire causes, environmental impacts, and mitigation strategies. Their insights helped guide our research direction and strengthen our understanding of wildfire dynamics. These discussions helped shape the focus of our research, especially in understanding how ignition sources, climate variables, and public resources interact in high-risk zones. Building on this foundation, we conducted our own research and analysis, focusing on factors like climate change, vapor pressure deficit, and anthropogenic activity. We later reconnected with several of the researchers we had spoken to in order to validate our findings and ensure the accuracy of our conclusions.

We also learned to use QGIS (Quantum Geographic Information System), a free, open-source geospatial analysis tool recommended by multiple experts. Using QGIS, we imported datasets from sources such as the Monitoring Trends in Burn Severity (MTBS)

program and OpenStreetMap to create original maps. These included hazard zone maps, historical fire patterns, and emergency resource locations specific to our local community of Highlands Ranch, Colorado. We used GeoCoding, a tool that plots latitudinal and longitudinal points based on geographical addresses, to identify and locate warming centers, shelters, and emergency services across the state. These maps were designed to support public preparedness efforts and improve evacuation planning. These maps aim to support public awareness and improve wildfire preparedness, especially in our community, Highlands Ranch, which faces a higher wildfire risk than 88% of towns in the United States [10].

Causes of Wildfires

To understand how wildfires have become more destructive in Colorado, it is important to examine both immediate ignition sources and broader environmental factors. The two primary drivers of wildfires are human activity and climate-related environmental changes.

The majority of wildfires in the United States are started by human activity [3]. While many of these fires are unintentional, they can be triggered by small sparks — such as from hot vehicle engines, dragging chains, or power tools near dry vegetation [24]. Human-caused fires occur more frequently than lightning-caused ones and are responsible for greater destruction. They tend to spread faster, burn longer, and result in more structural damage, especially in areas where human development borders flammable land.

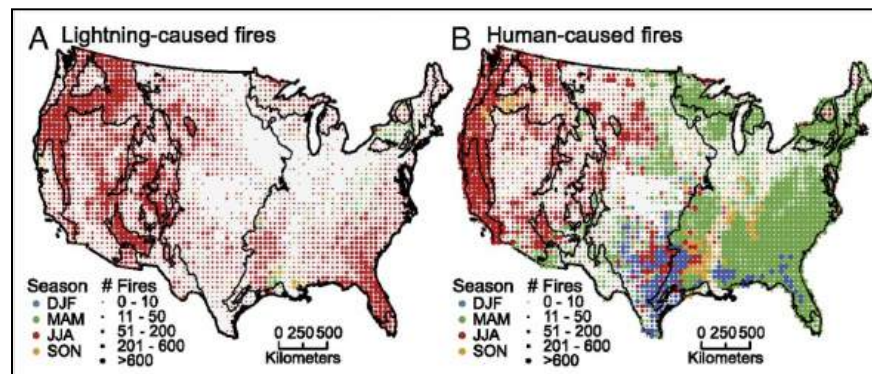


Figure 1 [3]

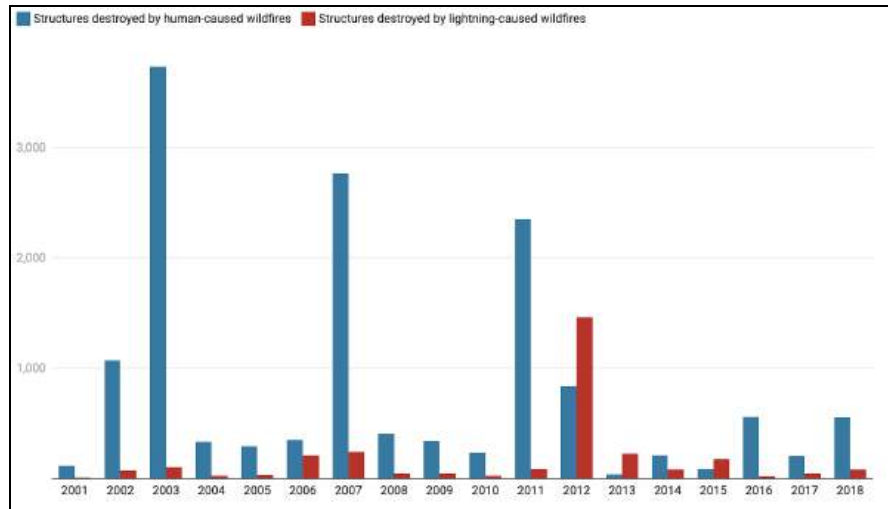


Figure 2 [15]

These destructive outcomes are made worse when combined with environmental conditions intensified by climate change. Anthropogenic climate change is a major underlying driver that worsens fire conditions. Rising CO₂ emissions, primarily from fossil fuel combustion, have contributed to warming temperatures and longer periods of drought. These conditions dry out vegetation and extend the fire season. According to Abatzoglou and Williams (2016), anthropogenic climate change has accounted for 55% of observed increases in fuel aridity since the 1970s, contributing an additional 4.2 million hectares of burned forest from 1984 to 2015.

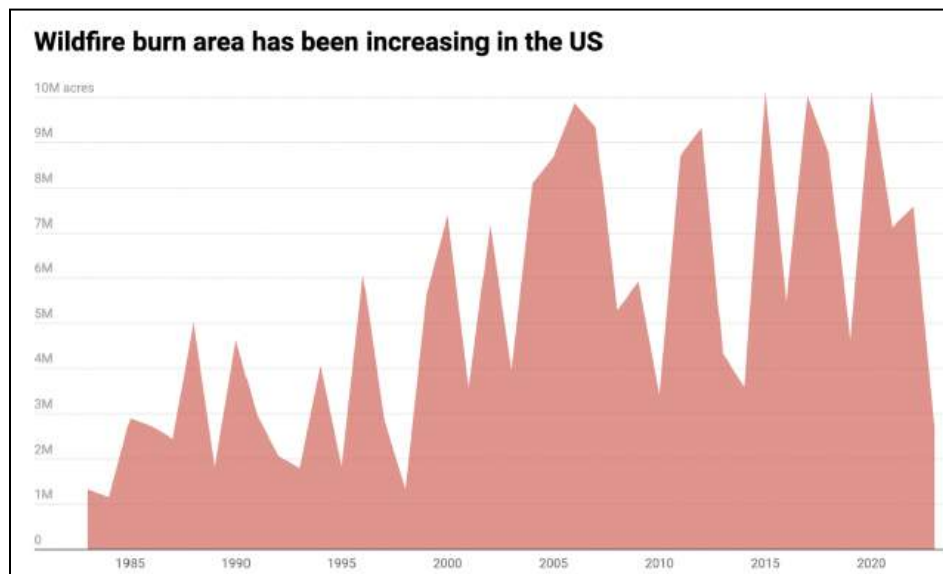


Figure 3 [15]

These climate-induced changes create specific environmental conditions that directly influence wildfire behavior, particularly through fuel aridity, vapor pressure deficit, and vulnerable landscapes.

Another environmental factor that plays a key role in wildfire risk is the type of vegetation. Vegetation is one of the most important factors in discerning which areas of Colorado are most susceptible to wildfires. As mentioned previously, the Cameron Peak Fire, the Marshall Fire, and the Alexander Mountain Fires occurred in the Rocky Mountains of Northern Colorado. Three of the most widely distributed plants in this area are the Douglas fir (*Pseudotsuga menziesii*) (Figure 4a), the Engelmann spruce (*Picea engelmannii*) (Figure 4b), and the common juniper (*Juniperus communis*) (Figure 4c). All three of these plants are highly flammable for several different reasons. The common juniper contains considerable dead plant material under its crown and emits volatile oils that burn intensely [10]. The Engelmann Spruce has thin bark, low-growing limbs, and shallow roots. The Douglas fir, when still in the early stages of its life, has flammable needles and small buds, both of which contribute to increased flammability. Areas with higher concentrations of these plants burn longer and more intensely. They can cover more ground and cause a more devastating impact on the natural ecosystem and communities. However, their presence can also indicate danger zones where fire prevention efforts, like prescribed burns, can be focused. Awareness of flammable vegetation can inform fire bans and safer behavior, possibly lowering the risk of wildfires in Colorado overall.

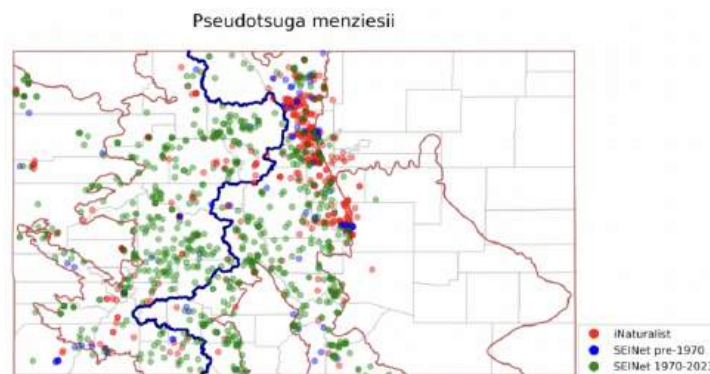


Figure 4a [7]

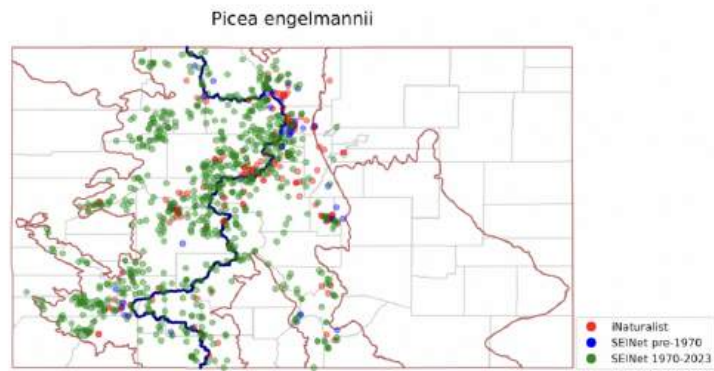


Figure 4b [7]



Figure 4c [7]

Environmental Risk Factors

VPD is the difference between how much moisture the air can hold at saturation and how much it currently holds. High VPD means drier air, which draws moisture from vegetation and increases fire risk [1]. This causes trees and plants to lose water more quickly, making them more flammable [1]. Figure 5 from Abatzoglou et al. (2016) shows vapor pressure anomalies rising significantly since the late 20th century and continuing to climb in climate model projections [1].

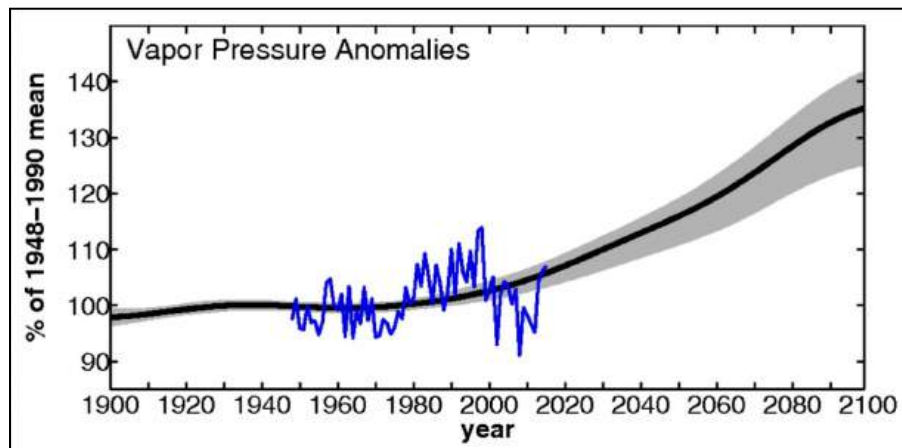


Figure 5 [1]

Another factor is fuel aridity, which refers to how dry the vegetation (fuel) is in a given area. When VPD is high and temperatures are elevated, fuel aridity increases. This means forests already contain elevated amounts of dry, highly flammable material [1]. The combination of high fuel aridity and ignition sources leads to fast-spreading, intense wildfires.

The WUI is where human development meets wildland vegetation, such as suburbs built near forests or grasslands. The rapid expansion of housing developments into flammable landscapes is largely due to population growth and increased demand for affordable housing. This trend has expanded WUI exposure and placed more people and infrastructure in high-risk zones. These areas are particularly vulnerable because they're close to high levels of anthropogenic activity, and surrounded by flammable material [22]. Fires in the WUI are both harder to contain and more likely to destroy homes. As shown in Figure 6 [22], fires in the WUI tend to cost more to suppress and threaten more homes than those in wildlands or low-density housing areas.

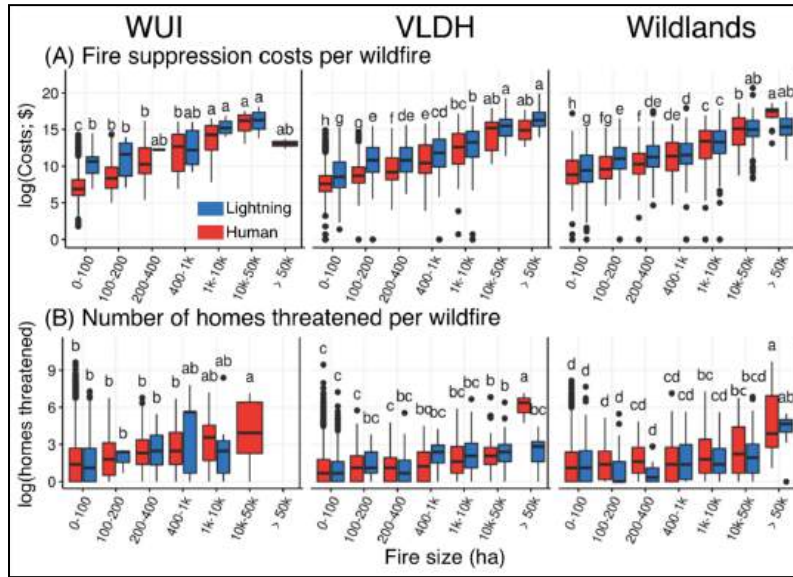


Figure 6 [22]

Additionally, hazard zones play a critical role in understanding where wildfires are most likely to occur and cause damage. These zones are determined by analyzing factors such as burn history, vegetation types, and proximity to human development [9]. In Colorado, many of the areas susceptible to burns are located in mountainous terrain and forested regions. Our team analyzed trends in burn severity to identify areas at higher risk and visualize patterns of repeated fire activity. Additionally, this map serves to inform individuals in Colorado of hazard zones to increase awareness.

Figure 7 illustrates these hazard zones using data from the Monitoring Trends in Burns Severity (MTBS) dataset [12] and was created using QGIS. The map highlights high-risk areas across the state.

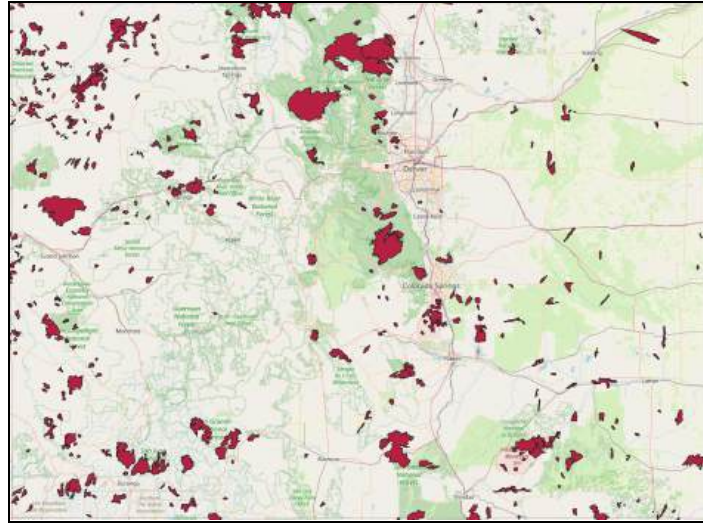


Figure 7 [12]

Effects

Wildfires have far-reaching impacts on human populations, particularly in Colorado communities where burn areas continue to grow. These effects range from health hazards to financial issues and emotional stress. One of the most concerning impacts is air quality. According to the Institute for Health Metrics and Evaluation (IHME), air pollution is the fourth leading risk factor for death and disease [16]. Wildfires only exacerbate this issue, causing more individuals, especially those nearby, to inhale particulate matter (PM) and smoke particles. These particles can lead to serious respiratory issues such as asthma, bronchitis, and long-term lung damage [26].

Figure 8, created using data from the IHME (2019), illustrates the consistent ranking of air pollution as a leading cause of death and disability since 1990, with wildfire smoke increasingly contributing to the problem [26]. As fires become more common and intense, vulnerable populations such as children, the elderly, and those with preexisting conditions are placed at even greater risk.

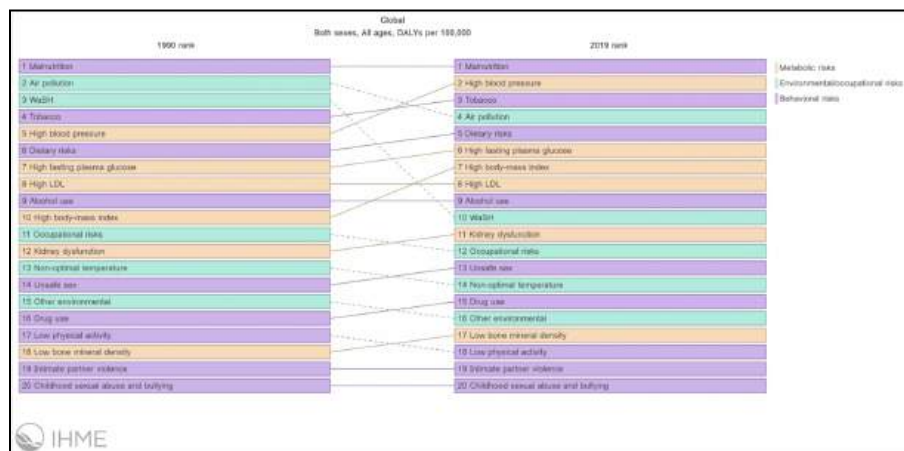


Figure 8 [19]

Fire-related fatalities have also increased. As shown in Figure 9a, there has been a 22% increase in the number of deaths caused by fires from 2013 to 2022 [27]. While some of these deaths occur during evacuations or fire suppression efforts, many are due to prolonged smoke exposure. Additionally, over 41% of outdoor fires were unintentionally caused (Figure 9b), showing how avoidable these fatal consequences can be [24].

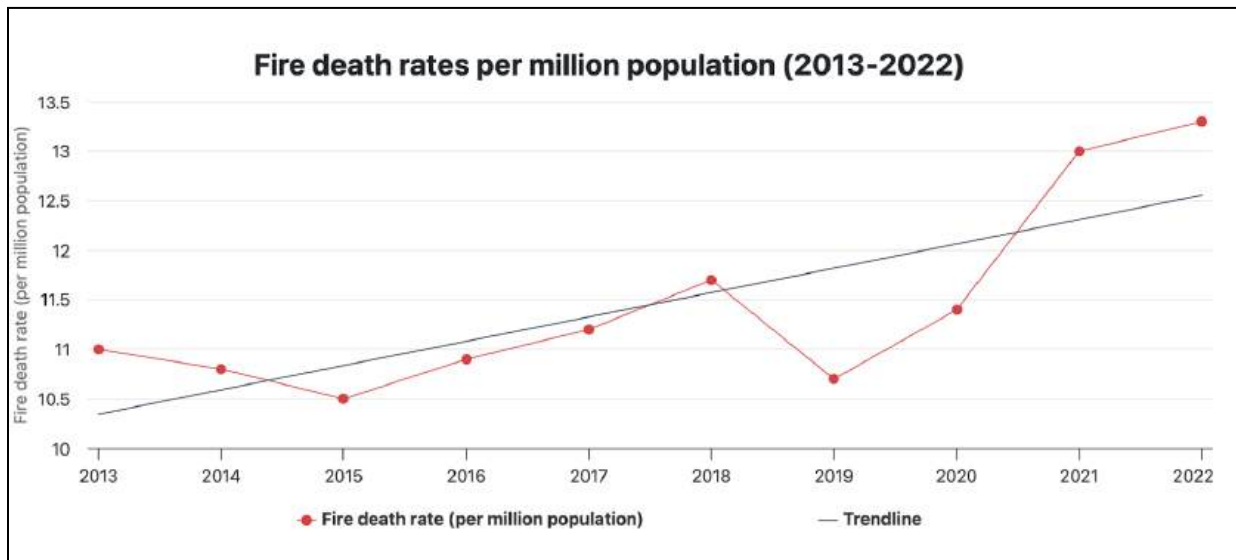


Figure 9a [27]



Figure 9b [27]

Displacement is another major issue caused by wildfires. Families are often forced to evacuate with little notice, and in some areas—especially northeast Colorado—there is limited access to warming centers or shelters. Figure 10, which we created using QGIS, shows that many verified shelters are clustered in western Colorado, leaving other regions with fewer options [6]. This uneven distribution of resources increases the vulnerability of certain communities during wildfire events.

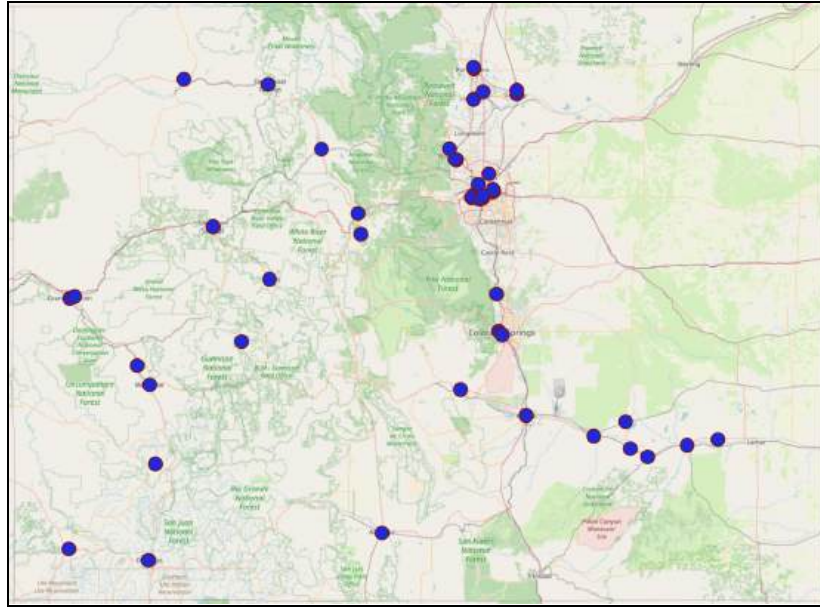


Figure 10 [5]

Wildfires also place a heavy financial burden on individuals. Structures like homes or buildings get destroyed, requiring costly reconstruction. Figure 6 Panel A shows that fire suppression costs for human-ignited wildfires in the WUI are consistently higher than for lightning-caused fires, and Panel B shows a greater number of homes are threatened in those zones [22]. As highlighted in the Marshall Fire timeline (Table 1), fires can escalate so quickly that even well-prepared residents may have no time to evacuate with valuables or pets [17].

In addition to physical and financial losses, psychological distress is a growing concern. Studies of urban firestorms have shown that families affected by sudden evacuations and home loss often experience long-term grief and trauma [25]. These emotional effects are particularly strong in communities that experience repeated wildfire threats year after year.

Altogether, the human impacts of wildfires extend far beyond smoke and flames. They affect people's health, homes, stability, and mental well-being. Recognizing these interconnected effects is key to developing policies that address not only wildfire prevention but also public health, housing security, and equitable disaster relief.

Wildfires not only affect communities and individuals but also the environment. Wildfires in Colorado have serious and long-lasting effects on the environment. Fires destroy large areas of trees and plants, some of which may take decades to grow back. In places like the Colorado Rockies, many tree species—such as Douglas fir, Engelmann spruce, and juniper—are especially flammable due to their oils, thin bark, or shallow roots [7]. When these trees burn, entire forest habitats are lost, which affects the animals that rely on them for food and shelter. Wildfires also affect wildlife by displacing animals, destroying nesting areas, and removing food sources. Some animals may be able to escape fires, but many, especially smaller species or those with limited mobility, are killed or left without shelter. Even after the fire, surviving animals

often struggle to find food and water in the altered landscape [23]. The damage to habitats disrupts entire ecosystems, leading to long-term changes in biodiversity and species balance.

Soil quality also declines after a wildfire. Burned soil undergoes structural changes that reduce its ability to absorb and retain moisture, which hinders vegetation recovery and increases the risk of erosion [11]. It can take decades for the soil to regenerate after a wildfire. These changes to the soil also affect nearby water systems. Figure 11 illustrates how wildfires significantly deteriorated water quality by altering runoff patterns in the burned North Inlet watershed, which was severely impacted by fire, compared to the unburned East Inlet watershed (Figure 11). Despite similar daily rainfall across both sites in 2021 and 2022, the burned watershed exhibited a clear increase in runoff, particularly in 2022, compared to the historical average from 2011 to 2017. This elevated runoff indicates that the soil in the burned area lost its ability to absorb and retain water, due to several factors, including vegetation loss, the formation of water-repellent layers, and structural damage to the soil. In contrast, runoff in the unburned watershed remained relatively consistent with historical patterns. The heightened runoff in the burned area suggests increased erosion and the transport of sediments, nutrients, and pollutants into nearby water systems, ultimately leading to degraded downstream water quality. This degradation can cause harmful ecological impacts such as reduced oxygen levels in streams, disruption of aquatic habitats, and contamination of drinking water sources. It may also increase the frequency of flooding and mudslides, complicating recovery efforts and threatening the resilience of both natural ecosystems and nearby communities.

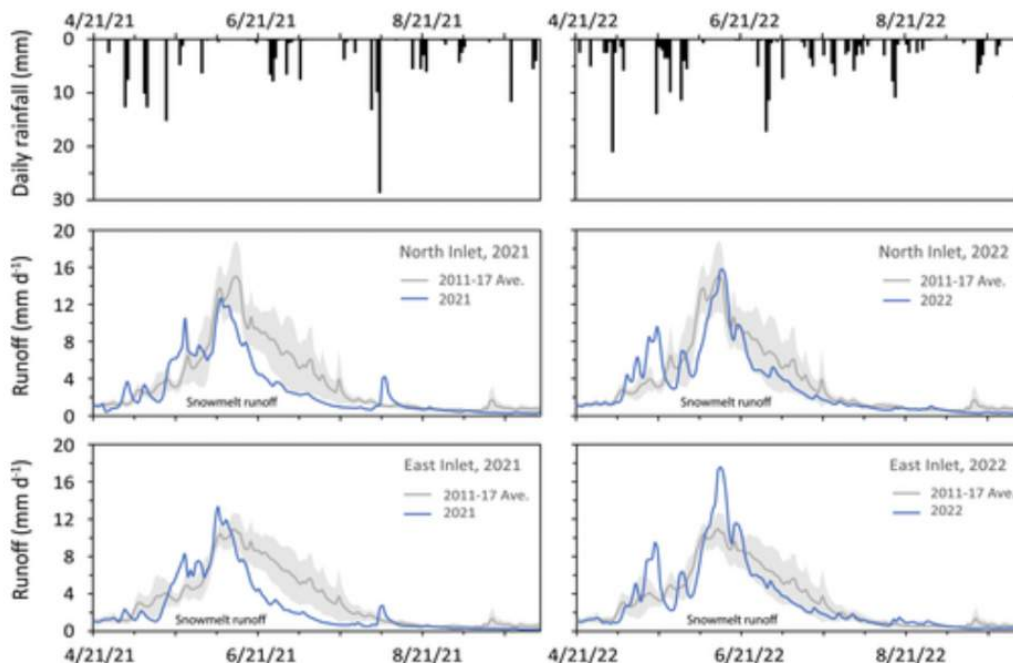


Figure 11 [9]

Climate change also creates a dangerous positive feedback loop, intensifying wildfires. To further explain, a positive feedback loop is a process where change in a system causes further changes in the same direction, amplifying the initial change. Wildfires contribute to global warming by releasing large amounts of greenhouse gases, including CO₂ and methane [1]. These emissions trap heat in the atmosphere, which increases temperature, dries out vegetation, and leads to even more fires. This cycle, wildfires creating conditions for more fire, makes long-term prevention and recovery even more difficult. Over time, this feedback loop not only increases fire frequency and intensity but also makes fire seasons longer, stretching into the spring and fall.

Overall, wildfires disrupt ecosystems, kill and displace wildlife, pollute water sources, and leave forests weakened and vulnerable to future threats. These environmental effects often last for years, making it harder for the land to heal and return to its natural balance.

Possible Solutions

Addressing the escalating threat of wildfires requires both preventative strategies and innovative technologies capable of detecting and reducing fire risk before it intensifies. Our research identifies a range of preventative strategies that can reduce wildfire damage and improve preparedness. One of the most effective solutions is prescribed burning, which reduces the buildup of dry vegetation and limits the fuel available for future fires. These controlled burns can prevent more destructive, unplanned wildfires by managing flammable material in landscapes [18].

Another important preventative measure is community awareness. Because 85% of wildfires are caused by human activity, it is critical for the public to understand how their actions, such as outdoor fires, campfires, and equipment use, can unintentionally spark fires [3]. Public education on fire-safe practices is essential to reducing unintentional ignitions. In addition to informing the public how to keep their surroundings safe, it is also important to raise awareness on how to evacuate and what to do in the event of a fire. Individuals should know where to evacuate to, what to take with them, and if they live in hazard zones.

Climate change mitigation is another essential step. Reducing fossil fuel consumption, promoting cleaner energy sources, and lowering greenhouse gas emissions are necessary to curb the rising global temperatures that contribute to longer fire seasons and drier vegetation [8]. In addition, emerging technologies like drones, thermal imaging, satellite imagery, and LiDAR can play a significant role in fire detection and prevention [2]. These tools allow for real-time monitoring of vegetation dryness, high-risk zones, and fire behavior, enabling faster response times and more efficient resource allocation.

Lastly, increasing the number and visibility of emergency shelters and evacuation routes, especially in under-resourced areas, is a vital part of reducing harm during active fires. Many northeastern areas in Colorado, for example, lack verified resources, making proactive planning even more critical.

Predictions

Based on our geospatial analysis we expect wildfires in Colorado to become more frequent, more intense, and harder to control. When combined with human development in wildfire-prone zones and climate change, these conditions create an ideal environment for destructive fires. As temperatures rise, VPD increases, pulling moisture from plants and soil. Vegetation becomes drier, more flammable, and less able to recover between fire seasons [14]. Feedback loops will further intensify the problem as wildfires release large amounts of carbon dioxide into the atmosphere, which contributes to climate change, creating hotter, drier conditions that fuel more fires. In addition to environmental degradation, these trends will impact human health, increase economic strain, and widen social inequality. Wildfire smoke will worsen respiratory and cardiovascular health outcomes as well, while damaged water sources and infrastructure could lead to greater financial instability [9]. Vulnerable populations, including low-income families and the elderly, are disproportionately affected. Recent examples like the Cameron Peak and Marshall Fires show how fast wildfires can escalate. If current patterns continue, these events will become more common. Our prediction is that without intervention Colorado and the Western U.S. will face an escalating wildfire crisis that threatens both people and ecosystems.

Limitations

While this study provides insight into the causes and impacts of wildfires in Colorado, it has several limitations. First, although the data focuses on Colorado, climate change is a global issue. Limiting greenhouse gas emissions within the United States, while important, is not a complete solution. Carbon dioxide and other emissions do not remain confined to one region. As greenhouse gases accumulate in the atmosphere, they affect weather patterns and wildfire conditions across national boundaries, meaning that global cooperation is essential to reducing climate-related fire risk [19].

Second, the geographic scope of this study is limited. All maps, data, and analysis are specific to Colorado. While many of the trends we observed may apply to other Western states or high-risk regions, they may not reflect conditions in places with different topographies, climates, or land use patterns.

Third, the availability of data limited the completeness of our geospatial maps. For example, in creating Figure 11, our team was unable to locate or verify every available warming center or evacuation shelter in Colorado. This reflects not just a limitation in our research but a larger gap in accessible resources and infrastructure for communities at risk [6].

In addition, climate projections such as vapor pressure anomaly maps (Figure 5) are based on model simulations that include a range of uncertainty. These models provide useful insights, but their accuracy depends on the quality of the input data and the assumptions behind each scenario [1].

Finally, while our team engaged with CU Boulder researchers and used expert-reviewed datasets, we were limited by time and access in conducting broader interviews or field surveys. We were also unable to explore all human impacts, such as long-term mental health effects,

socioeconomic inequalities, or Indigenous land vulnerability in wildfire zones. These limitations suggest areas for future research, particularly in improving data access, expanding geographic scope, and supporting more equitable emergency response planning.

Continued Research

Future research should expand into additional regions across the Western U.S. and even other locations across the globe. Using QGIS and other geospatial tools, we plan to analyze more communities, particularly those with limited emergency resources. These new maps can highlight underserved areas and guide efforts to improve local preparedness by identifying which areas need them. Additionally, it is important to prioritize under-resourced communities such as the northeastern area of Colorado and even Indigenous lands that are often overlooked. Another goal is to collect field data, including soil samples and air quality measurements, from recently burned regions. Analyzing how wildfires change soil water retention, pollutant levels, and vegetation regrowth over time can help identify which ecosystems are most vulnerable and which restoration methods are most effective. In addition to data collection, we hope to explore the role of post-fire restoration techniques, such as reseedling with native plants or introducing fire-resistant vegetation. The study of Cameron Peak's regrowth showed signs of ecological recovery [29], and similar practices could be replicated elsewhere to reduce fire risk and promote forest health. Continued research will help shape proactive strategies to reduce wildfire damage and support both environmental restoration and human safety.

Conclusion

As wildfires grow more frequent and intense in Colorado, their consequences are becoming harder to overlook. Human activity continues to be a leading factor of the majority of wildfires, while climate change contributes to the risk by creating a warmer, drier climate that lengthen fire seasons and dry out vegetation. These risks are magnified in risk areas such as the Wildland-Urban Interface, where expanding development puts more people and structures at risk. The impact extends beyond the burn area, damaging ecosystems, degrading air and water quality, displacing communities, and worsening public health.

It is of utmost importance to build public awareness to reduce accidental wildfires and decrease greenhouse gas emissions that contribute to climate change. Tools like QGIS allow communities to visualize risks and plan better while prescribed burning and the use of new remote sensing technologies like LiDAR can enhance early detection, guide where to focus prevention efforts, and help shape better strategies over time. Together, these tools and strategies can reduce fire risk, protect vulnerable communities, and support preparedness as environmental conditions grow more unstable.

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What Targeted Gene Therapy Strategies in Huntington's Disease Hold the Potential for Effective Treatment of Juvenile Huntington's Disease? By Haadiya Habib

1.0 Abstract

Huntington's disease (HD) is an autosomal dominant neurodegenerative condition characterized by an expanded CAG repeat in exon 1 of the huntingtin (HTT) gene on chromosome 4. This study investigated 11 gene therapy treatments for HD, varying from preclinical to clinical use. The purpose of this investigation was to distinguish one therapy from each of the four categories of gene therapy: gene editing, gene replacement, regulatory gene modulation, and gene silencing, and apply it to Juvenile HD (JHD), a form of HD that impacts individuals under the age of 21.

To determine the therapies with the most effective application in JHD, criteria based on animal models, response to CAG expansion, early onset capability, and durability were employed. Afterward, the four therapies were limited to one through equivalent criteria.

This paper conducted a literature review of 53 papers related to each therapy, its clinical or preclinical models, and the mechanism of the treatment. Analysis demonstrated that the four most applicable therapies for JHD were Antisense Oligonucleotides (ASOs), AAV-mediated neurotrophic factor delivery, Zinc Finger, and CRISPR/Cas9.

Among these treatments, ASOs showed the most significant prospect for implementation in JHD due to their stage 3 clinical model status and their mechanism of targeting mHTT.

Key Words

Juvenile Huntington's Disease (JHD), clinical models, regulatory gene modulation, gene editing, gene replacement, gene silencing

Flowchart depicting therapy selection process for application in JHD

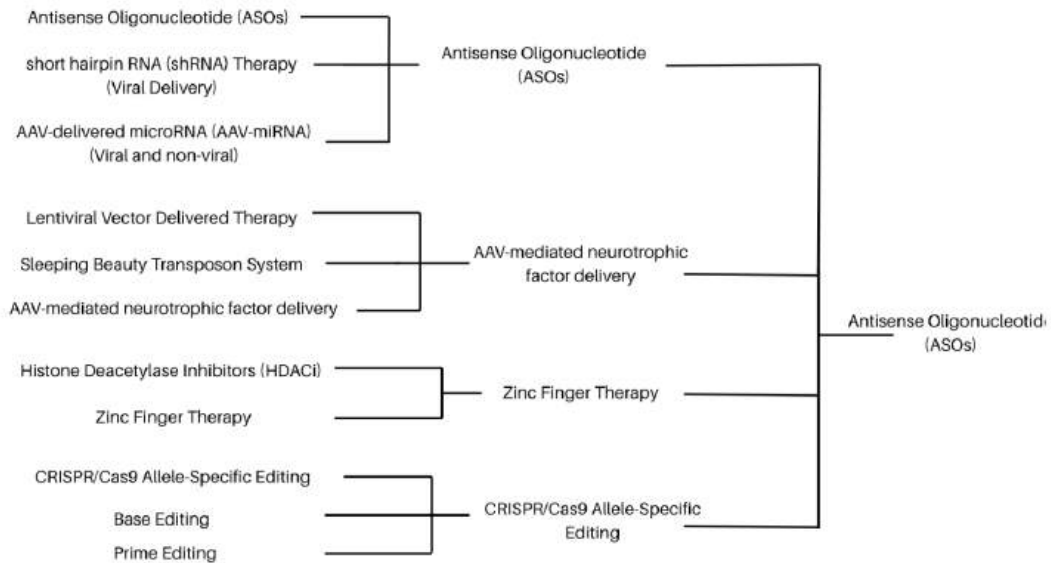


Fig. 1. This flowchart illustrates the concentration of therapies, starting from a broad spectrum of 11 treatments, narrowing down to the four most applicable ones, and ultimately focusing on a single one.

2.0 Introduction

Huntington's disease (HD) is a devastating autosomal dominant neurodegenerative disorder that impacts around 41,000 individuals in the United States. This condition is characterized by an abnormal expansion of the cytosine-adenine-guanine (CAG) repeat in exon 1 on chromosome 4 of the huntingtin (HTT) gene (Oosterloo et al., 2024). This mutation results in motor disorders, gradual cognitive decline, psychiatric symptoms, and speech impairments.

Variation of Symptoms and Genetics of JHD vs HD

Juvenile Huntingtons Disease	Huntingtons Disease
60+ CAG repeats	40+ CAG repeats
Age Onset: Less than 21	Age Onset: Typically 30-40
Speech Delays and Impediments	Slurred Speech
Rapid cognitive dysfunction	Gradual cognitive decline
Rigidity	Chorea (Uncontrolled Movement)
Seizures: Apparent in a small percentage of cases (Roughly: 30%)	Seizures: Almost completely absent across the majority of cases
Early and aggressive psychiatric symptom development	Slower and less prominent psychiatric symptom development

Fig. 2. This table depicts the key differences between HD and JHD. These include genetic basis, age of onset, and symptoms of the disease.

Juvenile HD (JHD) is a rare and severe form of HD that impacts individuals under the age of 21. This disease often presents symptoms of stiffness, seizures, rapid cognitive dysfunction, severe mental disorders, and speech delay. There are no therapeutic mechanisms that can intercept or delay the progression of HD or JHD.

This lack of therapy is primarily due to the multifactorial nature of the pathogenesis, which results in limitations regarding effective treatment due to its complexity. Furthermore, ethical issues have been presented surrounding the administration of therapies with potential

off-target effects. For these reasons, it is challenging to develop significant laboratory applications, especially for JHD, given the targeted population and the low patient concentration. Currently, only symptomatic therapy is in clinical use (Olmedo-Saura et al., 2025).

However, one emerging field—known as gene therapy—has shown immense promise for JHD treatment in terms of effectiveness and safety (Piao et al., 2024).

This study will review 11 therapies for HD, select the four most effective for application in JHD, and focus on one based on its potential for future clinical implementation in JHD.

3.0 Methodology

This literature review used PubMed Central and Google Scholar for the 53 papers cited in this review. Key terms used were "JHD" OR "Juvenile-Onset Huntington's Disease" AND "Huntington's Disease" AND "Gene therapies in HD" AND "CRISPR/Cas9" AND "ASOs" AND "Animal models for gene therapy" along with additional searches for each of the 11 therapies' mechanisms, animal models, and relevance to HD. Papers chosen for this review were published between 2019 and 2025, written in English, and focused on gene therapy, JHD/HD, and animal models with relevance to gene therapy and HD. Abstracts were evaluated for pertinence and chosen if applicable to animal models, mechanisms, or disease reviews.

4.0 Genetic basis of HD and JHD

HD is a genetic neurodegenerative disorder caused by an abnormal expansion of the CAG repeat in the HTT gene, located on chromosome 4 in exon 1. This expansion results in the messenger RNA (mRNA) transcribing and translating the DNA containing the faulty repeat into the HTT protein, which includes an expanded polyglutamine (polyQ) repeat (Maiuri et al., 2024). This abnormal enlarged component leads to protein aggregation and misfolding (Pengo & Squitieri, 2024).

Healthy individuals with the wild-type *HTT* (wtHTT) gene typically will have a CAG repeat of 35 or fewer. However, patients with HD carry the mutant HTT (mHTT) gene, which contains a CAG repeat of 40 or more (Aldous et al., 2024).

This study focuses on JHD, a rare form of HD that impacts individuals under the age of 20. The pathophysiology of JHD exhibits more than 60 CAG repeats, categorizing this disease as significantly more severe and rapid than HD. Currently, there is no effective clinical treatment available to stop or slow the progression of JHD (Bakels et al., 2021).

Gene therapy, however, is a rapidly emerging research hotspot for JHD. This therapy works by specifically targeting the DNA or RNA for the mHTT gene. By doing so, this approach targets the root cause before the mRNA can be transcribed into the mHTT protein. Gene therapy primarily employs the use of viral vectors as delivery systems for modified genes. This tool releases the gene into the CNS to selectively target the mHTT (Tabrizi et al., 2022).

Gene therapy can be categorized into four broad sections: regulatory gene modulation, gene replacement, gene silencing, and gene editing. Each category contains several therapies that

have been proven effective in treating HD (Wang et al., 2024). However, in the context of JHD, these therapies have received comparatively less attention.

5.0 JHD

JHD is a severe genetic disorder caused by a CAG expansion of over 60 repeats. This leads to drastic symptoms in patients, including psychological issues, stiffness, stagnant movement, seizures, speech impediments, and cognitive function loss (Bakels et al., 2021). In contrast, patients with HD have 40 or more repeats, resulting in slower and less pronounced protein aggregation.

As a result, the symptoms are similar yet prolonged and less severe, including mood disorders, chorea, and mild cognitive impairment (Massey & McLauchlan, 2024).

This difference in severity is further underscored by the average lifespan of a JHD patient, which is 9 years, compared to the median lifespan of 18 years after diagnosis for HD patients (Bakels et al., 2021).

Furthermore, the scale of both of these disease variations is an important factor to examine. HD is apparent in 4–10 per 100,000 people, with a rough estimate of 41,000 people with the disease in the United States. By contrast, only 1–5% of all HD cases are JHD (Bakels et al., 2024).

JHD, being a genetic disease, is primarily transmitted through the father; however, in some instances, there is maternal transmission. Typically, if a parent's DNA contains the mHTT gene, each offspring has a 50% chance of inheriting the condition. JHD generally manifests in childhood or adolescence.

When the CAG repeat is passed down genetically, it often increases in length, primarily when transmitted through the father, because the sperm CAG repeat is less stable during transmission than the egg CAG repeat. If the parent already has HD, the CAG repeat is significantly elongated, resulting in an earlier onset and more severe symptoms in JHD (Caligiuri et al., 2024).

While the transmission factor and mechanism of this disease are well understood, its rarity makes it challenging to treat due to the complex nature of the disease, which requires significant research and funding to investigate. Despite specific therapeutic methods existing, the current medical stance focuses on symptom regulation rather than targeting the genetic cause (Oosterloo et al., 2024).

However, before incorporating therapy, the current diagnostic status of JHD must be thoroughly examined. JHD comes with a multitude of issues regarding misdiagnosis. Due to the rarity of this disease, children and adolescents are often admitted to physicians and pediatricians rather than HD specialists. Because of this, JHD is frequently misdiagnosed as attention-deficit/hyperactivity disorder (ADHD) or autism spectrum disorder (ASD), given the overlap in specific neuropsychiatric characteristics among these disorders and JHD (Oosterloo et al., 2024).

Another major challenge regarding diagnosis is the limited availability of diagnostic tools. Currently, DNA analysis is the only definitive test for JHD. However, without the support of multiple confirmatory tests, achieving a timely and accurate diagnosis becomes challenging (Oosterloo et al., 2024).

However, other tests are currently being analyzed for the diagnosis of JHD. These include neurophysical assessment, which is used to detect cognitive issues, and neuroimaging (e.g., MRI), used to detect neurological component deterioration. However, these scans may be easily misinterpreted unless conducted over extended periods with repeat scanning (Oosterloo et al., 2024).

Thus, when patient symptoms begin to surface, the most vital component of the diagnosis is observation of change. Often, a single scan may underplay symptoms; however, by conducting multiple tests that show changes within JHD, it is possible to obtain an accurate and comprehensive diagnosis of the disease (Oosterloo et al., 2024).

While DNA testing is currently the most reliable and standard diagnostic tool, it comes with several related ethical concerns. Often, HD is diagnosed clinically by a specialist, and DNA analysis confirms the diagnosis (Oosterloo et al., 2024).

However, due to there currently being no treatments capable of stopping or slowing disease progression, early diagnosis in adolescents and children—though it may identify the mHTT well before clinical onset—often contributes primarily to familial distress rather than preventing disease manifestation. Furthermore, early diagnosis may reveal symptoms of ADHD or ASD that can be misinterpreted as JHD and further contribute to household anxiety (Oosterloo et al., 2024).

6.0 Application of gene therapy in HD

Gene therapy is an emerging treatment premise for HD. While it has not yet been clinically proven to stop or slow the disease's progression, it has shown significant promise due to various circumstances.

Firstly, this form of therapy works by specifically targeting the DNA or RNA of the mHTT gene. By doing so, the issue is addressed at the root cause before the mRNA can translate the DNA into the faulty HTT protein (Lin et al., 2025). Furthermore, the majority of currently examined therapies outside of gene therapy are experimental and lack confirmed results.

However, evidence from preclinical and clinical models has shown that gene therapy could slow down or treat the disease with further research. Due to its current advancements, gene therapy is considered to possess the most effective mechanism for the application of HD and eventually JHD (Parambi et al., 2021).

This therapy can be administered *in vivo*, meaning the therapy is delivered directly into the body, *ex vivo*, meaning the cells are taken out, modified, and re-administered, or *in vitro*, meaning the research is conducted through a laboratory dish or test tube rather than on a living organism.

Gene therapy is categorized into four sections: gene editing, gene silencing, regulatory gene modulation, and gene replacement. Each of these categories includes in vivo administration, ex vivo administration, and in vitro administration depending on the therapy within the section (Piao et al., 2024).

1. Gene editing: This therapy works by directly editing specific pieces of DNA or RNA within the nervous system that contain the mHTT gene. This therapy is conducted in several ways. The first is by gene integration, in which the correct DNA sequence is added to a gene, allowing it to form functional proteins if the gene's protein production is insufficient. Next is gene activation, in which cells with previously deactivated genes are reactivated to compensate for a lack of protein. The third approach is to "knock out" a gene in a cell if there is excessive protein production or if the produced protein is dysfunctional (Yan et al., 2023).
2. Gene silencing: This therapeutic method is widely regarded as the most effective way to reduce mHTT DNA and mRNA growth, due to its demonstrated effectiveness in animal models and specific HD trials. It works by inactivating the HTT DNA or mRNA. By doing so, production of the faulty protein is blocked entirely, which is tackled directly (Hernan Garcia-Ruiz, 2020).
3. Regulatory gene modulation: In this category, genes are targeted by either being turned on, in which they are activated, or off, in which they are suppressed. In the case of HD/JHD, regulatory gene modulation causes the gene to be turned off due to its harmfulness within the brain. (Butterfield et al., 2025).
4. Gene replacement: This therapy aims to target diseases by inserting a modified version of a mutated gene into the patient's DNA. In JHD/HD, the inserted gene would be an altered version of the mHTT known as the cDNA (Piao et al., 2024).

Each of the four categories includes specific therapies, each with distinct functions. These include:

Gene Silencing:

- Antisense Oligonucleotide (ASOs)
- short hairpin RNA (shRNA) Therapy (Viral Delivery)
- AAV-delivered microRNA (AAV-miRNA) (Viral and non-viral)

Gene Replacement:

- Lentiviral Delivered Therapy
- Sleeping Beauty Transposon System
- AAV-mediated neurotrophic factor delivery

Regulatory Gene Modulation:

- Histone Deacetylase Inhibitors (HDACi)
- Zinc Finger Therapy

Gene Editing:

- CRISPR/Cas9 Allele-Specific Editing
- Base Editing
- Prime Editing

Gene Therapy Methods with Potential Application in Juvenile Huntington's Disease

<u>Gene Silencing</u>	<u>Gene Replacement</u>	<u>Gene Editing</u>	<u>Regulatory Gene Modulation</u>
Antisense Oligonucleotide (ASO's)	Lentiviral Vector Ex Vivo Therapy	CRISPR/Cas9 Allele-Specific Editing	Histone Deacetylase Inhibitors (HDACi)
short hairpin RNA (shRNA) Therapy (Viral Delivery)	Sleeping Beauty Transposon System	Base Editing	Zinc Finger Therapy
AAV-delivered microRNA (AAV-miHTT) (Viral and non-viral)	AAV-mediated neurotrophic factor delivery	Prime Editing	

Fig.3. The table represents the 11 therapies chosen for review in this paper based on categorical organization by gene therapy types.

While there are other types of therapies in these categories, these 11 treatments have shown the most potential in gene therapy and HD-specific targeting.

However, this study aims to choose one therapy for each category based on effectiveness in JHD treatments. This will be achieved through the examination of animal models and therapeutic mechanisms to elucidate potential applications in JHD.

The criterion is demonstrated by effectiveness in animal models for HD, a relationship to increased CAG repeat, early onset capability, and durability. The four therapies that exhibit this criterion most effectively include ASOs, AAV-mediated neurotrophic factor delivery, Zinc Finger, and CRISPR/Cas9.

6.1 Gene Silencing

6.1.1 ASOs

In this therapy type, gene suppression is done using ASOs. These are single strands of modified DNA that are engineered to pair with mRNA. This gene suppression tool is injected into the Cerebrospinal Fluid (CSF), the liquid surrounding the brain and spinal cord, providing direct access to the Central Nervous System (CNS). It is conducted with both in vivo and in vitro experimentation.

Once injected, the ASOs bind to their complementary RNA using the Watson-Crick base pairing method, creating a DNA-RNA hybrid. This pairing method involves merging Adenine and Uracil through two hydrogen bonds and Guanine and Cytosine through three hydrogen bonds, thereby forming a double helix structure.

Once this pairing method is undergone, the ASOs catalyze a degrader in the CSF, which destroys the mRNA. The most commonly used degrader in ASOs is Ribonuclease H (RNase H), which cleaves the RNA from the DNA, creating two separate components and rendering the RNA defective.

This therapy has notable advantages and disadvantages. First off, a significant benefit of this therapeutic mechanism is its long half-life (a time measurement used to determine how long it takes for half of a substance to decay) and broad distribution in the CNS. This allows the therapy to be taken up by neurons and other cellular components without the assistance of a carrier (Rook & Southwell, 2022). This contributes to the safety, efficiency, and effectiveness of ASOs in retaliation against JHD.

However, an issue with this therapy is that the advisability of silencing the HTT gene is still under consideration due to its vital role within the CNS. About 86% of HD patients are heterozygous for the HTT and possess the wtHTT and the mHTT. Due to the commonality of this circumstance in several therapeutic processes, both genes are reduced in expression.

While studies have suggested that partial lowering of the wtHTT is not harmful, several reports have shown that reducing the wtHTT partially can lead to uncontrollable movements, a decrease in cognitive ability, and neuronal loss (La, Weydt, and Pineda, 2020).

This is due to the gene's function within the body. The wtHTT plays a crucial role in several organelles and aids in various molecular processes, making it vital in cellular procedures such as regulating damage caused by toxic molecules, facilitating the movement of cellular components along a neuron, promoting neuron communication, and recycling and disposing of biological components. Thus, by reducing this gene, fatal side effects may be associated with the therapy. As a result, this issue must be resolved to enable proper patient injection and prevent off-target and harmful effects (Barron et al., 2021).

Currently, several ASO variations are undergoing clinical trials from various companies. One notable example is the Tominersen ASO therapy developed by Ionis Pharmaceuticals, in partnership with Roche. The treatment has undergone several clinical trials, including phase 1/2a, an open-label extension study (OLE), and a phase 3 trial.

Trial 1/2a is a test that uses the intended therapy and a placebo, emphasizing the safety, dosage, and effectiveness of the treatment. OLE functions as an extension of the 1/2a trial and invites participants to continue use of the therapy, without the placebo, after the initial 1/2a trial. The phase 3 trial conducts testing on a broader scale, aiming to identify the general population's reaction to the therapy.

In the Phase 1/2a trial, participants received intrathecal injections. Out of all the trials conducted, 98% of patients reported unfavorable effects, with the majority being mild. The testing did not result in any severe side events occurring. The average reduction rate of the

mHTT was 20-42%, with a maximum reduction of 63%, emphasizing the significant positive effects of the therapy.

The OLE study reported 621 setbacks that occurred during the therapy, with 14 being serious events. About mHTT reduction, a mean of 44% occurred within patients.

Finally, the phase 3 trial was initiated. However, in March 2021, an independent safety monitoring board examined the therapeutic trials. It concluded that the risk-to-benefit margin was not acceptable for further trials to be conducted. The mHTT reduction in this trial had not been shown to stop or slow the progression of the mHTT, and the trial's outcome would likely mirror that of the previous trials discussed above.

Wave Length Sciences conducted another notable ASOs trial. It was a Phase 1/2 trial that had the potential to lower allele-specific HTT. WVE-120101 and WVE-120102 are the two therapies tested by this company. Results showed indirect targeting and no notable reduction in mHTT (Tabrizi et al., 2022).

Each of the specific criteria can provide an analysis of this therapy. Firstly, regarding effectiveness in animal models, this therapy has progressed the farthest in testing among the 11 therapies. Despite the termination of the testing, ASO's progress into a Phase 3 clinical trial demonstrates evidence of its effectiveness in treating the disease. This advancement suggests significant potential for further application in JHD.

Concerning the increased CAG repeat, research has shown that the expansion observed in JHD can enhance the effectiveness of ASOs. This effect is due to the primary issue regarding this disease stemming from off-target effects, as the HD target is not extensive enough for accurate ASO targeting, exhibiting only 40 or more CAG repeats. In comparison to JHD with 60+ repeats, this therapy would be able to bind significantly more effectively to the JHD mHTT than in HD, thereby increasing the reduction.

Regarding early onset capability, ASOs likely would be cautioned against. While it could be more effective in JHD, its off-target effects in HD, as well as its permanence, could result in critical damage to the Juvenile brain, especially when administered early, given that the brain is still undergoing development at that stage.

Finally, regarding durability, this therapy requires repeated injections, which proves it is not sustainable for long periods. In a juvenile brain, this overinjection may contribute to damaging effects.

6.1.2 shRNA Therapy (Viral Delivery)

shRNAs are non-coding RNAs that are delivered in vivo to target the mRNA. This therapy's function involves reducing HTT expression through the use of RNA interference (RNAi). RNAi may trigger protein clearance mechanisms that combat mHTT-induced changes. It is hypothesized that silencing the mRNA directly will prevent the production of the mutated protein. RNAi, induced by short hairpin RNAs (shRNAs), could reduce the expression of mHTT and improve associated abnormalities.

The shRNA can be either produced outside the cell and reintroduced or synthesized within the cell and amplified during its production. The RNA polymerase III, a cellular enzyme used to create the shRNA, copies the DNA segment and produces a short RNA that then folds into the hairpin structure of the shRNA. This is then processed into the siRNA, which then joins the RISC complex. The RISC complex's function involves using the siRNA as a guide to the mRNA, allowing the RISC complex to cleave and degrade it.

In the case of non-viral vector delivery methods, this therapy proves to come with issues such as repeated injection, inhibiting fast recovery. However, through the use of viral vector delivery, the half-lives of shRNA and siRNA are significantly increased. This enables longer, more effective treatment with fewer repeated injections (Kang et al., 2023). The shRNA therapy is typically delivered via plasmid or lentivirus (lab-based) (Sigma Aldrich, 2025).

The shRNAs were delivered through the use of intrastriatal injection of the AAV5 vector. The model used to examine the shRNA therapy was a YAC128 mouse model of HD with a CAG-targeting shRNA (shA2) in use. The results of the shRNA demonstrated a 50% reduction in the mHTT gene level, with allele specificity for the mHTT.

Silencing effects were observed in the hippocampus and cortex, with reductions of 30% and 20%, respectively. Additionally, cognitive and motor effects were shown to be positively influenced by this therapy. However, despite the shA2's effectiveness in trials, several setbacks are associated with this approach.

Throughout the trial, it was demonstrated that the shRNA vectors could have significant toxic effects on the mice when administered in vivo. Some severe cases involved early termination of the mice treated with high dosages before trial completion due to extreme health issues. (Kotowska-Zimmer et al., 2022)

Another therapeutic test for siRNAs involved the use of the compound SNP6-11. Due to issues regarding off-target effects and non-allele-specific treatment, this compound was chosen due to its on-target specificity. The first part of the testing involved the use of NSCs derived from induced pluripotent stem cells (iPSCs) to determine whether the SNP6-11 could differentiate between the wtHTT and the mHTT, as compared to a nonselective siRNA. Results showed it to be effective in this area.

Afterwards, the NSCs were used once more to determine whether the therapy could reduce the mHTT. While the SNP6-11 was unable to achieve a significant reduction in the mHTT, the nonselective siRNA was able to lower both mHTT and wtHTT protein by 80% and 78%, respectively.

While the mHTT reduction is significant in the non-specific siRNA, caution is advised when using therapies involving wtHTT decrease due to its importance in the CNS. However, from the selective standpoint of the siRNA, while safety was more pronounced in this therapy, its specific effects were not impactful in HD overall (Conroy et al., 2022).

Finally, to accurately assess the overall animal model status of this therapy, it is essential to note a study conducted at the University of South Florida that utilized siRNAs administered via nose drops in a mouse HD model. Four different mHTT-heavy regions were targeted: the

olfactory bulb, striatum, hippocampus, and cortex. Each experienced a minimum 50% reduction of the HTT. However, this therapy is not allele-specific, and thus the lowest mHTT reduction was observed in the cerebral cortex, with a 38% reduction, and the highest mHTT reduction was found in the olfactory bulb, with a 53% reduction (Baier, 2019).

The listed criteria can be used to evaluate the shRNA therapy. Firstly, regarding animal models, this therapy has only progressed to the early preclinical stage, with its primary target being mouse models. However, a number of these models, such as the YAC128 mice model, have large CAG repeats, which prove to be an accurate analysis of JHD. However, at its current standpoint, this therapy has underdeveloped trials, particularly compared to the miRNA and ASOs, which are in late preclinical and clinical trials.

Regarding CAG repeat capability, this therapy has been shown to have variants with on-target capability, which would be effective in JHD analysis to ensure safety while targeting the CAG repeat. Furthermore, due to the current preclinical data involving models with large CAG repeats and effective mHTT reduction as a result, shRNAs have demonstrated the capability for JHD, given the significant similarities.

Regarding early onset, this therapy is on target and likely responds more accurately and safely to developing brains.

Finally, regarding durability, it can last weeks or months on a single injection, demonstrating its durable nature, which is preferable for JHD.

6.1.3 AAV-delivered miRNA (AAV-miHTT) (Viral)

MicroRNAs (miRNAs) are naturally occurring, short, non-coding RNAs that bind to a specific mRNA to suppress its function and promote mRNA degradation. miRNAs are used to target several mRNAs, one of which is the HTT mRNA. If the miRNA is increased, it can reduce underlying neurodegenerative symptoms, including those associated with HD. Thus, this therapy method works to increase the function of the HTT miRNA, which suppresses the mRNA transcribed from the HTT gene.

The miRNA therapy is administered once using an adeno-associated viral (AAV) vector, a virus-based gene delivery system, into the CNS. Once within the body, it targets chromosome 4 of the HTT gene. The AAV Vector delivers a therapeutic miRNA precursor that activates the endogenous miRNA silencing machinery.

The mature miRNA is then loaded into the RISC complex, which uses the miRNA as a guide to identify and bind to matching HTT mRNA. Once the match is found, the RISC either cuts the mRNA or blocks it from being translated into the mHTT protein. This reduces overall HTT protein translation within the body. In the case of HD, targeting the mRNA before it can translate the CAG repeat in the polyQ expansion addresses the issue before it becomes severe (Nguyen et al., 2022).

Multiple versions of this therapeutic strategy have been identified; however, only a few have been supported by preclinical evidence. For example, one preclinical study involved injecting an exosome-based miRNA-124 into the striatum of an R6/2 mouse model. While this

therapy showed specific benefits in reducing the target protein, it did not yield improvements in behavioral issues due to various factors, including the delivery method (Thomson et al., 2022).

Another popular form of the miRNA is the AAV5-miHTT. Research has shown that a single shot of the miRNA AAV5-miHTT can reduce levels of pathogenic HTT protein in minipigs up to five years post-treatment. It has also been shown that trials on rodents are effective in lowering the mHTT protein (Thomson et al., 2022).

However, due to the rodents' minuscule brains, other animal models have been tested, including sheep, monkeys, and minipigs. Because these animals express a whole human HTT transgene, they are effective in testing human-designed sequences. However, these models did not demonstrate severe cases of HD due to low levels of mHTT, the long life span of animals, which caused the disease to progress slowly, and insufficient data. However, it remains effective in research for HD, as it helps bridge the gap between mouse trials and human preclinical trials (Sogorb-Gonzalez et al., 2024).

Using the listed criteria, this therapy can be evaluated. Firstly, regarding animal models, this therapy has progressed to the late preclinical stage using minipigs, sheep, and monkeys. In comparison to shRNA, miRNAs are significantly more advanced; however, they are not yet at the clinical level of ASOs.

Next, the application to the expanded CAG must be discussed. For this therapy, an R6/2 mouse model was used for early preclinical trials. This mouse model exhibits significant CAG repeats, and as the trial progresses to the large animal stage, it also demonstrates that this therapy is effective in this regard.

Furthermore, thus far, this therapy has shown minimal effects on overall behavioral improvement. These minimal effects could contribute to safety regarding JHD as less significant areas are targeted. In terms of durability, this therapy is administered through a single injection, which proves its strong durability standard.

6.2 Gene replacement

6.2.1 Lentiviral Delivered Therapy

Lentivirals, a type of viral vector derived from lentiviruses, are a tool used in several neurodegenerative diseases for the purpose of carrying large single-stranded RNAs (up to 10 kilobases (kB)) and infecting non-dividing and dividing cells, particularly neurons. These are especially useful due to their ability to integrate their genetic material into the host cell genome, enabling long-lasting or permanent gene expression, while exhibiting safety with in vivo treatment and exhibiting low immune responses (Wang et al., 2025).

They are also replication incompetent, meaning they can not replicate new viruses after entering the gene, which increases their potential for safe application. While this therapy primarily acts as a supplier of degraders such as shRNA or CRISPR, its impact is worth mentioning due to its ability to insert targets that can be directly effective for the use of HD in non-dividing cells (Bradbury, 2023) As well they can express therapeutic genes over a long period with minimal doses (Poletti & Mavilio, 2021).

This delivery mechanism has been examined in several studies for its efficiency in treating HD. One notable example involves a GDNF-containing lentiviral vector that was used in an R6/2 mouse model and administered in the fifth week following birth. Upon conducting the trial of the therapy, it was found to be incapable of administering an effective treatment that provided significant improvement in behavioral and neurological effects observed in the mice.

This therapy was hypothesized to have a larger effect in pre-symptomatic trials; however, these have not been currently undertaken.

While these results are undesirable, lentivirals have also been used for various other therapeutic deliveries, which have proven to be successful. For example, an experimental trial involving the use of lentivirus-expressing proteasome activator PA28 γ , a protein degradation enhancer in the nucleus, was administered in the striatum of YAC128 HD mice at 14–18 months of age and was assessed for therapeutic benefit twelve weeks following injection.

Significant improvements exhibited by this lentiviral vector delivery included increased peptidyl-glutamyl peptidase (PGPH) proteasome activity, an enzymatic function that aids the proteasome in protein degradation, enhanced mRNA levels of BDNF, and decreased levels of ubiquitin-positive inclusions —proteins marked with ubiquitin to flag them for degradation—in the striatum. Furthermore, mice involved in this trial demonstrated motor improvements (Kim et al., 2021).

Based on the criteria, this therapy can be evaluated. Regarding animal trials, this therapy is still in an early preclinical stage. However, it utilizes mouse models, such as YAC128 HD mice, which are effective at mimicking the mechanism of JHD.

Furthermore, due to its well-received response regarding this therapy, which exhibits large CAG repeats, it likely would possess potential in response to JHD's 60+ repeats.

Regarding early onset capability, this therapy has demonstrated specific off-target effects and could likely develop significant issues in juveniles if safety is not entirely considered. Finally, regarding durability, the treatment may require either multiple or single injections. Depending on the case, the durability varies.

6.2.2 Sleeping Beauty Transposon System

This therapy targets eukaryotic genomes through the function of two key components: the transposon and the transposase. The transposon is a DNA sequence within the body delivered alongside the transposase. The transposase is an enzyme that is engineered to be delivered into a target cell within the body.

This enzyme can be delivered using plasmids, lipid nanoparticles, and mRNA. Once within the target cells, the transposase facilitates the delivery of the transposon into the genome and aids in cutting and pasting the transposon into the DNA sequence.

By doing so, several cellular processes can be aided, and this therapy can counteract the effects of the mHTT. While it does not explicitly target a gene, it does add DNA to a sequence and can supply therapeutic genes to aid in HD.

It is a safer process than a majority of viral deliveries due to its ability to directly insert the DNA in a targeted cell, which, in preferential target sites, can be engineered to aim for less risky sequences that are less active and can reduce the risk of a mutagenesis-related safety concern or concerns with the therapy causing harmful mutations.

By inserting the Sleeping Beauty Transposon System, aid can be provided that restores or replaces function in the CNS (Imre et al., 2023).

Currently, this therapy does not include any experimental studies within the specified time frame of this paper. However, despite its presently inactive experimental status, a trial was conducted by Chen et al. (2005), which demonstrated the use of the Sleeping Beauty transposon system in combination with RNAi. It involved the use of human cell line models engineered to target Exons 1, 4, 6, and 62 of the HTT gene. Results showed a 90% reduction in protein expression of the HTT; however, despite this successful trial, the therapy was unable to progress to later preclinical stages.

Using the criteria, this therapy can be evaluated. Firstly, regarding animal models, this therapy's model is outdated and not a reliable source to assess its effects in HD. Furthermore, when this therapy was conducted, it was in a very early preclinical stage. Thus, there is insufficient data in the available animal models to assess its application in JHD accurately.

Regarding the effectiveness in response to the CAG expansion, this therapy's mechanism is less direct in its targeting and is unlikely to exhibit a significant effect in JHD.

Concerning early onset, due to this therapy's indirect and reversible targeting, it may prove to provide safe measures in JHD; however, further research will be needed to confirm this point. Finally, regarding durability, this therapy's mechanism requires only a single injection, which proves its durability.

6.2.3 AAV-mediated neurotrophic factor delivery

Neurotrophic factors are secreted proteins (proteins made in the cell that are then delivered outside of it) that regulate multiple aspects of neuronal development, including neuronal maintenance, survival, axonal growth, and synaptic plasticity.

However, in HD, the amount of neurotrophic factors produced is underdeveloped due to the progression of the mHTT throughout the CNS. To resolve this issue, scientists have used bacteria, yeast, or mammalian cells in the lab to produce neurotrophic factor proteins. This protein is then injected directly into the cell.

Another functional way to contribute to this therapy is by inserting a modified gene into the cell, rather than the protein itself (as with AAV). This allows the cell to produce the protein and administer it, rather than having it done in a lab (Ye et al., 2024).

One notable preclinical trial for this therapy used rodent models to inject AAV Vectors containing BDNF and GDNF into the rat striatum. After three weeks, they injected a liquid to increase neuron death and mimic HD; however, both AAV-BDNF and AAV-GDNF significantly reduced the decay. This demonstrated that AAV-delivered neurotrophic factors can protect

neurons in HD models. This is useful in HD because it prevents symptom progression and protects the brain from collateral damage (Li et al., 2019).

Furthermore, notable studies for this therapy have been conducted in rodents, non-human primates, and clinical trials for Parkinson's Disease (PD). While these trials were not specifically geared towards HD, their effectiveness as a drug candidate and safety in clinical trials demonstrated strong application potential for HD (Nam et al., 2024).

Concerning the criteria, this therapy can be analyzed systematically. AAV-mediated neurotropic factors have been tested in several early preclinical trials focused on HD, as well as in clinical trials for PD. While it has not yet reached the clinical trial stage for HD, it has shown significantly more advancement in trials for HD compared to the other listed therapies in this category.

Regarding the response to an expanded CAG repeat, this therapy's mechanism is geared towards aiding recovery of the mHTT rather than preventing its growth.

Due to this therapy's mechanism, it is unlikely to have a significant impact on the expanded JHD, and its effect may be minimal. Furthermore, its durability varies between multiple injections and single injections; however, it primarily exhibits single injections.

6.3 Regulatory Gene Modulation

6.3.1 Histone Deacetylase (HDAC) Inhibitors

Acetyl groups are used to modify histones, allowing them to loosen their association with the DNA. HDAC removes acetyl groups, resulting in histone proteins that limit gene expression by wrapping around the DNA. Typically, histone acetyltransferases (HATs) are other enzymes used to counteract HDACs, so their function does not become problematic (Ranganna et al., 2020).

However, in mHTT, the function of HDAC increases significantly and becomes out of balance with that of the HATs, resulting in the dysregulation of gene expression in the CNS. Thus, specific inhibitors have been developed to counteract this increasing tightening, which mitigates some of the disease's effects (Ranganna et al., 2020).

HDACi has had testing in R6/2 mouse models in recent years. The mild relief of motor symptoms has demonstrated the effectiveness of symptom recovery in HD. However, regarding the symptoms such as psychological issues, speech deficiencies, and cognitive dysfunction, this therapy has not been as effective a treatment as needed for recovery (Hyeon et al., 2021).

Another significant HDACi undergoing testing is the HDAC6 inhibitor. This specific therapeutic mechanism targets non-histone proteins in the cytoplasm, rather than specifically removing the acetyl group from histones. It includes various targets, one of which is a protein called α -tubulin that creates microtubules, which act as carriers in the CNS. The HDAC6 removes acetyl from α -tubulin, leading to severe consequences, such as protein aggregation of the mHTT. This specific model aims to enhance the function of α -tubulin by inhibiting the histone deacetylase HDAC6.

The two experimental trials conducted for this therapy regarding HD were an in vivo YAC128 transgenic (TG) mouse model, which expresses a full-length human mHTT protein with 128 CAG repeats, and a neural stem cell (NSC) model. The specific model is referred to as CKD-504. This trial was conducted by the Korean company CKD Pharmaceutical Corp.

The results of this therapy demonstrated a significant reduction in HDAC6, resulting in improvements in motor and cognitive function in the mice. Experimentation in the mouse model demonstrated that higher doses resulted in more significant improvements. The NSC model, prepared from the YAC128 mice, showed a substantial reduction in the target α -tubulin acetylation at varying doses. Regarding side effects, minor issues occurred during the therapy (Li et al., 2023).

In the context of JHD, several components can be used to evaluate this therapy. Firstly, regarding animal models, this therapy is currently in the early preclinical stage, with primarily NSCs and YAC128 transgenic (TG) mouse models being used in trials. Compared to Zinc finger therapy, this therapy's animal models are at a similar stage; however, due to the nature of YAC128 transgenic (TG) mouse models, this type of trial is considered more effective in mirroring HD and JHD.

Regarding larger CAG repeats, the model used in this therapy suggests that it is likely to respond effectively to JHD; however, this cannot be confirmed without further analysis.

Concerning early onset, this therapy does present mild effects of recovery, and minimal off-target effects have been reported thus far, which shows its potential for early injection. Finally, regarding durability, this therapy requires several injections over a long time, which could hinder JHD patients.

6.3.2 Zinc Finger

Small protein domains that consist of Zinc Finger Proteins, proteins that are engineered to identify and bind primarily to DNA to suppress its function. These proteins are naturally occurring; thus, this therapy provides another example of a biological component being increased to combat HD. This process involves engineering the DNA in vitro, which is then inserted into a plasmid and transformed into a host cell. Afterwards, it creates the Zinc finger protein using ribosomes and amino acids (Cheng et al., 2024).

Each Zinc Finger binds to DNA through the use of a specific protein structure consisting of strands and a helix, as well as a three-base DNA sequence. In the case of HD, these Zinc fingers are used to bind to cellular components near the CAG expansion and transcriptionally repress the mHTT (Cheng et al., 2024).

However, this process poses the risk of the Zinc Finger binding to the unintended gene. The CAG repeat is common in several cellular components and can often be mistaken for the mHTT CAG repeat, which causes issues for patients when the Zinc Finger does not correctly target the mHTT. Therefore, this therapy requires refinement to ensure accurate treatment (Cheng et al., 2024).

Currently, this therapy remains preclinical, primarily in the form of mouse models. An example of these models is the use of mHTT lowering HA-tagged ZFPs (A-ZFP). The study was conducted using an R6/2 mouse model, and it was found to have an approximately 70% reduction in mHTT. (Gangwani et al., 2023).

Another notable therapeutic analysis was conducted using zinc finger protein transcription factors (ZFP-TFs) on patient-derived neurons and fibroblasts. This resulted in a 99% reduction of the HTT while 86% of the wtHTT was preserved (Zeitler et al., 2019).

These therapy models primarily consist of R6/2 models, indicating that they are currently in an early preclinical stage of development. Compared to HDACi, this therapy method, despite its significant merits, does not effectively mirror JHD and HD.

Concerning CAG expansion, this therapy is straightforward and has undergone trials (although not advanced enough to confirm entirely), which have shown a positive response to large CAG repeats. This suggests that it would likely fare well against the expanded repeat sequence.

Regarding early onset, this therapy is direct and targets core components within the CNS. If off-target effects occur, as they have been shown to do, it could result in significant issues in the juvenile brain. Finally, regarding durability, this therapy primarily uses a single injection, which, as previously stated, is more efficient in treating JHD.

6.4 Gene Editing

6.4.1 CRISPR/Cas9 Allele-Specific Editing

CRISPR/Cas9 consists of two parts. First, the Cas 9 enzyme, which functions by cutting a piece of DNA at a targeted location. It utilizes a single guide RNA (sgRNA) to direct the Cas9 to the protospacer, which is the DNA sequence that the Cas9 is programmed to cut, and the scaffold, which structures the Cas9 and sgRNA together.

In order for the Cas9 to carry out its function, the protospacer adjacent motif (PAM), a short DNA sequence that the Cas9 recognizes as being adjacent to its target, must be present while targeting a specific gene. In HD, this process is carried out to the target the mHTT. Several variations of this disease are associated with it.

Two different examples of mechanisms used in this therapy are allele-specific detection and non-allele-specific detection. Allele-specific detection is being revolutionized through the use of guide RNAs (gRNAs) targeting single-nucleotide polymorphisms (SNPs), which are single-letter variations in DNA that enable the targeting of a specific area. These SNPs differ among patients; thus, multiple gRNAs need to be generated to carry out the therapeutic function. Alternatively, sgRNAs were designed to target the gene in a non-allele-specific manner, thereby mitigating this issue. However, allele-specific targeting using SNPs, while significantly more time-consuming and expensive, can specifically target the mHTT without negatively affecting the wtHTT (Shin et al., 2022)..

Issues with this therapy involve several reported instances of off-target effects and incorrect DNA cutting. However, due to HD being one of the few purely genetic

neurodegenerative diseases, genome editing tools can be applied to it. Given CRISPR's function, it is often considered a favorable and effective treatment option for this disease (Shin et al., 2022).

This therapy used mouse models to identify its effects. In the R6/2 mouse model of HD, this therapy was used to disrupt the expression of the mHTT gene after its *in vivo* delivery to the striatum (where the motor function deterioration is caused). It was found that there was a 50% decrease in neuronal inclusions (clumps or aggregates of proteins that accumulate in neurons in the case of HD, referring to the HTT protein), a longer lifespan, and motor benefits. These mice presented a 15% increase in mean survival compared to control animals (Ekman et al., 2019).

Furthermore, a study conducted in January 2025 utilized knock-in mice models. The purpose of this approach was to utilize a modified CRISPR/Cas9 system, delivered via AAV, to knock out or suppress genes that facilitate CAG expansion. To test the effectiveness of this system, genes known for their role in CAG expansion were targeted, specifically mismatch repair (MMR) genes, including Msh2, Msh3, Mlh1, and Mlh3, which all function as enhancers, and Fan1, which acts as a suppressor. Despite the suppressors being beneficial to the recovery of HD patients, they were suppressed in this study to demonstrate the therapy's efficiency. The testing conducted yielded varying results, depending on the component the suppressor was targeting (Mouro Pinto et al., 2025).

In the context of the MMR genes being suppressed, the CAG expansion in 12-week-old mice injected *in vivo* with this therapeutic mechanism was equivalent to that of 6-week-old mice not injected with the suppressor. Inversely, mice injected *in vivo* with the suppressor targeting the Fan 1 experienced an onset of the CAG repeat within 12 weeks, equivalent to that of a mouse not injected with the suppressor in 20 weeks. (Mouro Pinto et al., 2025).

Finally, the last notable experimental trial for this therapy examined in this article is the use of CRISPR/Cas9 in an HD knockout pig model. Results from this model demonstrated a significant expansion of mHTT reduction at the DNA level, suggesting it as a potential therapeutic mechanism for HD. However, despite its effectiveness, certain risks are associated with the therapy that are worth noting. The primary risk arises from the potential for off-target effects that may occur when using the system. Due to the permanent nature of this therapy, significant clinical issues can be associated with it if these effects occur. Thus, despite its effectiveness in reducing the HTT, this therapy should be used with caution, especially at the clinical level (Lin et al., 2025).

This therapy has demonstrated late preclinical models in recent years, such as the use of a knockout pig model. Due to this advancement, more data and certainty are associated with this therapy, which is valuable in the context of JHD. Regarding expanded CAG repeats, due to its effectiveness in mouse models and knockout pig models, as well as its direct mechanism, CRISPR/Cas9 is likely to respond well to increased CAG repeats.

Furthermore, regarding early onset capability, this therapy has been associated with past reports of incorrect DNA cutting; however, these issues are being addressed for resolution, and further analysis may reveal it to be safe for JHD patients. Finally, regarding durability, this

therapy varies depending on the case; however, a large majority of these cases use a single injection, which, as mentioned previously, is more durable and practical for JHD.

6.4.2 Base Editing

A genome editing tool that involves changing one DNA base into another without cutting double strand DNA cuts; it utilizes a modified CRISPR-Cas9 system called Cas9n to modify the DNA by cutting only one strand. The base editor is fused to a deaminase enzyme, which allows for the alteration of a base in the DNA.

In cell and animal models, it has been demonstrated that specific parts of the CAG repeat contain genetic material that slows the progression of the disease. Exploiting these findings in animal and cell models can have beneficial effects on the disease progression. For example, if there is a CAG CAG CAA repeat, the process is interrupted and thus slowed down (Deneault, 2024).

It was demonstrated that when tested in Htt.Q111 mouse models, the base editors were able to effectively reduce the repeated expansions in the CNS, a significant step towards slowing progression (Matuszek et al., 2025).

A model conducted using human fibroblasts with CAG repeats demonstrated an editing precision of 66-82%. Afterwards, a trial was conducted on a Htt.Q111 mice model, which showed a CAG repeat length reduction by 1.6–5.4 repeats across various brain regions. Furthermore, this therapy has been shown to exhibit minimal off-target effects.

Results from data collected through genome-wide association with over 9,000 patients showed that a single CAA interruption in the CAG repeat can delay disease onset by an average of 12 years. Pedigree analyses, used to study genetic inheritance patterns within families, revealed a delayed onset of 13 to 29 years. (Matuszek et al., 2025).

Another study was conducted using AAV9 to evaluate the function of base editors in the liver. This was tested in knock-in mice containing 110 CAG repeats. However, this therapy was unable to determine the modified sequence of the incredibly long CAG expansion in the mice, as well as minuscule levels of base conversion and high numbers of errors when analyzing the CAG repeat (Doo Eun Choi et al., 2023).

This therapy is currently in the early stages of preclinical trials. In comparison to prime editing, the knockout models and the R6/2 models are at similar levels; however, compared to CRISPR/Cas9 large animal models, this therapy is significantly less advanced.

Furthermore, regarding the CAG repeat, the primary source of study for this therapy is the knockout mouse model, which does not effectively mimic the large CAG repeat and therefore raises questions about its effectiveness in defending against CAG expansion.

Regarding early onset, this therapy can slow down the onset of the disease by targeting the primary mutated component. Doing so could bring a significant recovery aspect to the JHD. By interrupting the code, the mHTT cannot take effect within the patient, which resolves the issue before it escalates. Finally, regarding durability, this therapy requires multiple injections, which may result in reduced effectiveness in combating the disease over prolonged periods.

6.4.3 Prime Editing

A precise genome editing technology that uses the search and replace method to cause deletions, insertions, and all 12 base-to-base conversions without double-stranded breaks. This occurs when both strands of the DNA are broken in the same area, resulting in severe issues. Due to the severity of double-stranded breaks, this therapy is considered desirable for several neurodegenerative diseases, including HD.

Prime editing requires a fusion between the prime editor protein and specifically engineered RNA (pegRNA) used to write a DNA sequence in a specific location. To create the prime editor protein, two components are fused: the nCas9, a version of the CRISPR-Cas9 that only nicks or cuts one strand of DNA rather than both, and the MMLV Reverse Transcriptase (RT), which is a protein that writes DNA through the use of an RNA template.

The pegRNA utilizes a spacer to facilitate the localization of the target DNA. Afterwards, base-to-base conversion can be conducted in the cell. In the context of HD, this therapy functions by targeting the HTT gene and only cutting one strand, which can modify the CAG repeat (Zhao et al., 2023).

Currently, this therapy has not been demonstrated in any HD-specific models.

Due to the lack of models for this therapy, its effectiveness can only be determined by its mechanism. Regarding CAG repeat, this therapy shows potential due to its primary target being the root cause of the disease.

Additionally, regarding early onset, this therapy cannot be evaluated as no clinical trials have been conducted to determine its safety in HD.

Finally, regarding durability, if tested in a trial, this Prime Editing would require a single injection, which demonstrates its durability; however, not enough data is available to confirm the effectiveness of this therapy at the moment.

While these three therapies each have their merits, CRISPR/Cas9 has been shown to have the highest potential for treating JHD due to its advanced research and the development of models. These have shown significant advancement as compared to prime editing and base editing.

7.0 Weighting and Scoring system

These 11 therapies were rigorously reviewed and evaluated by the researcher, and in order to determine the most effective of the 11 therapies, the researcher used a weighted numerical system pertaining to the 4 aforementioned categories: animal models advancement, CAG repeat reduction, early onset capability, and durability.

The first of the four categories, animal models, was given a weight of 3 due to their importance in determining the effectiveness of a given therapy. Because they are the primary method of testing whether or not a therapy is effective and safe, the level of experimentation is the most efficient way to determine how well the test responds to the disease; therefore, it is given the highest weight.

Effectiveness in CAG reduction is given a weight of 2.5 because it involves targeting the primary source of infection within the disease, and by determining therapies that have the most substantial effect on the recurrence, we can identify which would likely provide the best disease treatment. However, this criterion does not provide insight into the safety of the treatment and thus is given a lower weight than animal models.

Early onset capability is given a weight of 2 because JHD begins at a very early stage in life, and thus, being able to target the disease at this point is essential. However, this criterion does not directly correspond to the effectiveness of the therapy itself and thus is given a lower weight.

Finally, durability is given the lowest weight of 1.5. While it is crucial for the therapy treatment to maintain well within the body, this criterion primarily addresses safety rather than effectiveness.

8.0 Discussion

EVALUATION OF JUVENILE HUNTINGTON'S DISEASE THERAPEUTIC MECHANISMS BASED ON SCORING SYSTEM					
Therapy	Animal Model x3	CAG repeat x2.5	Early Onset x2	Durability x1.5	Total
ASOs	$5 \times 3 = 15$	$4.75 \times 2.5 = 11.875$	$2.5 \times 2 = 5$	$3 \times 1.5 = 4.5$	36.375
shrRNA	$2 \times 3 = 6$	$2.5 \times 2.5 = 6.25$	$2.5 \times 2 = 5$	$5 \times 1.5 = 7.5$	24.75
AAV mi-RNA	$3.5 \times 3 = 10.5$	$4 \times 2.5 = 10$	$2.5 \times 2 = 5$	$5 \times 1.5 = 7.5$	33
LV Delivered Therapy	$2 \times 3 = 6$	$3.5 \times 2.5 = 8.75$	$2 \times 2 = 4$	$3 \times 1.5 = 4.5$	22.25
SB Transposon Therapy	$0.5 \times 3 = 1.5$	$1.5 \times 2.5 = 3.75$	$1.5 \times 2 = 3$	$5 \times 1.5 = 7.5$	15.75
AAV neurotrophic factor	$4 \times 3 = 12$	$3 \times 2.5 = 7.5$	$2.5 \times 2 = 5$	$3 \times 1.5 = 4.5$	28.75
HDACi	$2 \times 3 = 6$	$2.5 \times 2.5 = 6.25$	$2 \times 2 = 4$	$1 \times 1.5 = 1.5$	17.75
Zinc Finger Therapy	$2.5 \times 3 = 7.5$	$2.5 \times 2.5 = 6.25$	$1.75 \times 2 = 3.5$	$5 \times 1.5 = 7.5$	24.75
CRISPR/Cas9	$3.5 \times 3 = 10$	$4 \times 2.5 = 10$	$2 \times 2 = 4$	$3 \times 1.5 = 4.5$	29
Base Editing	$2.5 \times 3 = 7.5$	$1.75 \times 2.5 = 4.375$	$2.25 \times 2 = 4.5$	$1 \times 1.5 = 1.5$	17.875
Prime Editing	$0 \times 3 = 0$	$1.25 \times 2.5 = 3.125$	$1 \times 2 = 2$	$5 \times 1.5 = 7.5$	12.625

Fig. 4. This table represents the 11 therapies reviewed in this study, evaluating each on a 1-5 numerical scale. The weighting of the individual criteria for the therapies is based on their significance in the application of JHD.

This study aimed to evaluate 11 therapies and determine the four most effective for application in JHD. Afterward, the four therapies were narrowed down to one based on criteria including animal models, CAG repeat expansion response, early onset capability, and durability.

From these 11 therapies, ASOs, AAV-mediated neurotropic factor delivery, Zinc Finger, and CRISPR/Cas9 proved to have the most effective responses to this criterion.

ASOs demonstrated strong clinical status, having progressed to Phase 3, with their CAG repeat expansion response showing significant benefits, particularly in CAG-heavy diseases such

as JHD. However, setbacks from this therapy include off-target effects in trials and weak durability, necessitating multiple trials. Overall, this therapy received a score of 36.375.

Continuing AAV-mediated neurotrophic factor delivery currently involves animal models in the late preclinical stage, primarily using large animal models. Concerning the CAG repeat, despite this therapy having advanced and effective trials, it does not explicitly target the repeat; instead, it focuses on recovery from the disease. This hinders the application of therapy in HD as well as JHD.

Regarding early onset capability, this therapy has demonstrated on-target effects in several trials. When injected, it has minimal side effects, which could impact the patient. Finally, this therapy varies depending on the case, ranging from single to multiple injections; however, it primarily involves single injections. This demonstrates its durability. Overall, this therapy scores 27.5.

Continuing HDACi animal models are in a similar stage as lentivirals, with a focus on YAC128 mouse models as the primary model. As mentioned previously, this corresponds to larger CAG repeats in the animal models, and due to its effectiveness in the trial, it has been shown to have potential effect for JHD.

Regarding early onset capability, this therapy does not have a significant effect on HD patients; therefore, it is unlikely to provide significant help in earlier cases with JHD. Regarding durability, this therapy requires multiple injections over extended periods, which compromises its durability. This therapy has a rating of 17.75.

Finally, regarding CRISPR/Cas9, it is currently in the late preclinical stage of study, with primary focus on the use of knockout pig models. This proves that it is at a significant state of advancement that is useful for JHD.

Regarding CAG repeat, due to its effectiveness in large animal and mouse studies, this therapy likely would respond well to larger repeats. However, a significant disadvantage arises from the issue of past off-target effects, which may hinder the early onset capability. Finally, regarding durability, this therapy is available in various models with different injection protocols; however, it is primarily administered using a single injection. This therapy has an overall score of 29.

However, out of these 11 therapies, ASOs have demonstrated the most significant potential for application in JHD. ASOs have had stage 3 trials, which is the most significant advancement among the 11 therapies. Despite the trial being halted due to concerns involving a significant margin between the disadvantages and advantages of the trial, it has still proven that, with further refinement, it could have a serious application to HD (Tabrizi et al., 2022).

Furthermore, this therapy's function involves targeting the mHTT specifically, which is crucial for its application in JHD to prevent the rapid onset of symptoms. Lastly, this therapy's main issue comes from indirect targeting, which hinders its function in Adult-Onset HD. However, in the case of JHD, due to the larger repeat of 60+, the therapy can more accurately identify the target. While this therapy may have several setbacks regarding HD, it shows strong

potential for JHD treatment, and with further development, could be a plausible therapeutic strategy used in a broad number of cases.

However, despite the effectiveness of these therapies in HD, JHD presents issues that make it significantly more challenging to treat. Firstly, due to its large CAG repeat, it is incredibly challenging to treat. Due to off-target effects, weak durability, over-injections, and side effects, administration is difficult for the 60+ CAG repeats this therapy exhibits. As well, significant ethical issues are outlined along with this disease due to issues regarding conducting testing on juveniles. Finally, due to the commonality of misdiagnosis, this disease is often unseen until it is too late for the patient.

In the future, additional tests will need to be conducted on HD to confirm the safety, durability, and effectiveness of these therapies. Once that is accomplished, these therapies will need further examination for application in JHD. However, to accomplish this, significantly more research and funding are needed to treat this condition.

8.0 Conclusion

This review aimed to summarize the current advancements in gene therapy towards the treatment of HD and to determine its application for JHD. It examined 11 therapies in total and determined the most effective ones for applicability based on a set of criteria, including advancement in animal models, relation to increased CAG repeat, early onset capability, and durability.

Overall, out of the categories discussed, the four that exemplified this criterion most precisely were: ASOs, AAV-Mediated Neurotrophic Factor Delivery, Zinc Finger, and CRISPR/Cas9.

This is due to their trials being the most developed, their specific targeting process directly aiming at the root cause, their ability to target the disease early and precisely, and their durable half-lives.

Out of these 4 therapies ASO treatment was chosen due to its advanced clinical model status, direct mechanism, and specific mechanism geared towards JHD.

However, a significant limitation of this research is the limited application of the model in JHD. Due to the rarity, rapidity, and specificity of this disease, it is challenging to conduct testing on JHD patients, resulting in underdeveloped research (Tereshchenko et al., 2019).

While these therapies hold strong potential for HD treatment, they need further examination and research for application to JHD. In the future, more models will have to be conducted on HD patients to guarantee the effectiveness and safety of these treatments.

Once these therapies are shown to be effective for HD, research must be conducted to analyze how they respond to JHD, focusing on safety for the juvenile brain. JHD is a severe neurodegenerative issue, and given its rapidity and apparent issues, it is a clinical necessity that it receives thorough research in the future.

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Genetic Mutations and Disease Severity in Atrial Septal Defects: A Focus on NKX-2, GATA4, and MYH6 By Ayushi Singh

Abstract

Atrial Septal Defect (ASD) is when the atria (the two upper heart chambers) fail to close completely, leaving an abnormal flow of deoxygenated and oxygenated blood. Although many cases have been reported to occur sporadically, an increasing number of them have been linked to familial forms of ASD, partly due to specific genetic mutations. This study reviews the most frequently associated genes crucial in cardiac development: NKX2-5, GATA4, and MYH6. Through a comprehensive literature review using scholarly sources, this paper analyzes how specific mutations in these genes affect protein function and lead to different severities of ASD. This study reveals that missense mutations in regions critical for transcription activity and nuclear localization can significantly disrupt the normal formation of the heart. Understanding these mutations can be essential for early diagnosis, improved risk assessment, and the potential development of targeted therapies or medication for ASD.

Introduction

Atrial Septal Defect (ASD) is when the two upper heart chambers (the atria) fail to close correctly. There are five main types of ASD listed in most frequent to least frequent order: patent foramen ovale, ostium secundum defect, ostium primum defect, sinus venosus defect, and coronary sinus defect (Menillo et al., 2023). The patent foramen ovale is a small flap-like opening in the upper atrium. When the opening closes at birth, it is considered the foramen ovale. When it does not, it is classified as a patent foramen ovale (Mayo Clinic, 2018). Ostium secundum defect (ASD II) occurs in the middle of the atrial septum, while ostium primum defect affects the atrial septum's lower portion. A sinus venosus defect is an opening in the upper portion of the atrial septum (Mayo Clinic, 2022). Lastly, a coronary sinus defect is a rare defect that occurs when there is a hole between the coronary sinus (a large vein that drains blood from the myocardium) and the left atrium (Miyashita & Suzuki, 2023). The specific cause of ASD is still unknown, as many cases of ASD are sporadic (Menillo et al., 2023). However, there has been a rise in familial cases of ASD, which suggests a genetic association. The genetics behind ASD have been under heavy research, and some major genes have been identified that play a crucial role in the early cardiac development of embryos. Some of these genes include NKX2-5, TBX5, GATA4, MYH6, ACTC1, and HAND1. This paper will focus on the mechanisms and impact of the mutations in the NKX2-5, GATA4, and MYH6 genes.

Methodology

A comprehensive literature review was meticulously conducted to understand these mechanisms and the impact of the mutation in the NKX2-5, GATA4, and MYH6 genes. Databases like PubMed, National Library of Medicine (NIH), Google Scholar, and Online Mendelian Inheritance in Man (OMIM) were extensively searched. Articles such as clinical

studies, genetic analysis, and peer-reviewed articles published in the last 15 years were considered. Key search terms included “atrial septal defect genetics,” “NKX2-5 atrial septal defect,” “atrial septal defect hereditary,” “MYH6 atrial septal defects,” and “GATA4 atrial septal defects. The OMIM database was also looked at to gather additional detailed information on these genes. This paper is a synthesis of multiple published sources to provide a comprehensive review of ASD genetic mutations and their contribution to the pathogenesis of the defect.

Results and Discussion

NKX2-5

NKX2-5 is a gene that expresses a homeobox protein called NKX2-5. Homeobox proteins form body structures in the early embryonic stage (*NKX2-1 Gene: MedlinePlus Genetics*, 2017). NKX2-5, in particular, plays a vital role in the structure and electrical conduction of the heart. NKX2-5 is a transcriptional factor regulated by upstream and downstream factors and works with co-regulators to control targeted genes. These factors regulate NKX2-5 through promoter and enhancer functions, RNA uncoiling, post-transcriptional modifications, etc. (Wang et al., 2020). Given its critical role, NKX2-5 has been linked to congenital heart defects (CHD), including ASD. Recent studies have identified specific variations in the gene that contribute to the severity of ASD by affecting the cardiac structure and electrical conduction. The following paragraph will examine mutations found in different populations and their implications.

A recent study sequenced the entire length of the NKX2-5 gene from recruited Chinese individuals, involving 439 patients diagnosed with sporadic atrial septal defect and 567 healthy individuals. Using a standard reference genome and annotation with a variant effect predictor, researchers found 30 variations. Among these 30 variations, the single nucleotide polymorphism (a variation of a singular nucleotide) rs2277923 (80.18%) was highly frequent in patients (Wang et al., 2019). These findings have also been consistent across different ethnicities. In a Moroccan population study, 32 non-syndromic ASD II patients were screened for NKX2-5 variants using direct sequencing of PCR-replicated regions, and it was found that there was a notable prevalence of the c.63A>G (rs2277923) polymorphism. This common variant was detected in 56.25% of the cohort, making it the most widespread alteration observed. While other missense variants were identified, their occurrences were significantly lower, with an overall rate of 9.4%, rising to 12.5% when including silent variants (Bouchikhi et al., 2016).

Additionally, a study conducted of 97 recruited patients with ASD for genetic screening using Sanger sequencing in Indonesia revealed three kinds of genotypes for the c.63A>G variant: homozygous AA (14.4%), heterozygous AG (42.3%), and homozygous GG(43.3%). Overall, this study frequently found that as much as 85.6% of research subjects and the variant were associated with a 20% decrease in transactivation activity. Although the pathogenicity of rs2277923 (c.63A>G) remains mostly undiscovered, the reduction in transactivation activity means that the affected transcription factor (NKX2-5) has reduced affinity to activate the expression of its target. Since NKX2-5 plays an essential role in cardiac development and

electrical conduction, a decrease in transactivation function at different rates can result in variable degrees of atrial septal closure defects. For example, if transactivation is severely decreased, the septum may fail to close correctly, resulting in a more severe ASD that requires invasive therapy. In contrast, mildly reduced transactivation could make the septation partially successful, leading to a smaller ASD.

In addition to these polymorphisms, some specific mutations in the gene have been associated with ASD involving atrioventricular block, namely Gln170ter, Thr178Met, and Gln198ter. Thr178Met results in a non-synonymous substitution, altering the protein in the homeodomain region. Gln170ter introduced a premature stop codon, halting the translation of the homeodomain. In contrast, Gln198ter introduced a stop codon immediately after the homeodomain, causing a truncated protein as it is missing its C-terminal region (Chung & Rajakumar, 2016; Aoki & Horie, 2018). The severity of the disease due to these mutations can vary depending on its location and other factors. Suppose these mutations, such as Gln170ter, are located on the homeodomain. In that case, it is likely associated with more severe cases as the homeodomain is crucial in binding transcription factors and development. Additionally, mutations like Gln198ter, which cause C-terminal deletions, can increase abnormal transcription in downstream genes associated with developmental disorders. In general, however, mutations in the NKX2-5 gene, especially in hereditary ASD, relate to sudden cardiac death (SCD) due to bradycardia or tachycardia (Aoki & Horie, 2018).

GATA4

GATA4 is a zinc finger DNA-binding protein that plays a crucial role in regulating early heart structure formation, such as proepicardium generation, heart tube formation, separation, and outflow tract development (Litwack, 2018, pp. 337–358; Fan et al., 2021). The interaction between GATA4 and other cofactors determines their specific activity. For instance, when GATA4 works with retinoic acid receptors like NKX2-5, it further regulates myocardial gene expression (Tremblay et al., 2018). Due to this function, GATA4 has been a gene that has been closely researched in terms of ASD. Recently, mutations in this gene have been considered pathogenic factors in familial ASD (Bu et al., 2021). GATA4 consists of 442 amino acids, including its C-terminus and N-terminus ends, and the nuclear localization signal (NLS) (a short amino acid sequence that acts like a tag protein for import within the cell's nucleus (Lu et al., 2021; Bu et al., 2021)). In the following sections, the specific mutations and their impact on the pathogenicity of ASD will be discussed.

Mutations in the NLS of GATA4, found in the 271 to 322 amino acids (Bu et al., 2021), have been discovered recently. One such mutation is the amino acid substitution of Methionine at the 310 position. In previous literature, a study conducted that accounted for the etiology in Chinese families with ASD involved direct sequencing of the genome of kindred spanning three generations, where 8 of 31 individuals were diagnosed with ASD compared with the control of 170 unrelated individuals. It was discovered that at the 310th position, Methionine was replaced with Valine (M310V) (Chen et al., 2010). By contrast, a similar study conducted that accounted

for the etiology in a Chinese family with ASD involved direct sequencing of the genome of a family spanning three generations in which 3 out of the 12 individuals were diagnosed with ASD, concluded with the identification of a novel mutation of M310T in GATA4 (Bu et al., 2021). However, despite the difference in the amino acid substitutions, both studies consistently highlight a precise mechanism: mutations in the NLS of GATA4 disrupt its proper transport into the nucleus, disabling its crucial role as a transcription factor in cardiac development. This disruption would ultimately lead to structural defects like ASD. Another study conducted also had a similar methodology, a family of three generations with seven patients with ASD, except these patients also had pulmonary valve stenosis (PS). This mutation, K319E in the exon 5 of GATA4, was predicted to be deleterious by three different bioinformatics programs and was detected and co-segregated with the affected ASD family members, expanding the spectrum of GATA4 mutations (Xiang et al., 2014). While there are no set answers on exactly how these mutations affect the severity of ASD, mutations in the NLS region can cause severe issues regarding protein localization and function. Since nuclear localization signals are messed up, the proper proteins may not be able to enter the nucleus, which can halt processes of the nucleus, such as transcription and gene regulation. In the case of GATA4, this could mean misregulation of essential cardiac genes, impairing septation or cardiac development. Given that GATA4 also works with other transcription factors, the NLS mutation may hinder its ability to work with other key factors. As a result, the severity of ASD due to NLS mutations in GATA4 can vary depending on the extent of nuclear mislocalization and the degree to which gene expression is affected, which can be understood by further research in this area.

Similar to mutations on the NLS region of GATA4, mutations in the gene's promoter region have been studied. A study analyzing 332 ASD patients with 336 ethnically matched controls concluded five heterozygous regulatory variants exclusive to ASD patients: g.31360 T>C (rs372004083), g.31437C>A (rs769262495), g.31487C>G (rs1053351749), and g.31856C>T (rs1385460518). Specifically, g.31360 T>C and g.31437C>A significantly weakened transcription factor binding. Decreased GATA4 levels may affect the interaction between other factors in the cardiac gene networks, disrupting the atrial septum (Fan et al., 2021). In another study, 100 CHD patients were analyzed, with atrial septal defect (ASD) accounting for 33% of the cases. Genetic screening was found on the GATA4 gene, revealing 19 mutations across various regions, including the promoter. Most importantly, they found a homozygous mutation rs61277615 in the promoter region of two ASD patients, suggesting a pathogenic association. Additionally, when parental DNA was analyzed, they found that the parents were heterozygous carriers of this mutation and passed it on to their offspring, reinforcing the genetic basis of ASD (Mattapally et al., 2015). Overall, mutations in the promoter region of GATA4 can significantly impact gene expression by altering the transcription factor binding and regulatory mechanisms. The mutations can lead to disruptions that can vary the severity of ASD and the degree to which septation and specialization in the cardiac cells occur.

MYH6

Myosin heavy chain 6 (MYH6) codes for a cardiac alpha myosin heavy chain protein. This protein is part of a larger protein complex called Type II myosin, which plays a significant role in the sarcomeres in the cardiac cell (*National Library of Medicine, 2013*). The sarcomeres function as structures that aid in the contraction of muscular cells, such as the heart's myocardial cells. The MYH6 gene has been closely associated with ASD. Therefore, mutations in this gene have been well-researched, as seen in the next section.

In a study involving 31 ASDII patients with positive family history and 185 control patients of all Caucasian origin, they were screened using array-based resequencing, and three interesting, novel mutations were found to be frequently present in ASDII patients. These mutations include R17H, C539R, and K543R. The R17H mutation replaced arginine with histidine, causing altered hydrogen bonding ability, showcased dominant inheritance with incomplete penetrance (not all carriers develop the defect), and was predicted as “probably damaging” by Poly-Phen-2 (a tool used to predict the possible impact of amino acid substitution). The C539R mutation was found in the helix-loop-helix region. It increased the side-chain length, which could potentially destabilize the structure and disrupt the actin-myosin interaction, which is crucial for the macromer to function. It was predicted to be damaged by PolyPhen-2. Lastly, K543R, also found in the same region as C539R, altered the interaction between MYH6 and actin by introducing a bulkier side chain that could interfere with energy conversion and muscle contraction in the heart. Interestingly, these mutations were found primarily in the MYH6 head domain, a crucial part of the alpha myosin heavy chain that functions in actin binding and ATP binding, which, unlike other cardiomyopathies, where mutations occur primarily in the rod or neck regions, was more frequently associated with ASDII in this study, suggesting a key role of MYH6 in the pathogenesis of MYH6 (Posch et al., 2011). This can be further supported by a study conducted involving two unrelated Han Chinese families with a history of familial ASD II. Researchers identified a novel mutation, p.E526K, which was confirmed by Sanger sequencing and other bioinformatic programs to be present in all patients with ASD in the families and was determined to be damaging. They also established that the mutation significantly impaired the myofibrillar organization but did not reduce ATPase activity (Xia et al., 2019). This suggested that, similar to the previous study, this mutation impacted hydrogen bonding, the only difference being which structures the mutation affected. In the case of E526K, it would be alpha helices in the neck domain with an actin-binding region. On the other hand, a similar study using whole-exome sequencing and Sanger sequencing conducted on a large Chinese Han family with ASD II found a novel mutation Arg1822_Glu1823dup in the coiled-coil domain (rod domain). Similar to the previous domain, the mutation variant significantly impaired myofibril formation, but it also increased apoptosis and did not significantly affect cell viability. Additionally, researchers found that the variant impaired the myosin alpha helix, increasing the stability of the coiled-coil myosin dimer (Huang et al., 2021). This would mean that there would be enhanced myosin filament production and potential formation, which could alter the myosin motor function.

In addition to its influence on ASD II, the MYH6 gene has also been closely related to ASD III (Sinus Venous). A study finds a mutation that may influence the pathogenesis of ASD III. Conducted on two patients in an Iranian family that had a history of ASD, the study used whole-exome sequencing (WES) on the male patient, and an autosomal dominant inheritance mode was analyzed for variants. They identified a mutation, R1279X, which eliminates 660 amino acids in the C-terminal of MYH6, including vital parts of the coiled-coil structure of the tail domain. They also deemed the mutation as likely to be a disease susceptibility. They indicated that there was an increase in haploinsufficiency (the situation that occurs when one copy of a gene is inactivated or deleted, and the remaining functional copy of the gene is not adequate to produce the needed gene product to preserve normal function (National Cancer Institute, 2012)) with reduced penetrance of MYH6 through further analysis (Razmara & Garshasbi, 2018). Some conclusions about the severity of this disease could be made, such as reduced penetrance, which indicates that other factors, such as genetic or environmental factors, could influence disease expression. Overall, the mutation's link to ASD can be investigated through further research and understanding of the mutation's mechanism.

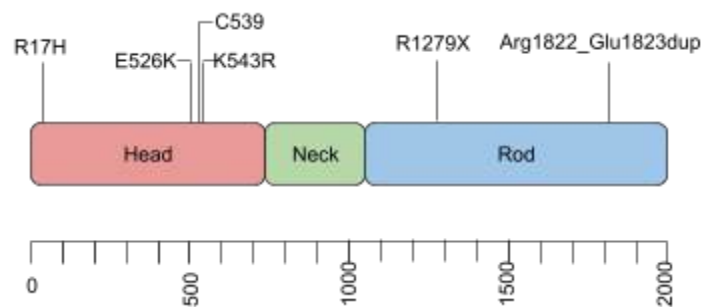


Figure 1
Visual Overview of alpha-myosin heavy chain 6 (MYH6), highlighting the domains (head, neck, rod) and location of mutations based on specific positions of these amino acids in protein structure.
Note. Adapted from Posch et al. (2011). © 2011 Posch et al. Licensed under CC BY.

Conclusion

Atrial Septal Defects (ASD) are a common and widespread birth defect worldwide, which emphasizes the need for continued research into its etiology. Throughout this paper, we have examined how specific genetic mutations influence the development of ASDs by disturbing the signalling pathways crucial to cardiac formation. While each study has its methodology and limitations, collectively, they convey a better picture of how specific genes shape the heart. This helps develop a deeper understanding of precise diagnostic tools and targeted therapies. These insights further allow us to advance in predictive screening, earlier intervention, and ultimately, better outcomes for patients born with ASD. While the journey towards complete understanding might be long and filled with discoveries, no matter how small, they add to the larger effort to benefit countless innocent lives in future years.

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Neurologic Music Therapy: Analyzing the Clinical Potential of Music in ADRD & PD through Project Andante By Nicholas Chen

Abstract

Age-related decline in motor function (MF) and memory function (MemF) constitutes a major risk factor for loss of independence and decreased quality of life in older adults (OA). Others also suffer directly from disease-associated symptoms, including patients with Parkinson's Disease (PD) and Alzheimer's Disease and Related Dementias (ADRD). This study examines the non-pharmacological, non-invasive interventions such as neurologic music therapy (NMT) and its ability to engage motor pathways and cognitive processes through rhythmic entrainment and emotional involvement. The present study, conducted through live performances organized by Project Andante (PA), examined motor and psychological responses of OA to multiple music genres within a nursing home (NH) environment, essentially demonstrating the powers of music as it pertains to its clinical potential as a source of neuromotor & memory therapy and rehabilitation. Participant responses were recorded using a graded intensity scale ranging from no response to extreme response (0-5).

Results indicated that rhythmically stable and familiar music genres, including Baroque, folk, and 1950s popular music, elicited the highest intensity scores, whereas unfamiliar or irregular music genres (e.g., contemporary anime) produced minimal to no observable response. Data suggest that predictable rhythm and music familiarity are critical variables in eliciting both voluntary and involuntary motor responses as well as associated emotional and physiological responses. Findings highlight rhythm and familiarity as key mechanisms underlying NMT and its capability, and support the development of user-specified therapeutic interventions aimed at motor rehabilitation, memory recall, and quality of life for those experiencing declines in MF and MemF.

Keywords neurologic music therapy, motor function, older adults, rhythmic entrainment, therapeutic intervention, Alzheimer's Disease and Related Dementias, nursing home, Parkinson's Disease

Introduction

Music is a universally shared construct that can influence cognition, emotion, and MF (Zatorre, Chen, & Penhune, 2007). Beyond its cultural and aesthetic value, evidence suggests music directly holds emotional and physiological ties with the neural systems underlying MF and MemF, producing outcomes ranging from simple motor responses such as finger tapping to more complex whole-body movements, as well as eliciting strong emotional reactions including humming or even crying (Chen, Penhune, & Zatorre, 2008). This auditory/motor coupling is particularly relevant for OAs and patients with PD, who frequently experience reduced MF, limited movement options, and elevated risk for falls, loss of independence, and diminished quality of life. Auditory/memory coupling is also relevant for those with decreased MemF (such

as ADRD patients), where NMT offers potential recall remedy as a therapy for diminished memory function and loss of recall abilities.

While conventional/standard physical therapy programs may provide measurable benefits for OAs, they sometimes lack the emotional salience required to maintain long-term adherence (Särkämö & Soto, 2012). And yet, NMT offers a non-pharmacological and non-invasive supplement that combines rhythmic entrainment with emotional involvement, thus activating both motor networks and cerebral cortex & memory pathways (Grahn & Brett, 2007; Salimpoor et al., 2011). Rhythm entrainment, specifically, occurs when external auditory stimuli synchronize with neural oscillations of the brain in motor planning areas, triggering initiation and harnessing real-time movement (Thaut, McIntosh, & Rice, 1997). But even so, its potential for ADRD patients is substantial; while conventional methods of dementia and memory stimulation don't work, as well as many other cognitive functions, certain memory systems activate when hearing familiar music, a phenomenon shown to be especially effective with certain patients suffering from advanced Alzheimer's (Jacobsen et al., 2015). This mechanism has shown clinical relevance in populations with PD and ADRD, further underscoring its potential therapeutic scope.

Previous studies show how both rhythmic stability and familiarity are drivers of MF and MemF engagement. For example, Baroque and classical music, characterized by predictable tempo and harmonic structure, reliably induces swaying and foot tapping (Thaut et al., 1999). Similarly, familiar music from an individual's youth, such as 1950s popular music, can evoke deeply rooted emotional associations, eliciting spontaneous emotional responses when reintroduced later in life (such as in the case of NMT). By contrast, music with irregular or unfamiliar rhythmic patterns often produces weaker motor and emotional responses, reinforcing the importance of predictable rhythm and familiarity in generating motor activation & memory recall (Janata, Tomic, & Haberman, 2012).

Building on these findings, this naturalistic observational study investigates the motor and psychological responses of OAs in live performances organized by PA, an organization dedicated to giving musicians a way to perform therapeutic music for residents at senior nursing homes (www.projectandante.org, 2022). Music in these NH settings included a wide range of music genres: 1950s pop, Baroque/classical, jazz, modern pop, folk, and contemporary anime instrumental music. Using a graded movement intensity scale, this study quantifies the extent to which different musical structures and levels of familiarity elicit voluntary and involuntary motor responses such as foot tapping, body swaying, and hand clapping. The overarching goal is to identify musical features most effective in enhancing MF and MemF engagement in OA & PD and ADRD patients, as well as showcase and model its potential utility for therapeutic interventions with NMT frameworks.

Participants

The study population consisted of OAs aged 70-95 years residing in long-term NH and senior center facilities. Inclusion criteria were intentionally broad to reflect real-world

heterogeneity in NH populations. Participants with varying levels of MF and MemF were included, and no residents were excluded because of existing medical diagnosis. Thus, participants included individuals with PD and ADRD, as well as those without neurological conditions. This approach reflects the exploratory and pragmatic framework often applied in non-drug intervention studies with OA (McCreedy et al., 2021).

Methodology

This research employed a naturalistic observational design consistent with clinical trials of non-pharmacological interventions. Live musical performances were administered over an eight-month period across multiple NH facilities in the Seattle metropolitan area through Project Andante (PA) performances, totalling to around 6. All field notes & data were recorded live during performance sessions to maximize validation and coding of observed responses.

Six primary categories of musical stimuli were selected to assess differences in rhythmic predictability, familiarity, and emotional salience:

1950s Pop:

Familiar chord progressions, diatonic harmonies, steady rhythms, vocals.

Classical/Baroque (e.g., Bach, Handel):

Predictable tempos, clear harmonic structures, rhythmic regularity.

Jazz:

Syncopated rhythms, moderate familiarity, improvisational elements.

Folk:

Moderate tempos, culturally familiar melodies.

Modern Pop:

Contemporary popular music, generational familiarity varying across OA cohorts.

Contemporary Anime Instrumental:

Rhythmically irregular, low familiarity among participants.

All pieces were performed live by the researcher (viola) and small ensembles as part of PA programming. Each performance lasted 2-5 minutes and was randomized in order of presentation to reduce order effects.

Evaluation

Motor responses were evaluated using a Response Intensity Scale (1-5):

1: No movement/negligible response

2: Minimal MF & MemF engagement (e.g., finger tapping)

3: Moderate MF & MemF engagement (e.g., foot tapping, head nodding)

4: Vigorous MF & MemF engagement (e.g., clapping, humming)

5: Whole-body MF & MemF engagement (e.g., standing, rhythmic movement, singing, crying)

Each music genre is ensured consistency by observing at least 50 senior residents for

each category ($N \geq 50$). Observable behaviors included finger/foot tapping, clapping, head/shoulder movement, humming, singing, crying, and facial expressions. Qualitative notes were taken on emotional involvement, MemF retrieval (e.g., recall of lyrics), and MF stimulation among senior residents. All performances were video-recorded, and recordings were independently reviewed to validate and code music response, memory stimulation, and motor engagement.

Data Analysis

Quantitative data were categorized by music genre. For each genre, average RIS scores were calculated, along with the percentage of participants exhibiting measurable MR. Qualitative data were thematically analyzed for evidence of emotional involvement, MemF retrieval, and peer engagement. These outcomes were evaluated in relation to established NMT principles, with particular attention to the therapeutic potential of predictable rhythm and familiarity in enhancing MF and MemF among OA, including those with PD and ADRD.

Results

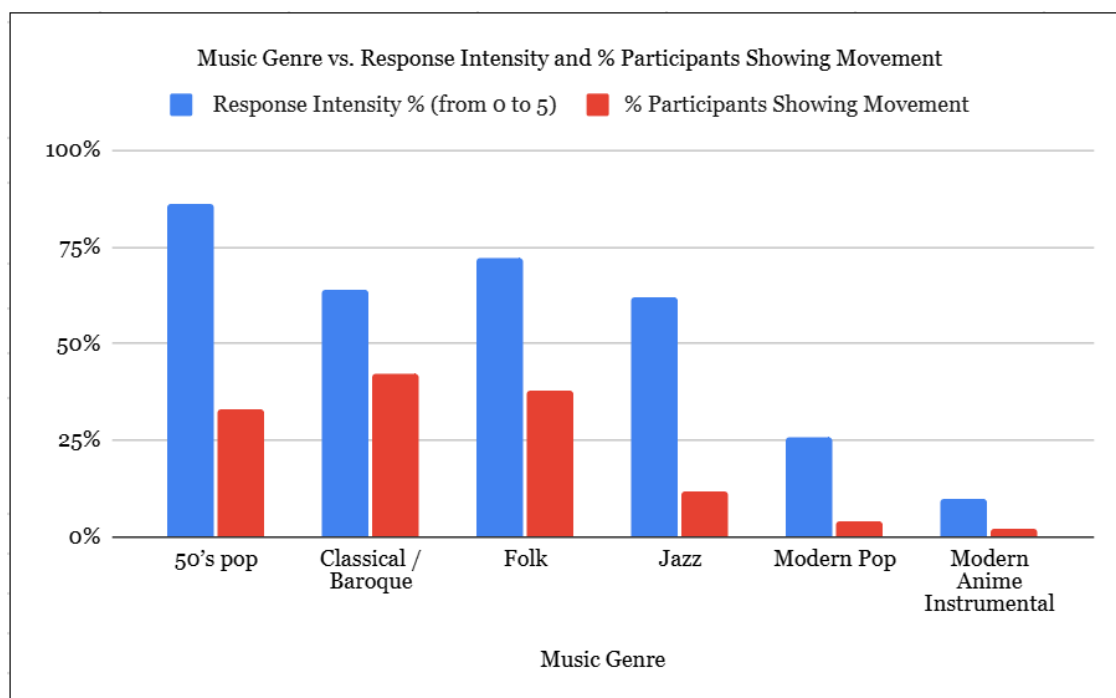


Fig 1: Music Genre vs. Response Intensity (%) and Participants Showing Movement (%)

Music Genre	Response Intensity % (from 0-5)	% Participants Showing Movement	Most Common Responses	Key Qualitative Observations
50's pop	86%	33%	Humming, clapping, finger tapping	Strong engagement for certain people; familiar tunes/chord progressions
Classical / Baroque	64%	42%	Finger tapping, foot tapping, swaying	Strong engagement; synchronized tapping; smiles/humming
Folk	72%	38%	Foot tapping, clapping, gentle swaying	Culturally familiar; steady rhythmic responses; singing
Jazz	62%	12%	Head nodding, finger tapping, clapping	Moderate engagement; syncopation reduced predictability
Modern Pop	26%	4%	Minimal finger tapping, slight swaying	Low engagement; generational familiarity variable
Modern Anime Instrumental	10%	2%	Rare tapping	Minimal response; low recognition; unpredictable rhythms

Fig 2: Data Table of Music Genre, Response Intensity, Participants Showing Movement, Common Responses, and Other Qualitative Observations

Calculations

Response Intensity Calculation	% Participants Showing Movement Calculation
$= (N/5.0) \times 100\%$ $\{0.0 \leq N \leq 5.0;$ $N = (n_1 + n_2 \dots n_x)/n;$ $n = \text{recorded RI};$ $x \geq 50\}$	$= (n/N) \times 100\%$ $\{n = \text{participant displaying movement};$ $N = \text{total \# of participants}\}$

Fig 3: Calculation Process of Response Intensity (%) & Participants Showing Movement (%)

Summary

1950s pop music elicited the highest response intensity % (mean = 86%), followed by Folk (72%), Classical/Baroque (64%), Jazz (62%), Modern Pop (26%), and Modern Anime Instrumental (10%) with respect to the Response Intensity Scale from 0-5. However, the percentage of participants showing physical movement was highest for Classical/Baroque (42%), with Folk (38%) and 50s Pop (33%) following. Modern Anime Instrumental elicited the least physical engagement, with only 2% of participants responding.

Discussion

This research explored the MemF and MF responses of OAs to various music genres and the effects of rhythmic familiarity and predictability on their level of engagement as indication of

future potentials of NMT for ADRD and PD patients. Results indicate that music with a fixed rhythm and cultural familiarity, especially 1950s popular music, folk music, and Classical/Baroque music, prompted the highest music responses in NH settings. These responses were not only quantifiable in terms of response intensity scores but also observable in qualitative behaviors (such as humming, clapping, swaying, and even tears).

These findings align with existing NMT literature showing that predictable musical patterns (e.g., steady tempos, diatonic harmonies) facilitate MF activation through rhythmic entrainment (Thaut et al., 1997). Beyond rhythm, MemF retrieval and affective engagement appear central. Cuddy et al. (2017) says that music encoded during adolescence, particularly emotionally salient works, leaves deep yet durable traces in the cerebral cortex, persisting even in OAs with advanced ADRD. This neurological preservation likely explains why mid-20th century repertoire, such as 1950s pop, with its recognizable chord progressions and vocal timbres, elicited humming/singing, clapping, crying, and other emotional expression in OAs at PA performances.

Dr. Ziyaad Jaber (2025) articulates that when Elvis Presley was popular, “The chord progressions and musical structures [of that era] directly stimulated [MemF] in the brain... associations that remain deeply encoded” (Z. Jaber, personal communication, September 10, 2025). This phenomenon aligns with the mere exposure effect (theory in psychology), where repeated auditory engagement during early years conditions OAs to demonstrate stronger affective and show MF responses to familiar musical styles. The characteristic “groove” of 1950s repertoire likely continues to evoke neurological responses in OAs, including those with PD or ADRD, by simultaneously activating motor pathways and autobiographical memory circuits (Janata et al., 2012). Within NMT structures, such responses model and show the therapeutic potential of historically familiar music, particularly in NH environments where interventions may be applied to enhance both MF and MemF engagement.

On the contrary, newer genres such as anime instrumental and newer pop music yielded significantly lower engagement rates. These genres are often characterized with higher rhythmic unpredictability, modern production styles, and harmonic unfamiliarity, all things that don’t directly prompt music-evoked responses in OAs. Such findings are in congruence with the idea that new/inconsistent musical stimuli are less likely to generate internally synchronized MF and stimulate MemF (Thaut et al., 1999).

Something to point out is that, while 50s pop had the highest average response intensity scores, Classical/Baroque music engaged a larger percentage of participants. This suggests that certain genres may offer broader applicability, affecting MF (classical), while others may trigger specific personal responses, affecting MemF (50s repertoire).

Also, the inherently predictable temporal structure of Baroque music provides a clear opportunity to harness the brain’s entrainment capacity, where an external cadence synchronizes with internal neural pulses across the cortex and subcortical networks (Thaut et al., 1999; Fujioka et al., 2012). This goes hand in hand with established NMT interventions, such as Rhythmic

Auditory Stimulation (RAS), which are actively employed in therapy for individuals with PD as rehabilitation (Thaut et al., 1996; McIntosh et al., 1997).

Qualitative reports from PA concerts highlighted the affective salience of these responses, with many OA participants demonstrating singing, smiling, crying, or other gestures related to the stimulation of music. Such behaviors are consistent with simultaneous activation of limbic and motor areas triggered by familiar musical material, as supported by fMRI evidence (Salimpoor et al., 2011; Zatorre et al., 2007). Notably, music from participants' youth years appeared to directly address aspects of cognitive decline, reviving autobiographical MemF and affective passions: features with high therapeutic potential in ADRD applications globally (Cuddy et al., 2017).

Importantly, this study models, through OAs demonstrating measurable MF engagement when exposed to rhythmically predictable music, NMT's therapeutic utility for neurodegenerative conditions. The preservation of MemF through musical cues suggests a mechanism for dementia therapy and sustained quality of life as well. These findings collectively show the powerful value of integrating PA-led interventions (NMT and other music rehabilitation) into broader clinical care frameworks for individuals worldwide.

Neural Mechanisms

The observed effects of NMT on MF and MemF in OAs, including those with PD and ADRD, involve the activation of specific neural circuits and cellular pathways.

Rhythmic auditory stimuli, like ones used in NMT, can entrain neural oscillations. This stimulates motor control in PD patients. This entrainment engages the basal gangliathalamocortical (BGTC) network; when the cochlea transduces sound vibrations into electrical signals, they are relayed via the auditory nerve to the brainstem and auditory cortex, where rhythmic cues synchronize MF regions (Nwogo et al., 2022; Ye et al., 2022). Rhythmic auditory cues can harness activity in these networks, improving MF in patients experiencing motor control loss.

In individuals with ADRD, music therapy has been shown to enhance memory recall & emotional response. This effect is likely due to the activation and stimulation of the cerebral cortex and hippocampus/parahippocampal regions, areas crucial for the processing of memory and often affected in cases of dementia and memory loss. Music, especially familiar melodic lines & tunes, can be stored as long-term emotional memories, suggesting that regions in the cerebral cortex can still respond to musical stimuli even in the presence of neurodegeneration (Clark & Warren, 2015; Koelsch et al., 2022). NMT and its effectiveness highlight the potential of NMT as a non-pharmacological rehabilitation therapy, capitalized on entertainment and memory recall.

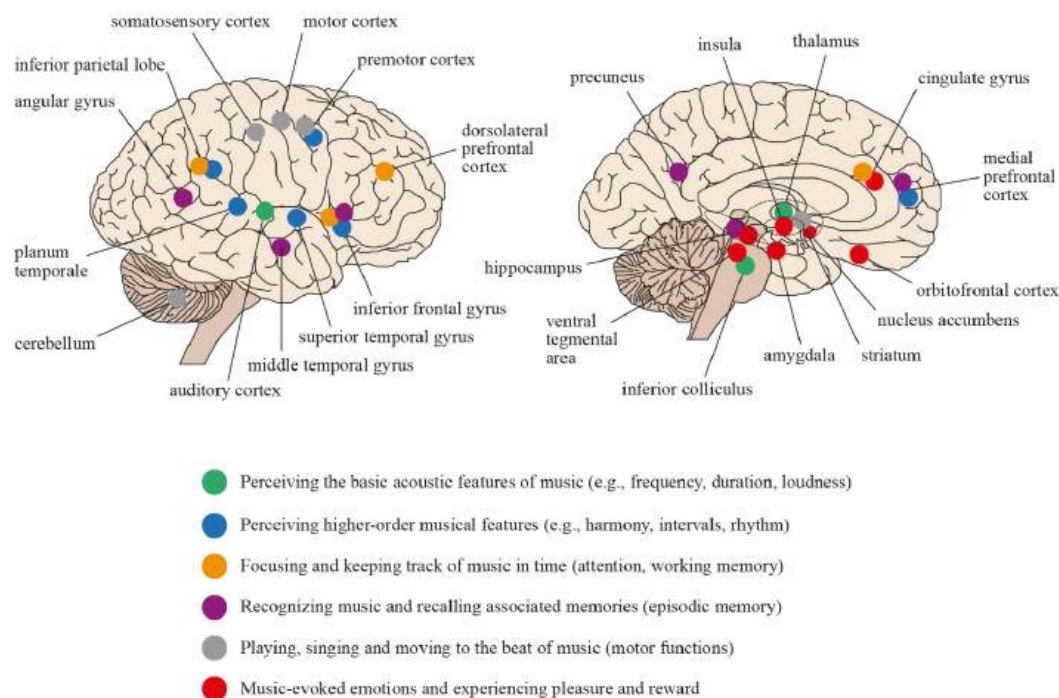


Fig. 4: Auditory Processing of Music with Respect to Divisions of the Brain

Conclusion

This study shows the power of music in its ability to evoke movement and emotion in OAs, specifically when music is rhythmically consistent and emotionally evocative. For instance, as validated by Dr. Ziyaad Jaber (physician, psychologist, and co-founder of Medvice Digital Health), Elvis Presley recordings and other music from the 1950s stimulate MemF due to its cultural and personal familiarity, showing that certain, generation-based musics are especially beneficial as a means of therapy and medical practice. These findings bring to light the non-pharmacological, non-intrusive use of NMT in clinical settings for memory engagement and motor recovery.

Unlike traditional physical therapy, which can get expensive and offer generic solutions for different people, music offers a patient-specific process that can directly help with MemF and MF. Research shows rhythmic auditory cues can entrain movements, assisting those with impaired motor control by offering an external beat/pulse for coordination; music not only motivates but also actively engages motor networks within the brain, thus helping rehabilitation.

In the future, individualized NMT programs designed around generation-appropriate music may support neurotherapeutic practice, in ways that extend beyond other interventions. These approaches could address quality of life, memory-related health, and motor pathways in patients with ADRD or PD, as well as the general population worldwide. However, further research is needed on the neuroplastic changes caused by repeated exposure to music, especially in individuals suffering from said neurodegenerative disorders. But the future of NMT is definitely promising with regards to its clinical applications, as articulated throughout this study.

This research is supported by PA, where young musicians bring live music into NHs and other care facilities as an adaptive process for different types of communities. PA highlights the role of music in both culture and medicine, showing how MF and MemF engagement can be complemented by an interdisciplinary approach of arts and sciences. This combination of neuroscience, music, and culture opens up a world where NMT can be applied worldwide as a non-invasive, widespread foundation of memory & motor rehabilitation.

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The Failures and Successes of the Current-day Roundtable Method in its Mission at a Boarding School By Janibek Subkhanberdin

Abstract

The aim of my research is to shine a light on the pedagogical student experience at an elite boarding school, and how it may compare to that of students at non-boarding high schools. I focused on the efficiency of the roundtable method of teaching and comparing students' learning experiences under this method with the experiences of students who learn a similar curriculum but under a traditional teaching method at non-boarding high schools.

Results showed that despite School A's (SA) intentions for the roundtable method to serve as a collaborative learning style, the current state of the method betrays those expectations. Students often find themselves pressured by the competitive nature of the roundtable, partaking in disjointed discussions wherein students talk for self-serving purposes as opposed to the intended goal of fostering an educational conversation. Many students also reported that an inconsistency in teachers' participation and delivery of the roundtable method weighed heavily on their experience with the curriculum.

The stigma of roundtable labels, graded participation, and the conformist culture of roundtable discussions were also cited as factors in the uneasy environment of SA classrooms. Student-written articles at a similar elite high school, School B (SB), make no mention of similar pressures in their absorption of the curriculum, likely stemming from the fact that the roundtable is not used for every subject at SB – and therefore not as deeply-rooted in the culture as it is at SA. SA students raised the idea that the roundtable's current flaws are caused by the competitive environment of the academy, and not by any innate quality of the pedagogy – many argued that to remedy the current roundtable atmosphere the academy would have to address the grade-obsessed environment of SA first.

Background

As an elite New England boarding school, School A shares many similarities with neighboring establishments, priding itself on being academically rigorous, sending many students to elite colleges, and having extreme selectivity in admissions. What sets SA apart from its peers is the usage of the roundtable method as a pedagogy for all its courses. Throughout their time at the academy, students are often reminded of the importance of the roundtable method to the SA experience. The use of the pedagogy for all courses is a decision relatively unique among elite high schools. That absolute adherence to a discussion-based approach to learning has created an environment for SA students where they absorb the curriculum differently from their peers in regular high schools. To investigate the potential difference in students' interaction with the curricula in traditional high schools versus in boarding schools, this paper will compare the experience of SA with SB.

The roundtable teaching method originated at SA from Richard Terry, a benefactor of the school. The SA principal at the time of the roundtable's origin explained the vision behind the

pedagogy as such: “Remember the conference system of teaching, that is the big idea! On one side a stubborn man with an idea, on the other an eminent schoolman who feels he may be wrong. Must prove our case and sell him an idea. Not recitations, conferences.”¹ With students seated, facing one another, at a rounded table for twelve students plus one teacher, and deliberating on topics in all subjects in that “conference” style, a roundtable classroom is formed. This conversation-based approach to learning is upheld as key by the school; they attribute a plethora of lessons and benefits to the method, such as the roundtable aiding students in developing their confidence and skills in collaboration.²

SA highlights the collaborative nature of the roundtable, and the increased avenues it opens for exploration and therefore learning – compared to lecture-style teaching – as some of the factors making the teaching method unique and beneficial.

Methodology

The school that I selected for comparison was School B (SB), a strongly academic New England non-boarding school. To narrow my choice down to SB, I used the criteria of having a school newspaper, being a similar size to School A, offering electives in the humanities, cultivating a similar environment of high academic rigor, and providing useful articles from the respective newspaper. My reasoning for these criteria is that schools fitting them will have the most relevant similarities to SA so that I can conduct a comparative study while limiting the need to account for outside factors/contexts that this research is not interested in (such as the possible differences in culture caused by population size and freedom of course selection). I needed each school to have a newspaper so I could perform a comparative analysis to *The School A Weekly*, School A’s official student-run newspaper. I used articles from SB’s *The School B Review* as sources from the School B perspective to compare against my findings from *The School A Weekly*. I coded all the chosen articles by keywords and themes like “diversity” and “delivery of course content,” before analyzing the texts. Due to time and energy constraints, I interviewed only SA-affiliated faculty and students. Faculty candidates for interviews were chosen based on their roles, with certain candidates being deans or chairs of humanities or mental health/diversity departments, as well as teachers. There were no strict criteria for selecting students to interview, though I aimed to gather information from a diverse group of voices in regard to grade, race, and neurodivergence/neurotypicality.

To proceed with interviewing students and faculty, I received approval from SA’s director of research. Prior to interviews, an informed consent form was included in all interview requests over email – which students and faculty signed to affirm their consensual participation in my project. All minors were required to obtain parental consent as well.

Furthermore, all references to my actual boarding school, the high school used for comparison, my school’s pedagogy, article authors of both newspapers, and interviewed subjects are pseudonymized.

¹ Chilwell, Lauren. “The Men Behind the Plan”, *The School A Times*. Fall 2006, 32

² “The Roundtable,” *School A*. Accessed 4 December 2024.

All interviews were conducted in-person, save for an interview with one student which was conducted over Zoom. All subjects reserved the right to pick their preferred location for interview, and whether they preferred to meet in-person or over Zoom. I emailed ten teachers total, of which one agreed to interview in-person. I emailed 24 students, of which six agreed to interview. I conducted five student interviews, as one of the subjects could not fit an interview into their schedule.

With interviewee consent, I recorded the conversations using the Voice Memos application on my phone. Audio files were then stored in a secure SA-provided DropBox folder and deleted upon completion of this project. These files were uploaded to the online Temi platform to be transcribed into text. All transcripts were then saved to the same DropBox folder before being analyzed and coded by themes. They were then incorporated into the article analysis. In total, I conducted six interviews.

Results

The Roundtable and the Curriculum Experience

The unique combination of using the roundtable for every subject and its importance in the grading system at an extremely competitive school that prides itself on academic rigor is what most separates students' experience with classes and the curriculum at School A compared to other high schools. However, the efficiency of the roundtable as a method of learning is limited in its current form, wherein students often fail to foster the spirit of debate and critical thinking meant to be enabled by the roundtable. Instead, be it a consequence of the competition brewed by the existence of roundtable grades, or of the culture of SA, students often avoid confrontation and instead use participation as a tool to boost one's grades based on quantity over quality.

The Benefits of the Roundtable

Despite its current flaws, the roundtable has still, for many, proved a success at School A. SA students highlighted an aspect unique to the pedagogy that shaped their absorption of the curriculum, when it succeeds in its mission. An important way that the roundtable changes students' engagement with their courses is that it forces them to understand the content, not just to memorize it.

"If you're able to discuss [material] with your classmates and articulate your thoughts, then I think it does get more ingrained in you -- that you know how to analyze a text and you have the ability to sort of look at something and then come up with an original interpretation, look at things from different angles," reflected Junior Michael Guo. Junior Elizabeth Piron echoed the sentiment: "I feel like specifically with the roundtable, I'm able to do a lot more critical thinking." She elaborated, "And I think that critical thinking is also elevated by having other people in my class, just having discussions in general. I feel like, specifically with humanities classes, I think I absorb the curriculum a lot better, I feel like I understand a lot more."

Senior Andrew Kovit reflected a similar opinion on the roundtable, placing particular emphasis on the benefit of exposure to a wide range of student perspectives. “I’d say for more reading-based subjects like humanities, English, I think I absorb a lot more through the roundtable because I feel like ideas come to you during a discussion that you wouldn’t have otherwise thought of, you know? And so, when I’m reading a text, I’m sure I’ll be annotating and I’ll have some analysis, but then the second I go into the conversation, being able to hear other people’s ideas and then all of that kind of linking together the bigger ideas for the text, I think that’s something that the roundtable does really well.”

Students shared that understanding a concept enough to come up with unique, nuanced insights is required to get a high grade at the roundtable, and that will innately push them to interact with the curriculum from a different angle than the traditional one perhaps offered at SB. In a more traditional lecture-based pedagogy, students are not exposed to the same breadth of voices that they can draw inspiration and knowledge from.

The roundtable also holds another merit for SA students: serving as a platform to build confidence. Kovit highlighted that advantage, explaining that through exposure to other voices and when given no other choice but to participate, his confidence in discussion and participation grew considerably. Sophomore Sarah Zhu shared, “I think that’s a really great part about the roundtable -- it’s never like you’re weird for jumping in with a comment or a question. But I think it really depends on the class environment.” On that note of comfort in curiosity, the roundtable is further lauded by some SA students for the sense of community fostered by the process of discussing a diverse array of perspectives to arrive at a class consensus.

Faculty member Lionel Freecss detailed: “I would say with the roundtable specifically, I think some of the pros of it are that the students really learn how to engage with each other in a meaningful and healthy way. They learn how to listen to each other and talk through complex ideas in the company of other people. And I think what’s especially nice about that is, if they approach intellectual territory that is filled with some uncertainty or doubt or anything like that, they can work together to overcome those obstacles and achieve a certain kind of understanding with the assistance of everyone else in the room, which I think is special.” He continued, “I would say it’s great in that it is a communal way of learning and the students are generating the knowledge, which I find exciting and I think it’s liberating for them to take charge of their education like that.”

Zhu affirmed Freecss’ thoughts: “I think having that sort of communal learning aspect makes a lot of the difficult topics you cover less daunting. So you’re kind of all struggling to get to one point together.”

The Absence of Disagreement in Roundtable Discussion, and Presence of Anxiety

However, some SA students noted that despite the diversity in voices platformed at the roundtable, students rarely disagree or confront each other often enough to fully take advantage of a discussion-based pedagogy. “Most of the classes that I’m in, most people seem not super comfortable disagreeing with each other. I think that one of the things that we can work [on]

better and improve on is that we should be able to clash with each other's points in a civil way that doesn't insult the other person but discuss[es] the matter at hand," declared Guo.

When reflecting on why many students hold an aversion to confrontation, Guo reflected that "it's more comfortable to agree with something for the table to be at 100% consensus and the teacher nodding all that, maybe it feels like we're disrupting the flow by saying, I disagree with this point."

He posited that perhaps a solution falls in some part to the teachers, that they should "almost encourage a little bit of questioning, a little bit of disagreement on their own to ease up the class's tensions."

Even though students will naturally be exposed to differing opinions at the table, their engagement with the curriculum is often still through a very safe perspective. In fact, many controversial or non-conforming lenses are often shut down by some "snarky comment"³ and rarely examined.

Some students, like junior Alexa Mansouri can brush aside the stigma around a domineering presence at the roundtable, the label of "roundtable warrior." "I'm aware that I'm kind of a roundtable warrior and it's not something that I'm particularly concerned about. I don't necessarily try to dominate the conversation, but sometimes it just happens."

Others, like Kovit, encounter more trouble with the level of judgement constantly present at the roundtable. Navigating the labels and norms of SA discussion serves as a regular struggle. "I think it does add more anxiety in my day. I think being in a roundtable discussion, it sort of singles people out if you're on either end of the roundtable warrior or the [quiet] spectrum." Kovit detailed his own experiences as such: "Most people want to be in the middle. I think, me being on the quieter side, if I come out of a class having spoken like once or twice, I'm like, 'oh man, that sucks.' People are going to think I didn't do the reading and the teacher's going to think I didn't do the reading. Even though I know I have my ideas and I know I have all of this analysis that I've done, but I just wasn't able to put it into words, you know?"

Freeccs offered a similar review of a flaw innate to discussion-based pedagogies like the roundtable: "I think with that comes this sort of the question of, if you're a quieter student, if you're more introspective, if you're not as comfortable speaking regularly, how do you partake in that learning and how do you ensure that you get the most out of it without feeling like you're kind of left behind?"

The feelings of being "singled out", and "left behind" make it clear that the daily reality of the roundtable can prove as a serious pressure on students and their perception of themselves. To address the issue, Freeccs explained that teachers may have to step in. "I think sometimes in cases where students are really struggling, individual meetings with them can be appropriate. Just sitting down with them and, and asking them, you know, 'what can we do here? To sort of make you more comfortable and how could we include you in the conversation more frequently or more intentionally sometimes?' Those kinds of interventions are necessary."

³ "Fixing our Roundtable classes", *The School A Weekly*, 13 October 2016.

The author of a 2016 article published in *The School A Weekly* recounted a common experience of SA students perceiving their peers' participation: "Then, out of nowhere, that annoying kid goes and drags their inflammatory views into the discussion and injects the reading with their uncultured interpretations of the world," wrote the author. "What do you do? You probably shot them a subtly snarky comment and complained about them at lunch. This is not the best way to handle an obtuse person at the roundtable. You know you should converse with them and try to understand their viewpoint while emphasizing your own, but it's a lot easier to talk to your friends about them and more satisfying to send a zinger his or her way."⁴ Through this article, experiences like Kovit's, and opinion pieces that poke fun at those at the roundtable with controversial opinions, it's evident that SA students are often self-conscious with regard to what they say, and how they are perceived by the class. The aim of the teaching system and how it affects students when it's at its best is lauded by most students, but in its current state it really builds on the pressure students face at a place of already considerable academic rigor. The intense culture of competition where students fight over each other for a voice at the roundtable, only builds on that as students antagonize each other and experience pressure to compete.

"I think I'm a victim of anxiety about the stigma because people tell me I'm a roundtable warrior. I don't think I am a roundtable warrior, I really don't think I am. But I do feel like being labeled as a roundtable warrior, having people hyper-analyze my participation at the roundtable makes me a little hesitant sometimes to speak," complained Zhu.

The anxiety surrounding participation also originates from the ever-looming pressure of a roundtable grade. Junior Elizabeth Piron described the worry as such: "It feels like, 'oh, I'm not saying anything. I'm going to get a bad grade. But all of these other people are really competitive at the roundtable.'" She did note, however, that such anxieties are dependent on individual class dynamics. In more relaxed classes, obviously there is less of a feeling of judgement.

Overall, though, most SA students do experience a daily level of pressure from the roundtable, as explained by Mansouri: "it does often feel like sometimes it's just too tense and I know a lot of people get really stressed out before their day-to-day roundtable discussions, which isn't great."

Over-competition and Grade-based Participation at the Roundtable

The roundtable as a pedagogy is one of the key environmental factors that influences how SA students are impacted by the curriculum, and many echoed Piron's choice of grades as a cause for the roundtable's key issues. An article published in *The School A Weekly* by alumna Sarah Woo details her experience with the system. "*Not for Oneself*," is a phrase SA students are very familiar with. It's inscribed with two other mottos on the school's seal, and on the front page of the official website," wrote Woo. "However, *not for oneself* does not correlate with the school's highly competitive and rigorous environment. Personal success is celebrated, and every aspect of the school is a breeding ground for jealousy as students strive to out-perform their dorm mates, teammates and classmates." The roundtable was used by Woo as a tool to describe the

⁴ "Fixing our Roundtable classes", *The School A Weekly*, 13 October 2016.

contrast in the school's motto with reality. Meant to be a system of learning based on collaboration and sharing ideas "not for oneself", the roundtable experience for Woo and many other students is actually experienced as such: "My friends and I would constantly complain about how our classes were filled with Roundtable Warriors and how discussions felt more like wars. Students would eagerly wait for a classmate to finish talking and jump in right after their last word, stealing the chances of those who were shy or simply slower in bringing up their point. Discussions would be fast-paced but long pauses would be common, especially after a certain point brought up by another student, as classmates would be less inclined to be as supportive of others."⁵

Woo, throughout her article, placed grades as the primary stressor and motivator for the existence of roundtable warriors, students that she characterizes as participating "for their own self-interest, and not with the intent of helping others."⁶

An article written by Senior Hannah Sully, published in *The School A Weekly*, expresses the ways that some students do feel that roundtable-induced burden. The roundtable, Sully argued, in its current form encourages competition to an unhealthy degree, actively meddling with students' experiences with their curriculum and its contents. By throwing out their own points for the sake of their grade, instead of giving attention to others' ideas, productive conversations that would delve deeper into the curriculum's contents and expand on everyone's ideas can't happen.⁷ "The Roundtable might be causing SA students more stress, tainting the discussion that is supposed to be our source of learning," to that point Sully posed the question "What if we focus more on listening to each other without the pressure of making good points a certain number of times in class just for a grade?"⁸

Many of Sully's peers expressed a similar complaint. Zhu, for one, said: "The thing that annoys me the most in humanities classes with the roundtable is when the students are participating, but it's so clear that the only purpose is for the grade. I think that makes sense because obviously you're getting graded on your participation, so you want to maximize that, but it's so awkward when someone's speaking, responding to a prompt or responding to a question, and they're just making eye contact with the teacher the whole time." The complete focus of some students on their grades has led them to behave in ways genuinely non-conducive to a collaborative and healthy class discussion.

Guo reflected on the opinion that the roundtable is too competitive: "That's a fair criticism. I've thought about this and talked about this with my friends. I think it certainly is the case in some classes where I've had roundtable discussions where the teacher seems checked out and you're just trying to sort of compete to put yourself in, or it's almost like you're not necessarily making the most original points. People are talking over each other and all that stuff."

⁵ Woo, Sarah. "The Irony of Not for Oneself", *The School A Weekly*.

⁶ Woo, Sarah. "The Irony of Not for Oneself", *The School A Weekly*.

⁷ Sully, Hannah. "The Pitfalls of the Roundtable", *The School A Weekly*. Accessed 26 September 2024

⁸ Ibid.

However, Guo disagreed to an extent: “I think first going to the idea that the roundtable is a competition, I think that’s, I don’t necessarily agree with that because in my personal experience, I haven’t spoken a ton in any of my classes and I think if you’re able to still isolate two or three meaningful points per class, I think that still yields a good result at the roundtable.” He affirmed that quality over quantity was often enough to succeed in the roundtable, and that competitive behavior was not necessarily mandatory. Mansouri echoed the sentiment, explaining that she often found good discussions at the roundtable despite the current level of competition. Many students, like Piron for one, also cited class dynamics as a key part of the issue, that competition varies by classroom.

The School B Perspective

At SB, discussion-based classes exist, but stereotypes akin to what it means to be a roundtable warrior don’t. At least, such notions are not as generally accepted or played into as at School A, with no articles written in *The School B Review* that reference the role. Socratic seminars at SB also lack the deeply-rooted competitive environment that exists at School A. Instead of advocating for their peers to focus on cultivating a healthy discussion over raising their grades, authors of an article surrounding the Socratic seminar, Harry Liu and Siddharth Jhanwar, advocated for students to actually participate more and engage with the curriculum through discussion.⁹ The level of unhealthy competition seen at School A and the previously described adverse effects that that has on students’ interactions with the curriculum are lacking from SB. That competition, combined with forced discussion in every class, then, can be singled out as the key differentiator in the experiences of SA and SB students. To avoid the drama and inhibitions brought by an overly competitive discussion, Liu and Siddharth raised the idea of making graded participation relative to individual students — with shyer students judged at a different level. No strides have been taken to implement that suggestion but – at a school which uses discussion-based learning far less, and whose students experience far less of the unique pressures of School A’s roundtable – such a drastic change in grading is less needed.

Speculation on how to Address the Roundtable’s Issues

What is interesting, however, is that in searching through the articles published in *The School A Weekly*, individual-based roundtable grading is very rarely argued for or even mentioned in the many pieces written that criticize or comment on the current state of the roundtable. Were individual-based roundtable grading to be implemented in School A, however, the culture surrounding the roundtable could potentially shed some of its toxicity as competition over grades would shrink with students knowing that they are no longer pitted against each other relative to the same rubric. Zhu proposed the devaluation of roundtable participation in grades as a remedy to the pedagogy’s illness, though acknowledged that such a change would be

⁹ Li, Austin and Shreyas Pokharna. “Graded Participation: Should We Raise Our Hand For It”, *The School B Review*, lhsmusket.com/1450/opinion/graded-participation-should-we-raise-our-hands-for-it/. 16 February 2024, Accessed 26 August 2024

complicated: “I don't know how they could change the way it's emphasized in classes, but I think there needs to be more emphasis on how learning from that style of teaching is supportive of experiences as a student and not just solely for the grade.”

Many SA students raised valid concerns about that solution and instead pointed to addressing the root of the issue. Freeccs pondered, “An easy solution, of course, would be to just not grade it. So the pressure of grading is not there. But then the question is like, how engaged are people, really? I mean, they would come and just sit there and stare at you. So, I think the grading incentive does help just people try to strive to meet the bare minimum a little bit.” He pivoted, explaining that SA’s intensely competitive environment was the root cause for the roundtable’s issues. “I think the competition of the roundtable is a larger cultural issue at the academy in terms of the academic rigor and the emphasis of grades that we try to instill in students. I think if some of that was loosened up a little bit, and we emphasized the fact that quantitative measurements of success are not necessarily the end all be all, I think that would trickle down a little bit and create a more easygoing and collaborative roundtable environment.” Mansouri shared the same opinion, that the roundtable was competitive because it is at SA.

Piron raised a similar concern to Freeccs, that the roundtable needs participation and so needs grading to incentivize that: “I mean, the school is based off of the roundtable. So, especially in the humanities classes, you can't grade the roundtable less because the whole point is that the class is [delivered through that pedagogy.] It's like you're analyzing the text, you're talking about the text.” She did consider, though, that such a change would be more plausible for STEM given its lesser emphasis placed on discussion.

Kovit also raised questions on the idea of devaluing roundtable grades: “I think you could do that. Do I necessarily think it's the best solution? Maybe not. It's difficult to know. It's complicated. I don't know, suppose in an English class the roundtable is like 30% of your grade, right I don't think it would make roundtable warriors any less motivated to constantly speak.” Overall, though, students did express that the roundtable has serious issues, and that competition is a core one of those.

Sully suggested other changes the academy could make to amend the current state of the roundtable, listing more teacher feedback on students’ performances as a change that would help facilitate and guide the underperforming.¹⁰

The Role of Teachers at the Roundtable

Another complaint forwarded by students is the lack of standardization and clarity from teachers at the roundtable. Whether it be in the degree to which teachers participate in discussions, what kind of participation they provide, or how they grade both the roundtable and assignments, students emphasized

“And that's the biggest [issue]. It's not very uniform,” noted Zhu. Guo, who appreciates when teachers guide, ask questions, and drive class forward expressed numerous complaints about the behavior of certain teachers at the roundtable: “Some, they're just

¹⁰ Sully, Hannah. “The Pitfalls of the Roundtable”, *The School A Weekly*. Accessed 26 September 2024

able to sort of sit back and sometimes you're not really sure if they're listening to the conversation, which I think inevitably happens in a format like the roundtable where it's so student-driven that it's a little regrettable. But I think by and large most teachers need to sort of guide the direction or give observations for the table to discuss.” Although naturally much of the responsibility to foster a healthy roundtable discussion weighs on students’ shoulders, teachers must also acknowledge their position of power and take advantage of their hierarchy at the table. As an authority who can guide students, invite shyer ones to talk more, and nudge more domineering ones to step back, teachers are the members of the roundtable who can most directly impact SA students’ individual experiences with the pedagogy. A balanced discussion, wherein all students participate, also benefits students beyond an individual level and deepens the class’s collective understanding of a topic as more perspectives can be compared. When teachers fail to effectively guide discussions, the roundtable serves no real benefit over a lecture-based approach; students instead speak over each other and grind the discussion to a halt. Quieter SA students are excluded as competitive students disrupt the class dynamic, and this effect only detracts from the learning experience of all the participants at the roundtable.

Of course, though, teachers must find a way to strike a balance between guiding a discussion and allowing ample room for students to participate. To wrestle with that equilibrium is undoubtedly a challenging task for instructors at School A. Through the descriptions offered by students, it appears that many teachers have not yet overcome that challenge. Some students, like Zhu, raised the concern that certain teachers were over-imposing their opinions on students at the roundtable, and in grading. “Especially US History. Dr. Mangrove guides the discussion so you only have one correct opinion. And a big part of history is historical interpretations. I haven’t taken history since last winter, but I think there should definitely be some space for students to have opinions. Like my friend had Dr. Mangrove last term and she said if you didn’t create a paper and your answer to the guiding question was the opinion Dr. Mangrove had, she would give you a bad grade just because of that.” Mansouri and Kovit recounted similar experiences. “I feel like the issue is some teachers can be very domineering and then it’s like you don’t even get a chance to analyze the material because they’re just talking. But I really like when teachers just ask you to give initial thoughts and then just let the conversation naturally flow into deeper discussions within that,” said Mansouri. “There’s some classes, like Dr. Colwill, if you disagree with him, you’re cooked. Your [final paper] is out the window,” complained Kovit. “I think something that kind of brings up anxiety for me at the roundtable is seeing the teacher’s reactions because sometimes teachers will have very visceral reactions to your points where they frown or they give you a confused look or they go ‘well...’ That can definitely be very discouraging. And oftentimes when that happens, if a teacher shuts me down in an impolite way or a way that’s not very constructive, I just fully won’t talk for the rest of the week in that class,” noted Mansouri.

What teachers must realize is that the confidence of students as well as their grades, which are valued immensely by most at School A, are at stake at the roundtable. Through the real-time reactions of instructors during discussions, as well as the way that teachers’ personal opinions manifest in the grading of both the roundtable and class assignments, the impartiality of

some of School A's faculty has proved seriously detrimental to its students. In an environment where a teacher's subjective opinion can hold such influence over a student's experience with their course, it is unrealistic to imagine a roundtable discussion in which students have full confidence to express themselves freely. As detailed in the prior section, students often filter their input at the table – both to avoid confrontation with the peers but also to avoid clashing with their instructor. A healthy discussion necessitates confrontation and disagreement, and that can only exist for students without the fear of disagreement impacting their grades. Roundtable teachers should remain more impartial than not – obviously, they should still raise their own points and perspectives to add to the discussion, but there is no need for them to factor much other than a neutral view of a student's logic and analysis into their grading or feedback.

Freeccs expressed a perspective backing up Mansouri's opinion on teachers' imposing their own interpretations on students: "I think it's really successful at the roundtable in English when students are free to explore their opinions or explore their ideas without you know, the fear of pushback and the fear of chastisement from the teacher."

Students suggested numerous ideals for teacher behavior, ideals to be standardized. "I think the teachers have to make that clear in terms of their incentives. I think they should be more clear in the way that they guide the roundtable to say that it is not about how much you participate but it's also about how in context, how helpful your comments are," said Guo. He added, "You want to be a neutral adjudicator of this conversation. Keep your personal opinions, what you think is right or wrong, maybe out of this. I think some teachers do a really great job of this, other teachers not so much. I think during classes we still want to remain somewhat ideologically neutral to hear both sides of the story."

The discrepancy in behavior and participation from teachers is so commonly noted by SA students and raised as an issue that it is clear that it has become prevalent across the School A Campus. SA students affirmed that the best teachers strike a balance in participation. "I think they have a lot of effect on the discussion. I think there's a sweet spot of being able to guide the discussion in the right direction while also not yapping too much. But, if you have no teacher input at all, I think everybody can kind of just go off on a tangent, you know? And sometimes, the teacher needs to be able to spur the discussion back in. I think teacher input is very important," said Kovit.

Piron agreed, reflecting: "I think it's helpful at some points. Like I have a history teacher right now who interjects, but I feel like his interjections are more on the helpful side; it's not just like speaking because they want to speak. It's not like he's a student participating in the conversation." Teachers can and should participate in discussion, but at a distance and not in the same way a student would. Not arguing like a student, nor contributing as often.

The current state of roundtable instruction at School A is flawed. Many students noted a disparity between how teachers approached the class discussion and advocated for that difference to be minimized. In particular, the responsibility of teachers to effectively guide a discussion whilst not coming off as overbearing was highlighted as a key facet of faculty participation at the roundtable. Students proposed that some teachers simply must take more agency in the

discussion and put in more work to foster a healthy roundtable dynamic that platforms all students equally. Moreover, SA students pushed for teachers to remain impartial in their grading and in their real-time reactions at the roundtable. The power imbalance between a teacher and student is self-evident, and so instructors must remain aware of that when considering their presence in the discussion. Students noted feelings of anxiety and stress that were caused by teachers reacting obviously negatively to a comment, and frustration at the fact that a teachers' personal opinion can hold a lot of sway on how students are graded. A healthy roundtable requires confrontation in discussion, two guidelines that cannot be followed when students fear that disagreeing with their instructor may impact their grade and may lead to the teacher reacting in an overtly judgmental fashion.

Some Measures Implemented by a Faculty Member that Address Students' Wishes

Some faculty do effectively handle roundtable discussions. Many excel at the roundtable and implement specific measures to ensure that they meet students' needs and wishes. SA classrooms house instructors that all approach the roundtable pedagogy differently – not all are clearly good or bad at guiding a class discussion. Faculty member Freecss highlighted many practices and opinions that he implements, that sympathize with the issues students previously detailed. Addressing a point of Kovit's, that “giving people an easy way to sort of jump into the discussion I think is a very powerful thing, leveling the playing field,” Freecss stated: “I think we as teachers really have to work to ensure that there's equity at the table, which is to say we want students who are not as comfortable with speaking frequently in class to demonstrate their engagement in other kinds of ways through non-verbal things: body language, eye contact, all that stuff.” Assessing non-verbal metrics accounts for participation from less confident students, effectively “leveling the playing field” for them. This balances the class dynamic, allowing for a healthier discussion.

Freecss described another one of his practices implemented to foster the best roundtable environment possible. “I think one of the most helpful ways is just doing regular kind of check-ins, making roundtable diagrams to have students visualize what the conversation looks like. We make charts at the table, we draw arrows between the names to see who's speaking to whom, what kinds of responses they're articulating, are they posing questions, are they responding by name to each other? All that kind of stuff. I think doing that stuff at, at semi-regular intervals is very helpful.” Guo expressed a wish effectively asking for that degree of regular feedback, and practices by instructors – like the check-ins and visualizations described by Freecss – do address that frustration. The issue is, though, that not all SA instructors provide that degree of communication and feedback to their students.

At the end of the day, a teacher's role is nuanced and limited. As Freecss puts it, “there's only so much you can do, unfortunately. I mean, you know, you can't really force students to start speaking. So, it's kind of a tricky thing to navigate.” Some of his best tools are the aforementioned check-ins and feedback, but also include methods that apply to an entire class, beyond an individual. Theming classes by the specific facets of a discussion – such as questions,

use of names, etc. – is another such tactic of his. “Just drawing from all those different kinds of techniques I think is important. And if you need to slow down and narrow in your focus on one particular element of discussion sometimes it helps to sort of build from the ground up and increase the complexity of the conversation as you get more comfortable with each other,” he said

In terms of course design, Freeccs explained that teachers are largely free to choose course materials and come up with courses, just that those must be voted on in meetings by the entire department before being implemented. The only top-down authority, department chairs and academy administration, are contacted on a “need-to-know” basis, notified on exceptional matters. Freeccs further explained that there are few problems with the administration when ensuring a diverse pool of authors and material not just in background but also in form (novels, poetry, plays) for his courses.

STEM and the Humanities in the School A Curriculum

Addressing the third research question, students explained that there is a real difference in the STEM and humanities School A experience. On one hand, the roundtable can function for STEM courses: “I think it helps you fill the gaps in your knowledge. Like, if I don't understand this math problem, I'm able to listen to somebody else do it and I'll be like, ‘oh, okay, that makes sense.’ And they explain through their whole solution. I can see it on the board,” explained Kovit. However, a functional STEM roundtable requires more work and lecturing from teachers to establish a basic level of knowledge from which students can create discussions. “I find that roundtable math works really well when you already have some ideas of what you're learning previously. So for me, when I came into School A as a new upper, I was moved down in my math quite a lot compared to what I had done in my old school. But I think that actually really helped reinforce the fundamentals so, I guess that kind of works, but if you're going into something completely fresh, I feel like it can be a little challenging sometimes,” said Kovit.

However, when that basic level of knowledge isn't present, STEM courses suffer greatly under the roundtable. Piron complained, “with STEM classes at the roundtable, if nobody understands what's going on, it's kind of just like a dead zone. And it's really awkward. And it's kind of rough because obviously the teacher's supposed to encourage us to think about it, but at the same time, if just nobody understands that it gets really awkward and not fun. And it gets harder to understand the material if, this might also just be a personal thing, but if the teacher isn't like telling you what you need to know for math and science, then I think it gets a lot harder to understand the material.”

Mansouri echoed her description: “I think for math, unless you have a teacher that really knows how to utilize the roundtable it's incredibly difficult because usually it just ends up being where the teacher kind of sits in the corner while people aimlessly mill about, and you don't really learn anything and it's not really conducive to understanding the material.” Zhu offered a similar complaint to Mansouri. “I just feel like it's not delivering the information at a normal rate. I feel like at my previous schools, you move so much faster because the lecture style makes

more sense for math and I don't think it works.” She continued, “in STEM classes there’s a lot less leeway for students just teaching themselves.”

Roundtable math is complicated. Generally, classes consist of students putting up a homework problem on the board and presenting it to their peers. Where the experience differs classroom-by-classroom, though, is in the presence of teachers during the class. Some teachers will take a more active role, probing the class to discover another possible solution or to solve an issue with a student’s work collaboratively, while others may essentially transform the roundtable into a traditional lecture-based classroom where the instructor takes over in presenting a homework problem.

Overall, the roundtable method does not exist or function equally across subjects. As Guo explained, “in certain classes like STEM and language classes, I’ve found the roundtable not to be a real roundtable. It’s like semi-roundtable, so it’s not a super big deal. I do think the shift away from lectures is helpful in classes. Like Latin for me, that you’re mostly just learning by doing math doing the problems and in Latin just doing the translation. I think it’s more of a problem guided approach instead of a real roundtable approach, which I do like.”

Although the roundtable does hold its merits for STEM classrooms, allowing for greater use and reinforcement of the fundamentals as well as the formation of more connections between topics, those merits only take shape when all the students have the basic level of required knowledge. In STEM, students cannot interpret or discover information on their own like is possible in the humanities – generally, facts must be taught, and from facts students can make connections and begin to discuss. Without that foundation, students cannot effectively experience the pedagogy as it was intended – instead, teachers often transform the classroom into something more akin to a traditional lecture-based class wherein the instructors present and explain all the information, until students reach the foundations required to implement the roundtable. Consequently, SA students noted that they experienced a great disparity between their experience with the roundtable in STEM v. humanities courses, with the former suffering greatly.

Limitations

Some limitations of this project are that I did not conduct any interviews with students of SB, meaning I cannot compare the differences in how SB students v. SA students experience the curriculum with much certainty. I also cannot delve into the culture of SB in the same way that I could with School A and so must rely on assumptions and deductions from the SB article that I referenced when comparing the student experience. I referenced that one article because it was the only one that I found that held valuable information about SB students’ experiences with their curriculum and a discussion-based pedagogy. Because of this, I used the SB perspective mainly to raise the possible solution of devaluing participation grades – not as a perspective to launch a full comparison to or to discuss the student experience.

Another limitation is that I only managed to conduct one faculty interview, meaning I cannot generalize what teachers think about the roundtable method. However, I can generalize the fact that teachers at School A can approach the roundtable method in many ways, given the

used interviews. This generalization is, of course, also backed by the student interviews. I only managed to conduct one faculty interview because of scheduling issues, certain faculty denying or ignoring my interview request, and because I only gave faculty a ~one week time frame to respond to my interview request.

Conclusion

Behind School A's promise of "an intellectual curiosity that extends well beyond the School A experience, a love of learning that lasts a lifetime"¹¹ as a definite benefit of its absolute faith in the roundtable, the disappointing experiences previously detailed by SA students reveal the reality of the school's classrooms. With the pressure to speak that spawns from graded roundtable participation, and subsequent competition as students view speaking more as correlating with a higher grade, the roundtable is often suffocated amidst the fighting of students trying to get a word in over building a productive discussion. The self-doubt and anxiety that follows the possible label of "roundtable warrior", and the pressure of conforming to a class consensus to avoid judgement, also hamper School A's student learning in effectively covering their curriculum.

At SB, and other similar high schools that use traditional lecture-style teaching, experimental classes that use Socratic seminars akin to the roundtable do not face the same problem; actually, the issue arises of students not participating enough. Students face far fewer social pressures from labels like "roundtable warriors" and participation-consciousness given the fact that such ideas simply don't exist to the same extent in the culture of those schools. The fact that graded discussions are not normalized at SB ends up as a possible key differentiating factor for how SB students intake the curriculum differently from SA students. Given the possibility to learn in lecture-style classrooms where everything goes smoothly enough, as opposed to from the disjointed and often surface-level discussions at the roundtable, SB students may simply be intaking the curriculum with more certainty as to what information is important (the role of teachers in lecture-style classrooms, who explicitly state what must be known, compared to School A's teachers, who can often be stepped back from discussion and often fail to provide an effective "guide," is a potential cause for that difference). However, they may lack the depth and nuance in engagement with the material that can be afforded by the roundtable – those benefits, though, only arise in classes with good teachers and good dynamics, conditions that are inconsistent from classroom to classroom. To counteract the current issues plaguing the roundtable at School A – which when working, work brilliantly to enhance students' experience – individual-based graded participation is a suggestion offered by SB students. By taking everyone off the same standards, competition could naturally decline. However, at School A, that approach would likely not be enough to fix the roundtable's issues. Due to the current School A environment, wherein competition and grade-obsession pervade every sector of life, any pedagogy would likely share similar issues to the roundtable. To uphold School A's promises and

¹¹ "Academics." *School A*. Accessed 5 December 2024.

wishes for what benefits the roundtable could afford to SA students, addressing the actual culture of the school seems a more reasonable solution than altering the roundtable much.

There are some aspects of the roundtable that SA students do argue for fixing, that are detached from the environment of School A and can be addressed independently in the short-term. The inconsistency of teacher delivery and participation is one of those key issues of the roundtable that can be fixed. SA students argued for a more standardized approach to guiding a roundtable discussion and to projecting teacher opinions (both in grading and at the roundtable). Students were mixed, though, in the extent to which they wanted teachers to platform their personal opinions – but generally agreed that their personal opinions should not be factored into the grading system. Some students felt pressured to agree with opinions forwarded by their teachers, while others found those opinions to be interesting and valuable additions to roundtable discussion.

The faculty perspective affirmed that there is inconsistency in how teachers deliver their courses. Freeccs explained that instructors are afforded a large degree of freedom in designing their courses. How they man the roundtable is more-or-less up to them. Only suggestions for new courses and new reading material are passed through a department-wide vote.

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Using Generative AI to Improve Academic Engagement and Arithmetic Skills of Children

By Melina Michalopoulou

Abstract

This program aims to address the problem of lack of engagement of students in classrooms. Due to shortcomings in the structure of the lesson in schools, levels of engagement are low, leading to a low performance from students. This has consequences in the future, affecting their everyday life and career. This program's goal is to increase engagement levels by providing students with a fun and interactive way to practice arithmetic. This is achieved through a game that rewards students with points for their answers on different arithmetic questions. There are different difficulty levels and types of questions ranging from simple operations to geometry and word problems. By gaining points, students can increase their status and get rewards. To understand the effectiveness, students will take a baseline exam before and after using the program, and results will be compared with a control group, and they will also answer a questionnaire. The intended result is to see a greater increase in scores of students using the program than students using traditional means of practice, and a more positive attitude in the answers to the questionnaire. However, the testing of the game hasn't been completed yet, therefore the description of the testing method is only theoretical. By providing an engaging means of practice to students, the program aims to improve their attitude towards arithmetic practice and help increase levels of engagement in the lesson.

Keywords

Education; Generative AI; Arithmetic Skills; Academic Engagement; Learning Tools

Introduction

Education is a fundamental part of a person's life. It allows them to gain basic skills, understand the world around them, gain independence and find their way into society. It also allows students to get to know their preferences and inclinations to decide which path they want to follow in their life. Whichever sector they decide to follow, there is basic knowledge from all different subjects that a student will need in order to get through life successfully. Such knowledge is basic math, adequate language and communication skills, and an understanding of basic science rules.

In a standard classroom, education is provided with a teacher displaying the material followed by means of practice. While this is the norm, it may not be the most engaging for students. Since there are many students in the classroom, a teacher is unable to ensure that everyone is paying attention and understanding the material. In addition, the educational system is not catered towards the unique specifications of each student and assumes uniformity. Furthermore, the constraint of time may cause teachers to rush education. This shifts the focus from active engagement to an overload of information. As a result, students may feel

overwhelmed and find it difficult to follow. In a nationwide poll in the US, about 75% of students reported negative feelings about school, 69% of which were “boredom”[6]. In addition, students fail to see the meaning in learning, and just view it as pointless memorizing of facts and formulas. Therefore, they get bored in lessons and do not put in enough effort in order to actually gain something from the lesson[4].

Moreover, the way lessons are delivered contributes to the level of engagement of the students and their attitude towards it. When students are passive learners, their engagement with the material isn’t solidified. For example, listening to a history lecture forces the student to memorize facts, but acting out a scene from history allows the student to conceptualize the setting.

Whatever the reason may be, students often neglect the importance of their education and choose to spend their time on other things during class, especially if there is no external pressure from parents or guardians to do well in school. This situation leaves students struggling and failing in school and not knowing where to ask for help. As a result of the difficult material and the pressure on students, many students leave school without acquiring basic skills, which will be an obstacle in the future when they are trying to perform well on a job[3].

It has been proven that attention problems in school correlate with adult behavior problems and life quality[1]. For example, attention deficiencies in primary school correlate with difficulty in maintaining the expected level of performance in future work environments. In addition, this problem is visible in the reading level of US adults, where over half of American adults (54%) read below a sixth-grade level and almost 1 in 5 adults reads below a third-grade level, showing significant gaps in reading ability[5]. It is evident, therefore, that there is a crisis in the concentration of students that has long term detrimental effects to their overall performance in the future. To prevent future generations from facing the same long-term consequences, a solution to this crisis needs to be found.

In order to increase engagement, a study suggests decreasing the number of repetitive tasks in classes. Instead, tasks that capture the student’s attention and help them learn through engagement should be incorporated in lessons. Activities like drama and role play, music and word guessing encourage participation and foster friendly rivalry that help students learn[2].

Methodology

This project provides young students with an interactive and engaging way to practice simple arithmetic operations- a fundamental skill needed in every aspect of their life- that differs from traditional practice sheets. This way, practice won’t seem overwhelming and boring, and students will be intrigued to practice and learn. In this paper, I will outline a game that should have been tested on participants in a way that will be described later, but it hasn’t been tested yet.

There are many other existent games with the same purpose, such as Prodigy and Math playground. However, this project brings something fresh and new, as it rewards students with points for every question they get correct. With these points, students will be able to then buy rewards ranging from avatar accessories to new designs for the interface. Therefore, this will

keep them engaged as they will have a motivation to keep going. As they unlock new rewards and accessories, their status will be shared with their friends, and allow friendly competition to advance to new levels. This healthy competition will keep them in the game, and they will level up their math skills quickly.

Data Analysis

When playing the game, users are asked a series of questions where for each question the user has three tries to answer it. If correct on the first try they receive 3 points. If correct on the second one, they receive 2 points. If correct on the last try, they receive one point. If they are incorrect in all tries, they receive no points.

In the program there are three types of questions: word problems, arithmetic problems, and geometry problems. Upon running the code the user has the ability to select difficulties ranging from level 1 to 4. Level one has multiplication, addition, division, subtraction where each operation has an equal likelihood. Level two now has a new set of questions that we will call geometry questions. When the player selects level two each question will have an equal chance of being either arithmetic or geometry. Within geometry questions there include questions involving a square, a rectangle and triangle. Among each of those shapes the user is asked to find the area or the perimeter. Level three is similar to level two, but division is no longer in the form of remainders but now takes in decimals and fractions. Level four adds in a new set of questions which we will call word problems. When the user selects level four, the question coming up will have an equally likely chance to be either an arithmetic problem, a geometry problem or a word problem. Within the word problems, there are thirty different templates that involve realistic applications of arithmetic and geometry problems. Throughout this whole process, random numbers pertaining to each question will be generated as each question comes up. The figures below show the distribution of each question.

In the first level, the player has an equal 25% chance of getting a question with each arithmetical operation, addition, subtraction, multiplication, and division, as seen in figure 1. In levels two and three, there is a 50% chance of getting a question from either category. In the arithmetic questions, the player has a 12.5% chance for each operation. In the geometry questions, the player has a 33.3% chance for getting each shape. The chance of getting a perimeter, or area question for a specific shape is 8.3%. This probability distribution is illustrated by figures 2 and 3.

Lastly, in level four, there is an 8.3% chance of getting each operation, an 11% chance of getting each shape and a 5.5% chance of getting an area or perimeter question for each shape. Lastly, for the word problems, there is a 33% chance of getting one. The probability of getting each question type in level 4 is illustrated by figures 4 and 5.

While the user has some say in the types of questions that can come up, the back end of the code can be altered as well. For example, some parameters open to change include the number of questions the student will be asked, the number of templates available, the point distribution, and the range of the numbers that are used in each question,

Discussion

In order to determine whether the program increases engagement in classrooms, students will use the program and the results will be analyzed. The students would be divided into two groups: the experimental group and the control group. In order to attain accurate results, the students in the groups would have similar age distributions and have received the same type of education. In other words, the groups would seem identical.

First, the students would be split into groups randomly. Then to understand the students' baseline competency of arithmetic, they would take a baseline exam in the beginning of testing and their scores would be recorded. Then, the control group would continue to practice and be taught in the same way that students are taught now in schools. In comparison, the experimental group would be introduced to the program, and asked to practice using it.

After a few weeks, the students would take another exam, similar to the baseline one. In addition, the students would be asked to answer a questionnaire about their experience with practicing and their overall attitude towards their respective arithmetic practice. To determine whether the program is effective, we would compare the results of the final baseline exam to the initial baseline exam by conducting an ANCOVA test to see the change in their performance. Moreover, in order to understand if the program is entertaining and improves student's view of practice and studying, we would compare their answers to the questionnaire.

Depending on the results of the questionnaire and the baseline result differences, one can determine if the program presented does what it was intended to do. To understand whether the program meets its intended purpose, we would first compare the change in the baseline scores of the students in the two different groups. If the change in the scores of the students in the experimental group is greater than the change of the students in the control group, we would conclude that the program is effective and helps students improve their performance successfully. If the change in the scores of the students in the two groups is similar, we would conclude that the program does not help students more than the traditional means of practice, and it does not meet its goal. Lastly, if the change in the scores of the students in the experimental group is smaller than the students in the control group, we would conclude that the program is not effective and that it is actually less helpful than traditional means of practice.

In addition, to determine whether the program is engaging, we would compare the results of the questionnaire. If the attitude towards arithmetic practice and the overall experience of the students in the experimental group is rated more positively than the students in the control group, we would conclude that the program is engaging and improves students' view of arithmetic practice. If the attitude and experience of the students in the two groups is rated similarly, we would conclude that the program does not make a significant difference in the levels of engagement and it therefore does not meet its goal. Lastly, if the students in the experimental group rate their experience more negatively than the students in the control group, we would conclude that the program is not effective and it therefore decreases the level of engagement of students.

Conclusion

Overall, the program manages to address the issue, as it helps resolve the lack of engagement in classes as shown above. Students feel inclined to practice their math skills as they also entertain themselves while doing it.

In order to further understand its appeal and effectiveness, the program needs to actually get tested on students. However, due to time limitations, the game hasn't been tested, as it would be difficult to recruit participants that quickly and also go through with the whole testing procedure. After testing on students, through their level of improvement, we can understand whether the program actually contributes to learning and increases student's engagement with the lesson. In order to achieve more widespread use, an interface needs to be added to become more appealing aesthetically. Moreover, the program needs to be improved and new features need to be added, so the student can collect points and buy rewards. In the future, the goal is for this game to be recognized by young students and schools, in order to contribute significantly to the improvement of education.

Conflict of interests

The author declares that there are no conflicts of interests related to this work.

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Figures



Figure 1: Probability of getting an addition, subtraction, multiplication or division question in level 1



Figure 3: probability of getting each type of operation question, and each type of geometry problem in levels 2&3

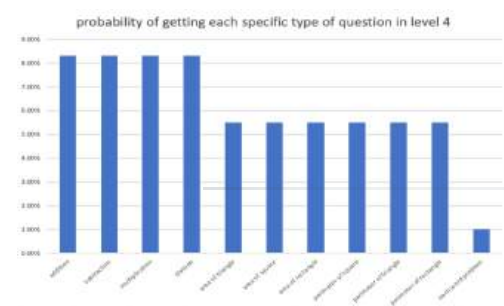


Figure 5: Probability of getting each type of operation question, each type of geometry problem and each different word problem in level 4.

Enemies of My Enemy: Hajj Amin al-Husseini and His Collaboration with the Nazis

By Jungbin Yoon

Introduction

On November 28th, 1941, in the halls of the Reich Chancellery in Berlin, sat two powerful figures forming an alliance that would echo through history.¹² On one side of the table sat Adolf Hitler, the Führer of Nazi Germany and the architect of the Nazi terror raging in Europe. Opposite to him sat Hajj Amin al-Husseini, the former Mufti of Jerusalem and a passionate Arab nationalist. This meeting extended far beyond diplomacy, but was rather the bridge formed between the Nazi rooted ideology of antisemitism and the extremist ideas of Arab nationalism. This alliance was a symbiotic relationship in which both parties benefited from each other. For al-Husseini, he viewed the Nazis as a major power backing their goal of a free Arab country. With a major European power, al-Husseini believed that the resources the Nazis could provide would serve instrumental purposes. The benefits of this alliance for the Nazis were to weaken their biggest enemy, the British, in a strategic region, the Middle East. As the Nazis launched their North African campaign in Libya and Egypt, having an ally to oppose the British was critical in their war effort. Mohammed Amin al-Husseini's collaboration with the Nazi party, rooted to assert Arab independence and resist Zionism, resulted in the promotion of widespread antisemitism in the Arab world with broadcasts and leaf pamphlets. It also helped transform Arab nationalism from a political movement to one defined by armed resistance aimed towards the Jews and the British. The alliance left a controversial legacy due to al-Husseini's inflammatory language in his statements, which continues to influence Arab unity against the state of Israel in the postwar period.

A Brief Biography of Hajj Amin al-Husseini, 1895-1974

Al-Husseini's long road towards Berlin and the Axis powers starts all the way back to the Ottoman Empire. The Husseini family was the ruling elite of the local Ottoman administration in Palestine.¹³ They held religious appointments, collected taxes, and held land in the region of Palestine.¹⁴ The family was also heavily involved in the empire's politics as "they led protests against the government."¹⁵ The family's involvement in politics continued. Following the demise of the Ottoman Empire, the Treaty of Versailles gave the British rights to the Mandate of Palestine.¹⁶ When the British took control of Jerusalem in 1917, "it was Salim al-Husayni, mayor of Jerusalem, the brother of al-Husseini, who handed the key of the city to General

¹²United States Holocaust Memorial Museum, "Hajj Amin al-Husayni Meets Hitler," *Holocaust Encyclopedia*, accessed April 20, 2025, <https://encyclopedia.ushmm.org/content/en/film/hajj-amin-al-husayni-meets-hitler>.

¹³Phillip Mattar. "The Mufti of Jerusalem and the Politics of Palestine." *Middle East Journal* 42, no. 2 (1988): 227–40. <http://www.jstor.org/stable/4327735>.

¹⁴ Ibid

¹⁵ Ibid

¹⁶ Merry E. Wiesner-Hanks, Patricia Buckley Ebrey, Roger B. Beck, Jerry Dávila, Clare Haru Crowston, and John P. McKay, *A History of World Societies*, vol. 2, Eleventh Edition (Boston, Massachusetts: Bedford/St. Martin's, 2018), 856–7.

Edmund Allenby.”¹⁷ This continued cooperation with the British enabled several members of the Husseini family to assume the role of Mufti of Jerusalem, an influential religious authority. In the case of Hajj Amin al-Husseini, it was no different, as in January of 1922, he was able to ascend to become the Grand Mufti, replacing his deceased half-brother.¹⁸ Despite the trust, the British commissioner emplaced onto al-Husseini by the summer of 1922, and he had already begun to oppose the British rule in Palestine.¹⁹ His involvement in Arab nationalism and anti-Zionism grew as the “Jewish immigration increased from 4,075 in 1931, to 9,553 in 1932, to 30,327 in 1933, to 42,359 in 1934, and to 61,854 in 1935.”²⁰ The true turning point in his political stance was when the British proposed a plan to partition Palestine in 1937.²¹ This triggered fear in many Palestinians, including the Mufti, as they believed that Jewish settlements and land ownership would ultimately displace the Arab people. Organized with the Arab Higher Committee, led by al-Husseini, the revolt began with strikes and escalated to armed rebellion. Following this, the British decided to strip al-Husseini of his political title and arrest him for his involvement in the violence ensuing the Arab revolt. This warrant pushed al-Husseini to continue his anti Zionist movement and Palestinian freedom movements to Lebanon. After his escape to Lebanon and Iraq, al-Husseini grew bitter and desperately needed a more powerful ally. With the Palestinians taking significant casualties in the revolt, al-Husseini was backed into a corner. At the same time, the tensions in Europe were rising. The fascist government in Germany under the leadership of Adolf Hitler grew into an imminent threat to the peace in Europe.

Hajj Amin al-Husseini’s Contribution to the Spread of Antisemitism

Al-Husseini served as the bridge between the Nazi ideology of antisemitism and extreme Arab nationalism. His collaboration with the Nazis served as a critical tool for propaganda by actively spreading antisemitic values in the Arab world. At the heart of the alliance was a deeper ideological alignment. Al-Husseini went beyond opposing the creation of the Jewish state. He adopted the racialized rhetoric of Nazi antisemitism and reframed Zionism as a global Jewish conspiracy theory. In Jeffrey Herf’s book regarding the Nazi propaganda in the Arab world, he develops the Nazi claims of a global Jewish enemy “The thesis of the Arab nationalists ... alleged control by ‘international Jewry’ over world finance.”²² This foundation of an enemy being “persistent and cunning”²³ is a narrative continuously expressed in al-Husseini’s memoirs. This vilification of the Jews created a common enemy that united Arab nationalists and Nazis. In al-Husseini’s memoir, he further expresses this point by stating, “It is fighting our common

¹⁷ Phillip Mattar. “The Mufti of Jerusalem and the Politics of Palestine.” *Middle East Journal* 42, no. 2 (1988): 227–40. <http://www.jstor.org/stable/4327735>.

¹⁸ Phillip Mattar. “The Mufti of Jerusalem and the Politics of Palestine.” *Middle East Journal* 42, no. 2 (1988): 227–40. <http://www.jstor.org/stable/4327735>.

¹⁹ Ibid

²⁰ Ibid

²¹ Ibid

²² HERF, JEFFREY. *Nazi Propaganda for the Arab World*. Yale University Press, 2009. <http://www.jstor.org/stable/j.ctt1npq5k>.

²³ Al-Husseini, Mohammad Amin. *Memoirs of Haj Amin al-Husseini*. Edited by Abdul Karim Al-Omar. Damascus: Arab Higher Committee for Palestine, 1999. (Translated by Author/GPT)

enemies—global Jewry and the colonial powers that oppress the Arabs. This, I said, is the strongest bond that unites us with you.”²⁴ The Nazi leadership strongly supported this rhetoric and echoed this ideological connection. In 2017, the National Library of Israel uncovered the telegram exchange between SS Commander Heinrich Himmler and al-Husseini. The telegram wrote, “The recognition of this enemy and our common struggle against him form the firm foundation of the natural alliance between National Socialist Greater Germany and the freedom-loving Muslims of the whole world.”²⁵ This reassuring statement made by one of most influential figures in Nazi politics affirmed the claims that Nazi leaders were not only willing to ally with the Arabs but were also eager to frame the alliance as a shared cause. Furthermore, with Hitler advocating for the “removal” of the proposed Jewish homeland in Palestine,²⁶ al-Husseini became further integrated into the Nazi cause.

Al-Husseini’s ideological alignment with the Nazis in their collaboration enabled him to spread antisemitic values to the Arab population. Through radio broadcasts, Radio Zeissen, and Nazis propaganda leaflets, al-Husseini sought to incite and fill the Arab people with fear of the Jewish people. His portrayal and depiction of the Jews as infidels and a religious enemy spoke to many Arabs. In one broadcast, al-Husseini repeated the allegation that “the Jews wished to wipe out the Arabs and Islam.”²⁷ He created the persona that the Jewish people were inherently destructive and expansive, and threatened their very safety. The Arab people, already enraged at the Balfour Declaration and false promises the British had made regarding their independence, adhered to these provocative words. These statements sought to strike deep resentment and fear among the Arab listeners. Al-Husseini’s messages became more and more inflammatory as he drew on Islamic history to justify the aggression and violence against the Jews. He referenced the Prophet Muhammad’s expulsion of Jewish tribes in the 7th century, stating,

“Muhammad drove the Jews completely out of the Arab countries,” he declared in one broadcast, “and in so doing, he gave us a great example.” He then called tolerance toward Jews “a stupid plan and a shameful crime against the fatherland,” concluding that “the only solution is the expulsion of all the Jews from all the Arab countries. This is the only remedy. It is what the Prophet did thirteen centuries ago.”²⁸

By aligning Islamic views to the Nazi rhetoric, al-Husseini tailored the genocide and deeply rooted antisemitism to the broader Arab audience. Through his broadcasts and leaflets, the

²⁴ Ibid

²⁵ Joel Fishman. “The Recent Discovery of Heinrich Himmler’s Telegram of November 2, 1943, the Anniversary of the Balfour Declaration, to Amin al-Husseini, Mufti of Jerusalem.” *Jewish Political Studies Review* 27, no. 3/4 (2016): 77–87. <http://www.jstor.org/stable/44510573>.

²⁶ United States Holocaust Memorial Museum, “Hajj Amin al-Husayni Meets Hitler,” *Holocaust Encyclopedia*, accessed April 20, 2025, <https://encyclopedia.ushmm.org/content/en/film/hajj-amin-al-husayni-meets-hitler>.

²⁷ Jeffrey Herf. “Haj Amin Al-Husseini, the Nazis and the Holocaust: The Origins, Nature and Aftereffects of Collaboration.” *Jewish Political Studies Review* 26, no. 3/4 (2014): 13–37. <http://www.jstor.org/stable/43922000>.

²⁸ Ibid

extremist values he advocated became normalized, creating a culture in which opposition to Zionism became inseparable from anti-Semitic Hatred. Despite the war ending in 1945 and al-Husseini's activism dying down, the ramifications of his broadcast echo today's world. His portrayal of the Jewish people has left a lasting imprint on Arab nationalists and their perception of the Jewish people.

Hajj Amin al-Husseini's Role in the Militarization of Arab Nationalism, 1939-1945

Al Husseini's collaboration with the Nazis extended far beyond ideological involvements. Their relationship quickly evolved into the militarization of Arab nationalism. We are shown a significant turnaround in the escalation of Arab nationalist violence, following al-Husseini's meeting with Hitler. The contents of the conversation truly reveal how it has impacted al-Husseini to militarize his people for their independence. According to a full German record of the meeting, Hitler declared that Germany stood for "uncompromising war against the Jews."²⁹ This was referring to the Jewish national homeland in Palestine. The war he referred to was framed as a "battle between National Socialism and the Jews,"³⁰ and he promised to give his full support to anyone who partook in this "war of survival or destruction."³¹ Hitler even went on to state that Germany would also then actively help each country, European and non-European, on their "Jewish question."³² This series of promises ideologically aligned with al-Husseini's antisemitic values and reinforced his goal of Arab freedom.

Following this meeting, al-Husseini quickly became a vital figure in the 1941 Golden Square coup in Iraq.³³ The coup was led by Rashid 'Ali al-Kailani, an anti-British nationalist, four high-ranking army officers named the "Golden Square, and al-Husseini. As al-Husseini was forced to seek refuge from the British government in Palestine, he became a forefront of anti-British activity in the Arab world.³⁴ Together with Iraqi politicians, they founded a pro-German government and eventually won the Iraqi Army's support and the administration's support.³⁵ This militant act of Arab nationalism believed that in an Axis victory in the war, they would receive complete independence.³⁶ However, the British military quickly intervened, and within weeks, they were able to launch a full-scale counteroffensive.³⁷ The collapse of the coup left a power vacuum, leading to the Farhud, a pogrom carried out against the Jewish population. The casualty toll rose to 150 to 180 Jews were killed, over 600 were injured, and Jewish homes

²⁹ David Kaiser. "What Hitler and the Grand Mufti Really Said in 1941," *TIME*, October 22, 2015, <https://time.com/4084301/hitler-grand-mufti-1941/>.

³⁰ Ibid

³¹ Ibid

³² Ibid

³³ Philip Mattar. "Amin Al-Husayni and Iraq's Quest for Independence, 1939-41." *Arab Studies Quarterly* 6, no. 4 (1984): 267-81. <http://www.jstor.org/stable/41857733>.

³⁴ United States Holocaust Memorial Museum. Accessed May 10, 2025. <https://encyclopedia.ushmm.org/content/en/article/the-farhud>.

³⁵ Ibid

³⁶ Ibid

³⁷ Ibid

and businesses were looted.³⁸ This event marked one of the first large-scale anti-Semitic acts of violence in the Second World War. It signaled the rapid and dangerous shift towards a militarized Arab freedom movement, encouraged and led by al-Husseini.

Al-Husseini's militarization was not restricted to his location; being forced to escape and seek refuge in Berlin, he continued his fight. He continued to actively coordinate with the German high command to be fully prepared for the Arab-Jewish conflict that would take place in Palestine. In his memoirs, he recalls, "While we were in Germany, we heard about Britain's announcement regarding the creation of this Jewish Legion... In response, we did everything we could to increase recruitment, training, and readiness for the battle we expected between the Arabs and Jews in Palestine once the war ended."³⁹ In his account he met several times with SS commander Heinrich Himmler and proposed to Hitler of the creation of the Arab Legion. Furthermore the German high command allegedly prepared a "large stockpile of excellent light weapons to commemorate the disastrous Balfour Declaration. They also agreed to help us with weapons for guerrilla warfare, which the Germans had perfected after their experiences in the Balkans and Russia."⁴⁰ These tailored weapons the Germans made for the Palestinian fighters further reassured al-Husseini's emboldened militarization. Although the German military presence and extent in the Middle East died after the North African Campaign fell through, it truly illustrates how intertwined al-Husseini was in the German military. Many of the promises the German high command made to al-Husseini were fulfilled. For example, Nazi authorities conducted training operations and had a graduating class of sixty young Arab men from a Nazi commando training course.⁴¹ Al-Husseini's efforts in recruiting for Arab freedom were restricted only to Palestine. He has a central role in negotiating the formation of armed units among Bosnian Muslims, stating: "A number of young Muslims from the provinces of Bosnia, Herzegovina, and Sandžak would be recruited to form military and public security forces... The military forces would be part of the SS."⁴² The Mufti did not directly lead this group. However, he was in charge of the recruitment and expansion of Muslim fighting groups backed by the Nazis. Many of these newly found forces members would take part alongside the Waffen-SS. Later, as the program grew, they quickly formed the 13th Waffen Mountain Division of the SS Handschar. The name itself held significance as Handzar was a fighting knife or scimitar carried by Ottoman policemen. This showed the bridge and fusion of Islamic culture. Furthermore, the division became the first non-Germanic Waffen-SS division, marking the new beginning in the alliance and the expansion of a multi-ethnic military force.⁴³ The Handschar Division was ultimately an active group working in the Middle East. It took part in war campaigns resulting in participation in civilian deaths, burning of towns, and anti-partisan operations in

³⁸ Ibid

³⁹ Al-Husseini. Mohammad Amin. *Memoirs of Haj Amin al-Husseini*. Edited by Abdul Karim Al-Omar. Damascus: Arab Higher Committee for Palestine, 1999. (Translated by Author/GPT)

⁴⁰ Ibid

⁴¹ Ibid

⁴² Ibid

⁴³ Ibid

Yugoslavia.⁴⁴ Although not all Bosnian Muslims supported al-Husseini and the SS, we are shown how far the Mufti was willing to militarize the Arab people. His participation in the recruitment and militarization of Arabs forever transformed Arab nationalism from a political movement to a militarized campaign.

Hajj Amin al-Husseini's Post-War Legacy and Impact

World War II ended in 1945; however, the ideological legacy of Hajj Amin al-Husseini has had an enduring impact on the Middle East. His wartime collaboration with the Axis powers not only signified one of the most controversial periods in Arab nationalism but also laid the foundation for the radical antisemitism that still pertains today. The Mufti's active involvement in broadcasting avenues such as the Radio Zeissen and the leaf pamphlets served to inflame anti-Semitic values in the Arab world. He tailored the antisemitic values adopted from the Nazi party. By combining Islamic values and fears with Nazi theories, he was able to cast a perspective of the Jewish people as not only the political enemy but also a threat to Arab society. Many have claimed that his broadcasting and propaganda have set the groundwork for the new and radical strain of Arab unity. One of the most outspoken historians is Eran Lerman, a deputy director for foreign policy and international affairs at the National Security Council in the Israeli Prime Minister's Office.⁴⁵ He argues that "the rehash, in the original Hamas Covenant, of Nazi tropes about vast Jewish conspiracies, in language that goes back to the days of Hitler as delivered by the Mufti of Jerusalem and his ilk from Berlin on 'Radio Zeissen' during World War II."⁴⁶ The Hamas Charter of 1988's accusation and persecution of the Jews echoes the rhetoric presented by al-Husseini in his broadcasts. Al-Husseini's incorporation of Nazi ideology and tailoring it to the Arab audience has had a long influence on Palestine. The contemporary relevance and impact of al-Husseini are truly accentuated by the political controversies that surround him. In 2015, the Israeli Prime Minister Benjamin Netanyahu claimed that the Mufti inspired the Holocaust. According to Netanyahu, "Hitler then asked: What should I do with them? and the mufti replied: Burn them."⁴⁷ This bold claim received immense public backlash as many historians and experts rejected the theory. [The German Chancellor Angela Merkel further reaffirmed that the responsibility of the Holocaust lies solely on the Nazi regime.⁴⁸] Despite Netanyahu's false interpretation of the Mufti, the present controversy shows the enduring legacy of al-Husseini in modern politics. For some, he is viewed as a nationalist hero who combated the colonial rule of the British. To some, he is considered a fascist sympathizer who partook in one of the darkest chapters of history. It is hard to choose a specific side on what his actions led to or what kind of person he is. However, by understanding the deep ideological alignment he had

⁴⁴ Ibid

⁴⁵ "אלוף משנה (בדימוס) ד"ר ערן לרמן: Colonel (Res.) Dr. Eran Lerman." *J/SS*, November 5, 2025. <https://jiss.org.il/en/author/eranlerman/>.

⁴⁶ Eran Lerman. "The New Hamas Policy Document: Same Old Same Old (Mostly)." Begin-Sadat Center for Strategic Studies, 2017. <http://www.jstor.org/stable/resrep04504>.

⁴⁷ "Anger at Netanyahu Claim Palestinian Grand Mufti Inspired Holocaust." *The Guardian*, October 21, 2015.

⁴⁸ Ibid

with the Nazis and the militarization of Arab nationalism enables us to gain an insight into the roots of the Arab-Israeli conflict. It takes us a step forward in understanding the tensions in the region and the steps to be taken.

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To Report or Not Report?: Teenage Girls' Tolerance of and Tendency to Report Sexual Harassment By Siying Li

Abstract

The issue of sexual harassment, particularly within Chinese culture, is exacerbated by cultural taboos and patriarchal social constructs that limit the discussion of sex. 68% of sexual harassment victims do not report their case due to their fear of retribution, both from their perpetrator and from the victim-blaming and slut-shaming tendencies of society (Mansour, et. al., 2021). This study aims to explore the effect of sexual shame— a product of anti-sex ideologies in China— on people's tendencies to report sexual harassment and their tolerance of it. 11 Chinese girls between the ages of 14 and 19 were interviewed, and three key themes were identified: 1). Differing perceptions in defining sexual harassment, 2). The fear of “slut shaming”, and 3). The biological framing of sexual topics. These exploratory findings reflect the inadequacy of China's sex education, a temporal lag between girls' cognitive awakening and behavioral responses, and sexual repression.

1. Literature Review

1.1 Traditional Gender Roles and Sexism

The acceptance, or tolerance of sexual harassment, exists partly due to the lingering effects of traditional gender roles. An assessment at Penn State University indicated a positive correlation between levels of masculinity and tolerance of sexual harassment, as well as a negative correlation between levels of femininity and tolerance of sexual harassment (Russell, 2004).

Downing & Roush (1985) have developed a model for the development of a feminist identity within women. This process is outlined with the following steps: 1) Passive acceptance of the patriarchal society, 2) Revelations as she experiences contradictions with the core values of such a society, 3) Embeddedness & Emanation, when she seeks affirmations from other women and understands the consequences of abiding by the patriarchal values, and 4) Synthesis & active commitment towards creating an egalitarian society. Importantly, as women enter the embeddedness/ emanation stage, they become less tolerant of sexual harassment than men. For example, “women are more likely than men to perceive instances of gender harassment and unwanted sexual attention as sexual harassment” (Angelone et al., 2009). Additionally, women who endorse more traditional sex-role attitudes are also more likely to ignore the harasser and “experience negative personal effects”. In contrast, those with non-traditional attitudes are more likely to be confrontational (Malovich & Stake, 1990). This implies that shifting attitudes towards sexual harassment occur in conjunction with the development of a feminist identity, and that the rise of feminism is inextricably associated with less tolerance for sexual harassment.

Awareness of sexual harassment has also extended beyond solely female victims. A study entitled *Several key issues in anti-sexual harassment/anti-sexual assault in China (universities)*

conducted samplings of the Chinese national population in 2000, 2006, 2010, and 2015. The results reveal that the proportion of the population experiencing sexual harassment is, respectively, 21.2%, 35.1%, 29.9%, and 22.5% for women and 26.4%, 36.6%, 34.4%, and 28.8% for men (Zhao & Wu 2018). The study identifies no significant gender differences for sexual harassment; rather, it attributes sexual harassment to the abuse of power.

1.2 Attitudes on Sex in Chinese Culture

A professor at the Institute for Sexological research, Pan Suiming, has proposed that “socialist sexual morality” in the older generation is constructed based on four principals: “sex should be confined to marriage; men should be assertive and women should be passive; sex is not to be mentioned in public; and the purpose of sex is to produce the next generation” (Cited by Sigely & Jefferies, 2019).

This stems from the Chinese Qing Dynasty (1644-1911), which strictly adhered to the ideologies of Neo-Confucianism that emphasized values such as “obedience to authority, loyalty to superiors, and chastity for women” (Ng, 1987). Authoritative figures viewed sexual desire and relationships as a threat to familial relationships as the primary bond. Consequently, they feared that weakened family authority, a key construct of Chinese rulership, would erode the emperor’s authority (Yu et al., 2022). From there, the Qing dynasty developed what historian Vivien Ng described as the “state-sponsored cult of chastity”. The state operated under the notion that “It is a small matter to starve to death, but a serious matter to lose one's virtue”, which resulted in victims of sexual assault resorting to suicide to restore the reputation of her and her family (Ng, 1987). The high value of chastity is exhibited in the 1646 rape law, which outlines that if the victim of rape ceases to resist throughout the process, she is enjoying it. Thus, she will be considered a fornicator and be liable to 90 blows if she was married and 80 blows if she was unmarried. The perpetrator, in this case, will not be punished. This led to the emergence of victim-blaming and taboos regarding sex in Chinese culture, which extends to our Chinese society today. Today, the term “sexual shame” is defined as: “a feeling of disgust or humiliation towards one’s own identity as a sexual being and is composed of three factors: (1) relationship sexual shame, (2) internalized sexual shame, and (3) sexual inferiority” (Sævik et. al., 2023).

In recent years, however, China has undergone a sexual revolution (Buckley, 2016). This outlines various trends in the age of puberty, masturbation, first sex, first marriage, the prevalence of premarital sex, pornography, commercial sex, and concurrent sex; they are indicative of a shift in sexual attitudes from “sex for procreation” to “sex for pleasure” (Sigely & Jefferies, 2019). The New Culture movement (1915-1923), the May Fourth movement (1919), as well as the western concept of individualism, have weakened the Chinese emphasis on family lineage (*chuan zong jie dai*), and arranged marriages (Yu et al., 2022). Furthermore, the implementation of the One Child Policy (1980-2015) suggests that procreation is not the only purpose of sex; rather, sexual pleasure is a vital component as well (Pan, 2019). After all, couples can not just stop engaging in sexual activities after their first child. The government’s campaigns for family planning and the accessibility of contraceptives reinforced this notion. It

provides women with more autonomy over their sex lives, which was in conjunction with the rise of feminism in China. Furthermore, the term for unmarried cohabitation was changed from “illegal cohabitation” to “non-marital cohabitation” under the 2001 Revised Marriage Law of the PRC. This no longer associates unmarried cohabitation with immorality and therefore encourages more liberal attitudes on sex (Yu et al., 2022).

Despite the anti-commercial sex industry campaign (*sao huang da fei*), the commercial sex industry flourished in the patriarchal Chinese society in the process of transitioning to liberal attitudes. Specifically, chastity was expected for women, yet men’s pursuit of multiple sexual partners was accepted. This resulted in men’s high demand for sex, yet few women offered non-marital sex, causing a high demand for female commercial sex workers. Among men aged between 18 to 40, 11% of them reported having engaged in commercial sex in 2000, and this number rose to 22.3% in 2015 (Pan, 2017).

2. Methodology

2.1 Data Collection

This study aims to investigate the effect of sexual shame (namely, cultural taboos surrounding sex) on sexual harassment victims. It is intuitive to hypothesize that higher levels of sexual shame would correlate with more tolerance of sexual harassment, which can be exhibited in one’s inability to identify sexual harassment, as well as a lower tendency to report it.

To investigate this, eleven teenage girls aged 14 to 19 from varying parts of China were interviewed. They were recruited voluntarily via a snowball sampling approach, and consent forms were issued and signed by their legal guardians for safeguarding purposes. All data collected will not be used for other purposes than for this research essay.

The interview involved a series of quantitative questions surrounding sexual shame, requiring the participants to provide a numerical rating (eg, On a scale of 1-10, how comfortable would you be admitting to your friends of having a sexual desire?). These numerical results were added up to determine the extent of their sexual shame. Additionally, interviewees were given a list of scenarios, to which they had to decide whether or not they would consider it sexual harassment. Examples include: “Your male gym instructor touches you in your hips in a way that is slightly unnecessary for solely training, but his intentions are unclear.” This was complemented with open-ended questions, like their personal definitions of the term “sexual harassment”, anecdotes on the means through which they first learned about sex, as well as hiding menstrual products.

Moreover, two surveys were conducted:

1. The sexual harassment reporting attitudes scale (SHRAS)

This assesses an individual’s tendency to report sexual harassment, reflecting perceived futility and fears of retribution surrounding sexual harassment. Respondents select their degree of agreement on a 5-point scale (from strongly disagree to strongly agree), which reflects varying

perceptions on sexual harassment (eg, People should not be afraid to report sexual harassment in their places of work.), the conception that sexual harassment is normalized (eg, Reporting workplace sexual harassment creates new problems for everyone.), as well as pessimistic attitudes towards the fixing of the issue (eg, All things considered, reporting workplace sexual harassment is a waste of time.). Higher scores on the SHRAS were an indication of a higher tendency to report sexual harassment and a more victim-centric perception of it, and vice versa.

2. The sexual harassment attitude scale (SHAS).

This assesses respondents' attitudes on sexual harassment, using a 5-point scale measuring the respondents' degree of agreement. The scale items reflect varying degrees of feminism (eg, An attractive woman has to expect sexual advances and should learn how to handle them.) as well as attitudes on the severity of sexual harassment (eg, A lot of what people call sexual harassment is just normal flirtation between men and women). 13 items from the scale that best match the context of my research were selected. Higher scores are indicative of more feminist and less tolerant attitudes towards sexual harassment.

It is worth noting that the two scales were both translated into Mandarin to suit the linguistic backgrounds of the participants.

2.2 Analysis methodology

Analysis of the qualitative data was done by following the principles of thematic analysis outlined by Braun and Clark (2015), specifically a theoretical thematic analysis. This is a flexible process involving identifying themes and patterns within the interview transcripts that consists of a 6-step framework: familiarization with data, generating initial codes, searching for themes, reviewing themes, defining themes, and writing up (Maguire & Delahunt, 2017).

Firstly, interview recordings were converted into transcripts verbatim. Significant pieces of data that are relevant to the research were highlighted and coded manually, which allowed for the systematic identification of patterns. Next, these patterns were developed into more categorical themes and reviewed with reference to the initial coding. Finally, potential quotations were selected and translated into English for the writing-up phase.

These codes were paired with the respective respondents' survey results for further statistical analysis, particularly looking at whether or not interviewees who had mentioned certain codes had higher or lower mean survey scores.

3. Results

3.1 Thematic analysis of qualitative data

After a review of the interview transcripts, 3 major themes were identified. Firstly, differing perceptions in defining sexual harassment, as in the deviations of the interviewees' definitions of sexual harassment in terms of whether it's based on the intent of the harasser, or the subjective experience of the victim. Secondly, the fear of "slut shaming". Thirdly, the biological

framing of sexual topics – the phenomenon in which the stigmatization of sex is reduced when it is discussed from a scientific standpoint as opposed to a social one.

3.1.1 Differing perceptions in defining sexual harassment

Several interviewees defined “sexual harassment” from a victim-centric perspective, that is, the criteria of whether or not an action is considered sexual harassment is dependent upon the victims’ experiences rather than the harasser’s intentions. For example,

“Actions or jokes that make females physically uncomfortable.” – Interviewee 5

“If he [didn’t make derogatory comments directly towards me], then I don’t think it is considered sexual harassment.” – Interviewee 7

However, other interviewees framed the term “sexual harassment” around the intent of the harassers, as in the following:

“There must also be some malevolence on the part of the perpetrator; unintentional malevolence is also malevolence” – Interviewee 4

“[Making derogatory comments] is already considered sexual harassment [even if they didn’t say it to me]” – Interviewee 11

3.1.2 The fear of “slut shaming”

All interviewees unanimously said that they were uncomfortable with being perceived as “sexually active”. For example,

“As for myself, though I don’t think [being] sexually active is a problem, I know what it usually means in others’, especially elders’, opinion. Many people think that [being] sexually active is equal to being a slut.” – Interviewee 2

However, others specified that they are more uncomfortable being perceived as a sexually active person with multiple partners. Otherwise, sexual activity is not a problem.

“If it’s with a constant partner, then I don’t mind. But if they think I’m sexually involved with just anyone, then I can’t accept that.” – Interviewee 9

Furthermore, curiosity towards sexual topics is suppressed by this said stigmatization, particularly at youthful stages when sex education is insufficient.

“There is no doubt that my parents will be too curious about why I ask this question. Then I think it is possible for them to believe that I want to do something incorrect.” – Interviewee 2

“It seems [that] most people I know believe that as a 17-year-old girl, you are too young to talk about this.” – Interviewee 8

“I don’t think sex[ual] desire is embarrassing, but I do not want to be seen as a different person so I won’t try to talk about it.” – Interviewee 11

Others reflect that this stigmatization is dependent on the Asian social hierarchy, in which the stigmatization reduces in severity with people of equal social standing as them.

“I’ve discussed this a little bit with my classmates, but I’ve never asked those who are older than me or have a higher social status than me about it [sex].” – Interviewee 10

“With friends who are very close to me, there’s nothing too restrained. Like, my best friend sends me porn.” – Interviewee 1

3.1.3 The biological framing of sexual topics

Interviewees have reflected on how sexual topics are more approachable when it’s discussed from a biological perspective that solely focuses on science.

“Like in biology textbooks, we only talk about procreation and evolution, which is okay. But once we discuss sexual desire and pleasure, it feels so unspeakable.” – Interviewee 3

This is further seen in how taboos surrounding menstruation are less prominent than those of sex, as menstruation is involuntary, absent of desire, and more “biological”.

“Sexual desire and menstruation are still two different things, I guess. Menstruation feels more like a normal, biological phenomenon. But sexual desire is overly privatized by public opinion and what we’ve learned.” – Interviewee 5

“In fact, topics related to sex, including matters in that area, might not have been discussed. However, regarding menstruation, I actually discuss it quite a lot with my mother.” – Interviewee 6

“I think that when it comes to menstruation, how should I put it? Although it’s just as normal as sex, there’s a subtle perception that menstruation is considered more commonplace than sex...And I feel like sex might be associated with more stereotypes,

where if someone has a more active sex life, people might think, oh, they're a dirty person" – Interviewee 11

3.2 Survey analysis

Table 1: Data results

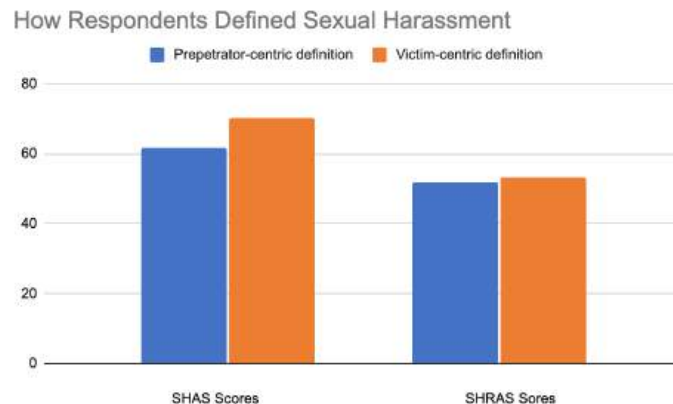
	Sexual shame (from interview)	SHAS	SHRAS
Maximum value	36.50	78.00	57.00
Minimum value	21.00	57.00	47.00
Mean	26.79	63.71	52.71
Standard deviation	6.20	6.90	4.03

Table 1 displays survey results derived from this study. To explore the implications of the data, two qualitative codes were developed by using the themes identified in the interview responses:

- 1). Defining sexual harassment from a victim-centric perspective.
- 2). Mentions their fear of slut-shaming.

These codes were matched with their SHAS and SHRAS scores for further comparative analysis of whether the presence of qualitative themes corresponded with measurable differences in the quantitative results. For example, figure 1 categorizes the participants' survey scores by the way in which they defined sexual harassment during their interview.

Fig. 1



As shown, respondents that defined the term “sexual harassment” from a victim-centric definition had higher SHAS and SHRAS, indicating less tolerance of sexual harassment and a higher tendency to report it. Although the data (n=11) is not statistically significant according to

the T-Test, this difference suggests that re-defining sexual harassment by focusing on the victim can reshape our perceptions towards it, ultimately developing a stronger feminist identity and a lower tolerance for sexual harassment.

Moreover, Figure 2 displays the respondents' score by the second code: Mentions their fear of slut-shaming. As shown, respondents who do not mention their fear of slut-shaming have higher reporting tendencies. These data points to the impact of victim blaming in sexual harassment cases. According to JACC reports, victim blaming attitudes, including slut-shaming, can discourage the victim from reporting the case of sexual harassment, despite being intolerant of it (Mansour et. al., 2021).

Fig. 2



4. Discussion

There are various implications of these findings, particularly in the patriarchal and sexually repressed Chinese society. However, due to the limited sample size and scope, findings are exploratory.

4.1 Inadequacy of Sex Education

The lack of a standardized definition for “sexual harassment” reflects the inadequacy of sex education in China, both within school settings and at home. This could be attributed to the following reasons.

Firstly, the sex education program has been inconsistently implemented due to the fluctuations of Chinese politics. For example, China shifts its natal policies from being anti-natal (the One Child policy) to pro-natal (Three child policy). In response, universities have been implementing “love education”, a course tailored towards increasing the fertility rate by fostering a “childbearing cultural atmosphere” (Palmer, 2024). Moreover, LGBTQ+ related content was censored in sex education textbooks due to the government’s homophobic policies (Zhou et. al., 2024). These changing policies obscure the implementation of a systematic sex education program that is consistently providing the same information to adolescents.

Secondly, China’s education is extremely exam-oriented, and subjects that are excluded from the national exams (*zhongkao* and *gaokao*), will be overshadowed and even replaced by

examined subjects like Maths and English. According to China's *Guidelines for Health Education in Primary and Secondary Schools* published in 2008, schools should allocate 6 to 7 sex education lessons per semester, but this number "can be flexible" (Disappearing Sex Education, 2023).

Altogether, the lack of sex education fails to inform teenagers of sexual harassment and the precise ways in which it should be defined, that is, from the victim's perspective. Consequently, 63.42% of Chinese teenagers obtain sexual knowledge from porn, an illegal and therefore unregulated market in China. This wrongly frames their perceptions of sexual harassment, and may even normalize sexual harassment or unconsensual sex.

4.2 Temporal Lag Between Cognitive "Awakening" and Behavioral Response

There is a discrepancy between teenage girls' cognitive acknowledgement of sexual harassment and their behavioral responses in practice. For example, despite understanding that sexual activity does not equate to immorality, girls still feel uncomfortable with being labeled as "sexually active". This reflects a temporal lag between cognitive awakening and the active resistance against the stigmatizing values held against sex. This gap is sustained by one's fear of retribution for actively discussing sex, which outweighs the mental discomfort of conforming to harmful social norms. Furthermore, this discrepancy extends to the reporting of sexual harassment cases. A study conducted with oncologists shows that 68% of sexual harassment victims do not report their case due to their fear of "retaliatory behavior", and out of those who did report, 52% did experience said retaliation (Graff et. al., 2022). Hence, further institutionalized support is crucially needed to create a safe space for sexual harassment victims. This phenomenon could be attributed to the coexistence of conservative culture and sexual liberalization. China's sexual revolution, in which the purpose of sex has transformed from procreation to pleasure, has occurred recently, liberalizing discussions of sex and eroding traditional taboos (Buckley, 2016). However, this revolution occurs predominantly among young people— A study shows that attitudes towards premarital sex, extramarital sex, and homosexuality are more conservative for people of elder age (Liu and Yang, 2024). Therefore, in a society where filial piety is pivotal and social respect increases with age, the younger generations' cognitive awakening could be silenced due to the persisting taboos among their parents and grandparents. Consequently, this awakening largely remains internal, with young girls' actions still predominantly following more conservative traditions, namely, not speaking about sex publicly, no promiscuity, and no homosexuality.

4.3 Sexual Repression

The repression of desire is a key aspect of sexual taboos. The dominant Confucian ideology in China emphasizes conscious control over individual biological desires and frames it as a critical component of "self-cultivation" (Hu, 2017). Hence, whilst the sex revolution in China has liberalized the discussion of sexually transmitted disease and pregnancy, this is often done from a public health, or broadly speaking, scientific standpoint that overlooks sexual desire.

Chinese sex education and related campaigns tackle the issue with similar approaches. The discussion of sexual desire and pleasure is still largely discouraged, cultivating sexual repression and ignorance to the innate desire for pleasure. However, this repression has not ceased sexual activity; rather, their obscured sexual needs are being exhibited through commercial sex and sexual harassment. Reports from post-cultural revolution indicate that groups of young men and women would group together for non-committal sexual activities in public spaces in highly urbanized cities like Shanghai (Hu, 2017). Moreover, a report from Zibo city's mental health center attributes sexual harassment tendencies to men's sexual repression and states that there is a positive correlation between sexual harassment and the frequency of their engagement in sexual conversations, often in derogatory or sexist ways.

5. Evaluation

A major limitation of this study is its limited sample size ($n=11$). Consequently, no statistically significant differences were established between survey scores with respect to the themes that were mentioned in the participants' interviews.

Moreover, the recruitment of seed participants was done via online platforms, in which the recruitment information is being delivered on users' feeds. Therefore, this system relies on the algorithm, which may be biased towards users who have initially demonstrated interest towards research on sex. Considering that sex is such a taboo, the participants could potentially be more open and liberal towards it than the nation's average.

6. Conclusion

This study aimed to explore the effect of sexual shame and cultural taboos on the tendencies to report sexual harassment, as well as girls' perception of sexual harassment cases in general. Through 11 interviews, three themes were identified: differing perceptions in defining sexual harassment, the fear of "slut shaming", and the biological framing of sexual topics. These themes point to the further exploration of China's sex education, the temporal lag between cognitive awakenings and active resistance against cultural taboos, and sexual repression. Although these findings remain exploratory, they highlight potential avenues for further research on how cultural taboos continue to shape young women's experiences.

The data suggest that cultural taboos around sex may discourage tendencies to report sexual harassment and influence young girls' perceptions of sexual activity. Whilst these correlations weren't proven from a statistical standpoint, these findings reflect the need of institutionalized support for sexual harassment victims focusing on their fear of retribution, as well as sex education programs that establishes a standardized definition of sexual harassment and that does not solely focus on scientific aspects of sex.

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Composite Thermal Insulation Materials from Secondary Raw Resources: A Global Review with Perspectives for Kazakhstan By Akhmetzhanov Sultanbeybars

Abstract

The development of thermal insulation materials is a central priority in sustainable construction, as the building sector accounts for nearly 40 percent of global energy use and over one-third of greenhouse gas emissions. Conventional insulation materials such as mineral wool and polyurethane foams provide effective thermal resistance but are associated with high embodied energy, limited recyclability, and negative environmental impacts. This review synthesizes research on the use of secondary raw resources (including recycled plastics, industrial by-products, and agricultural residues) in the fabrication of composite thermal insulation materials. Studies from Europe, Asia, and North America reveal promising results in terms of thermal conductivity, structural stability, and environmental performance. By drawing on recent findings, the paper examines current trends, challenges, and future directions in the field, while briefly connecting to Kazakhstan, where significant potential exists for incorporating industrial and agricultural waste into sustainable insulation materials.

1. Introduction

Buildings are responsible for a substantial share of global energy consumption due to heating and cooling requirements. Improving thermal insulation performance is among the most effective methods for reducing energy demand, lowering operating costs, and mitigating climate change. Insulation materials act as barriers to heat transfer, and their effectiveness is commonly measured through thermal conductivity values, compressive strength, and fire resistance. Conventional materials such as expanded polystyrene (EPS), mineral wool, and polyurethane foams dominate the market, yet their environmental footprint is increasingly scrutinized. Their production often requires virgin raw materials and significant amounts of energy, and their disposal at the end of the lifecycle contributes to landfill accumulation. In response, researchers have turned to secondary raw resources, which include recycled polymers, industrial waste like fly ash and slag, and agricultural by-products such as rice husk ash or hemp fibers. The aim of this review is to provide a comprehensive overview of research on composite thermal insulation materials based on secondary resources. It discusses the types of resources used, their performance characteristics, advantages and limitations, and the future trajectory of this field.

2. Literature Review

2.1 Secondary Raw Resources in Insulation Materials

Secondary resources are derived from waste streams and repurposed to reduce dependence on virgin raw materials. Recycled plastics such as polyethylene and polypropylene have been widely studied as polymer matrices for insulation composites. When combined with

fillers like ash or cellulose fibers, these composites achieve both reduced density and improved thermal resistance.

Industrial by-products such as fly ash, silica fume, and blast furnace slag are also of interest due to their high content of oxides that improve fire resistance and durability. In agricultural contexts, rice husk ash and flax fibers provide lightweight filler materials with favorable thermal properties. Studies in Europe have demonstrated that cellulose-based insulation from recycled paper achieves thermal conductivity values as low as 0.04 W/mK, making it competitive with traditional insulation products.

2.2 Thermal Conductivity Performance

Thermal conductivity is the key performance indicator for insulation materials because it directly measures the ability of a material to resist heat transfer. For conventional foams, values typically range between 0.03 and 0.04 W/mK. Many experimental studies have confirmed that composites with 20 to 30 percent recycled filler content can reach comparable values. For example, Li et al. (2020) reported thermal conductivities of 0.038 W/mK in composites containing recycled polyethylene and rice husk ash, while maintaining adequate mechanical performance.

Beyond laboratory experiments, large-scale pilot projects also confirm the feasibility of these materials. A Finnish study incorporating recycled cellulose fibers into wall insulation demonstrated not only effective thermal conductivity but also improved moisture regulation, which is critical in cold climates. Similarly, composites tested in India using rice husk ash achieved thermal conductivity values competitive with EPS, suggesting that agricultural waste has broad applicability across different geographic regions.

Another important consideration is the stability of thermal performance over time. While many conventional foams degrade under exposure to UV or moisture, composites with natural fibers tend to maintain thermal efficiency due to their inherent structure. However, durability challenges such as fungal resistance or water absorption require further modification, often through chemical treatments or hybrid blends with polymers.

2.3 Mechanical Strength and Durability

Mechanical strength is essential for insulation materials, particularly in applications where they serve as structural components. Excessive filler content may compromise strength, yet moderate levels of secondary raw resources tend to improve durability. Research from Finland and Germany has shown that adding 15 to 20 percent fly ash to polymer composites enhances compressive strength without significantly increasing thermal conductivity. These findings suggest that optimal formulations must balance filler content to achieve both insulation efficiency and structural reliability.

Other studies highlight the role of agricultural residues in influencing mechanical properties. For instance, flax fiber reinforcement has been shown to enhance tensile strength, allowing insulation boards to maintain shape and resist cracking under load. Rice husk ash

composites have similarly demonstrated improved fire resistance while maintaining adequate compressive strength for non-load-bearing wall systems.

Durability also encompasses long-term stability under environmental stresses such as humidity, freeze-thaw cycles, and exposure to UV light. Conventional foams often lose performance over time, while composites with secondary raw materials show varied outcomes. Some cellulose-based insulation products exhibit higher susceptibility to moisture unless treated with hydrophobic agents. Conversely, composites using industrial by-products like slag or fly ash tend to resist thermal cycling more effectively, providing longevity benefits.

2.4 Environmental and Economic Benefits

Lifecycle assessments (LCA) consistently confirm that using recycled inputs significantly reduces embodied carbon while diverting waste from landfills. UNEP (2019) reports that construction materials made from industrial and agricultural waste can cut carbon emissions by 20 to 40 percent compared to conventional alternatives. Composites that replace cementitious binders with rice husk ash or fly ash reduce reliance on high-emission cement production, offering major environmental benefits.

Economic feasibility is another major advantage. Since many waste resources have little to no market value, their use in composites reduces raw material costs. Studies in Europe and Asia indicate production cost reductions of 15 to 25 percent compared to traditional foams. For example, recycled polyethylene composites require less energy in production than virgin polymer foams, resulting in cost savings in both materials and processing.

The social and economic impact extends beyond cost savings. Agricultural waste composites create rural economic opportunities by monetizing residues that would otherwise be discarded or burned. Industrial by-product utilization also reduces landfill costs and aligns with waste management regulations in many countries. Together, these benefits demonstrate that composite insulation materials based on secondary resources are not only environmentally sound but also economically advantageous.

3. Methodology of Review

This paper is based on an extensive literature review of peer-reviewed journal articles, technical reports, and international energy agency publications. Sources were drawn from databases including ScienceDirect, Scopus, and Google Scholar, focusing on studies published between 2010 and 2023. Keywords included “composite insulation,” “secondary raw resources,” “recycled polymers,” “fly ash insulation,” and “agricultural waste composites.”

The review emphasizes comparative analysis of thermal conductivity, compressive strength, lifecycle assessments, and production costs across multiple studies. Regional perspectives were considered, with examples drawn from Europe, Asia, and North America. While Kazakhstan-specific studies are limited, the review identifies opportunities for applying global insights to local contexts.

4. Results from Previous Research

4.1 Thermal Insulation Properties

A synthesis of studies reveals that composites using recycled polymers and agricultural fillers consistently achieve thermal conductivities between 0.035 and 0.045 W/mK. For example, cellulose-based insulation produced from recycled paper in Germany has values around 0.04 W/mK, while rice husk ash composites in India and China demonstrate similar performance. These results indicate that secondary resource composites are viable competitors to mineral wool and EPS foams.

Beyond raw measurements, the performance of these composites in real construction applications is promising. Pilot buildings insulated with recycled composites in Scandinavia demonstrated 10 to 15 percent lower energy consumption for heating compared to buildings insulated with conventional materials. This suggests that in addition to laboratory tests, real-world use confirms the effectiveness of these materials.

Another factor is the adaptability of composites to regional climates. Studies from colder regions such as Finland emphasize the moisture-handling properties of cellulose-based insulation, which prevents condensation. Conversely, research in tropical climates shows that agricultural residue composites can regulate indoor temperatures by buffering heat transfer. These diverse findings highlight the versatility of secondary resource composites across climates.

4.2 Mechanical Strength Outcomes

Mechanical strength varies widely depending on the filler type and percentage. Research confirms that composites with moderate filler content, usually between 15 and 25 percent, maintain compressive strength sufficient for insulation boards. For instance, fly ash composites with 20 percent content achieved compressive strengths of 180 kPa, while those with 40 percent filler dropped below 100 kPa, making them unsuitable for structural applications.

Several studies also demonstrate that agricultural fibers can increase flexural and tensile strength, enhancing the versatility of composites in construction. Hemp fiber-reinforced composites used in wall panels not only improved insulation but also provided impact resistance. Similarly, flax fibers combined with polymer matrices produced lightweight but durable boards. Durability under long-term stress is still a concern. Freeze-thaw cycle testing in Canada revealed that some cellulose-based insulation degraded after repeated exposure, while polymer-based composites retained performance. This suggests that while mechanical outcomes are encouraging, long-term resilience must be validated through additional standardized testing.

4.3 Environmental Performance

The environmental benefits of composites based on secondary raw materials are substantial. Studies show consistent reductions in embodied carbon compared to conventional insulation. Pacheco-Torgal (2011) estimated carbon reductions of 30 percent when substituting

rice husk ash for cementitious binders. Fly ash composites similarly achieved significant reductions in emissions due to avoided clinker production in cement manufacturing. Further environmental benefits include waste diversion and resource efficiency. Agricultural residues like rice husks and bagasse are often burned, contributing to air pollution. Repurposing them in composites reduces harmful emissions and creates circular value chains. Industrial by-products like blast furnace slag, which are typically disposed of in landfills, can be reintegrated into useful products.

Water consumption is another important metric. Research shows that recycled composites generally require less water in processing than traditional foams or cement-based materials, further contributing to sustainability goals. This makes them particularly attractive in water-scarce regions.

4.4 Economic Feasibility

Economic studies consistently emphasize the cost-effectiveness of using secondary raw resources. Production cost reductions of 15 to 25 percent are reported across multiple projects, largely due to reduced raw material expenses. For example, recycled polyethylene composites cost significantly less to produce than virgin foam insulation, while offering comparable thermal properties.

Beyond production costs, composites create new economic opportunities in both rural and industrial sectors. Agricultural waste utilization provides farmers with new income streams for by-products, while industrial waste repurposing reduces disposal costs. These benefits align with circular economy principles that create value from waste.

At the macroeconomic level, governments can reduce public spending on waste management and landfill operations by incentivizing recycled composite production. Countries with strong sustainability policies, such as Germany and the Netherlands, have already established industrial symbiosis networks that support material reuse. Similar approaches could be expanded globally to strengthen the business case for recycled insulation composites.

5. Discussion

The review demonstrates that composite insulation materials based on secondary raw resources represent a sustainable and technically viable alternative to traditional products. The thermal and mechanical performances achieved in multiple studies show that these composites meet or exceed industry standards. The most significant added value, however, lies in their environmental and economic advantages.

Future research should focus on improving long-term durability and addressing moisture resistance. Many cellulose-based products, for example, require chemical treatment to prevent fungal growth and degradation. Exploring bio-based coatings and hybrid polymer blends may offer solutions to these limitations. Standardization is also critical: internationally recognized testing protocols are needed to ensure that results from one region are transferable to others.

Policy support is another crucial factor. Governments can accelerate adoption by introducing incentives for recycled insulation products, integrating them into green building certifications, and supporting research and development. Lessons from European policies on circular construction materials demonstrate how regulatory frameworks can create markets for sustainable composites. In regions such as Central Asia, including Kazakhstan, this approach could simultaneously address waste management challenges and energy efficiency goals.

Scalability also remains a challenge. While pilot projects demonstrate strong performance, industrial-scale production facilities are limited. Investments in infrastructure, technology transfer, and supply chain integration are needed to bring these materials to market at competitive scales. Partnerships between academia, industry, and government will be essential to overcoming this barrier. Finally, the integration of digital tools such as Building Information Modeling (BIM) with lifecycle data of secondary resource composites represents a future research direction. By combining material science with digital twin technology, engineers can better predict the performance of recycled composites over decades, further increasing their reliability and attractiveness for large-scale adoption.

6. Conclusion

Composite thermal insulation materials based on secondary raw resources represent an important step toward sustainable construction. Research demonstrates that these materials can achieve thermal conductivity values within the range of commercial insulation products while providing additional mechanical and environmental benefits. By using recycled polymers, fly ash, and agricultural residues, the building industry can significantly reduce embodied energy and carbon emissions, contributing to climate change mitigation.

Although global research has advanced considerably, further efforts are needed to move from experimental studies to large-scale applications. Kazakhstan, with its abundant industrial and agricultural waste, represents one of many regions where such innovations could provide both economic and environmental benefits. More broadly, the integration of secondary resources into insulation materials reflects the shift toward a circular economy in construction, aligning with international climate goals and sustainability initiatives.

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A Failed System: a Review of American Healthcare By Jared Harris

Abstract

The American healthcare system is fundamentally flawed and broken. The system currently in place has led to a system where insurance companies can charge exorbitant copays and premiums, while also being able to deny patients care without the approval of their doctor. This essay highlights these shortcomings and provides solutions using examples from other developed nations with free healthcare, namely Germany. This essay also addresses the concerns and contentions of opponents to expand socialised medicine in America by providing examples of successful socialized systems in other nations, namely Germany.

Introduction

Over the past decades, the American Healthcare system has come under scrutiny for its shortcomings. High prices, inefficiency and an exploitative health insurance system have drawn major criticism toward the current system. The recent assassination of the United Healthcare CEO Brian Thompson allegedly at the hand of Luigi Mangione, has further stirred opposition to the current system. The alleged killer Luigi Mangione's reasoning for the murder was his hatred for private insurance because of the greed in the industry(**Schnitzel**). It is obvious that the current system that the US healthcare system is under is too expensive and allows for an exploitative insurance system which denies care to patients against the wishes of their doctors. Furthermore, the current system is ineffective to warrant such a price tag and leaves millions uninsured. It is clear and evident that the United States needs to reform its healthcare system into a primarily socialized system, with an emphasis on affordability and improving care.

The current healthcare system in America is highly expensive without leading to better outcomes in comparison to other high income countries; In some cases it leads to worse outcomes. The United States spends more per person on healthcare than any country in the world. We spend 17% of our GDP on healthcare, which equates to 4.5 trillion dollars and 13,493 dollars per person respectively (Peterson Foundation). For reference, that is higher than the GDPs of Spain and Australia combined (Worldometer). With this high spending, one would be right to assume that the US has the best healthcare in the world; But we don't. The US has the lowest life expectancy, the highest maternal mortality rate, and the highest infant mortality rate out of the OECD countries. We have the third highest suicide rate, the highest rate of avoidable deaths, and the most amount of deaths from assault per 1000. Furthermore, we have the highest obesity rate and American adults are the most likely to have multiple chronic conditions(**Gunja**). With the amount we spend these statistics are utterly unacceptable, and shows how we need a system affordable but also provides the best care in the world to patients.

The current system of US healthcare allows for an exploitative insurance system that denies crucial care for their customers against the wishes of their doctors. The current system of US healthcare allows the health insurance industry to deny payment for your treatments, regardless of the doctors wishes if they deem it "unnecessary". This is done through the process

of prior authorization, in which the health insurer can deny coverage for a medical treatment if they deem it not to be “medically necessary”(NAIC). What's worse is that in many cases, the employees responsible for the initial processing of prior authorizations are not required to have education and training in the medical field(**Featherson**). This means that crucial care can be denied by someone that doesn't fully understand the medical field they are operating in. Furthermore, an article from InvestigateTV reports that, quote, “Physicians across the country say prior authorization policies interfere with their ability to care for their patients and lead to worse health outcomes. Doctors also say the administrative work required to process requests and appeals is an ever-growing burden on them and their staffs.”. According to an AMA survey cited by InvestigateTV, doctors and their staffs spend on average about 2 business days processing prior authorization requests and appeals. Almost 2 in 5 doctors say they have a staff member solely dedicated to prior authorizations(**Featherson**); And prior authorizations are only on the rise. In the same article they cite another report from the AMA survey, saying quote,”In a 2022 American Medical Association survey of physicians, responding doctors reported an average of 45 requests per-physician, per-week, up from an average of 31 per-week reported in the 2018 survey. The previous year’s survey found 84% of respondents said they’d seen an increase in the number of prior authorizations required over the preceding five years.”(**Peterson**). Coupled with the denial of healthcare coverage, customers can expect higher premiums, which is the monthly payment you pay for your insurance. According to an article by NBC, health insurers are charged much more than medicare,one of the 2 only forms of socialized medicine in America. The article writes, “A report published Monday by the research group Rand Corp. found that in 2022, the prices hospitals charged to private and employer-based insurance providers were, on average, 254% higher than what Medicare would have paid for the same services.”(**Lovelace**) These higher prices can lead to higher premiums, which will ultimately lead to higher prices for the consumer. Along with premiums, consumers also have to pay deductibles, copays, and coinsurance, which are other costs that come with health insurance(**Healthcare**). A system like this in a developed country is nothing but a travesty. If we as a nation are really the great country we claim to be, then we need to implement a system that ends these injustices.

It's clear that the inefficient and expensive system that we currently have, needs to be reformed into a primarily socialized system with an emphasis on affordability, and improving care. America should look to nations in Europe like Germany, which have both socialized and private insurance. Health insurance is also required in germany insurance, making it so that no one goes without being insured(**Blumel**). Germany also heavily regulates private insurance, so that customers aren't experiencing large premium increases as they age, and aren’t overburdened by premium costs if their income decreases(**Blumel**). We could imitate this model by expanding medicaid, requiring citizens to have health insurance, and by enacting stricter regulations on private health care providers. With this greater access to healthcare through this reformed system, America's health statistics will improve and the general health of its citizens will improve greatly.

Despite the successes of socialized healthcare systems in other countries, opponents still cite criticisms of such a system's viability in the US, pointing out how it could lead to less competition on the market of healthcare(MBA). But this is the central problem with healthcare in America. It puts the responsibility of providing health insurance into the hands of corporations, who often don't have the best interests of the common people in mind. Opponents also cite high wait times in countries with socialized healthcare such as Canada. According to a canadian institute for health information survey, which polled adults from 11 developed countries including the united states, 29% of Canadians reported waiting 4 or more hours for the emergency department which is 18% percent higher than the 11% survey average(Vogel). But the woes of the Canadian healthcare system should not deter implementing a socialized system as there are many countries that have short wait times like the aforementioned Germany. Germany has the third lowest reported wait time of over a month for surgery(world population review). This shows that socialized healthcare could work and be efficient in America, if we follow the model set by other nations.

In conclusion, the system we currently have is inefficient, expensive, and needs major reform. The current system we have allows for an exploitative health insurance industry, that charges customers high premiums and expensive extra fees. Even with these high fees, America's statistics aren't better than comparable countries, and in some cases even worse. With a reformed system, focused on affordability and improving care, America will become a nation with a robust healthcare system that provides affordable, quality care to all of its citizens.

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Personalized Learning in the Age of AI: Reflections and a Framework for Adaptive Education By Maksim Krylykov

Abstract

Personalized learning – tailoring education to individual needs and pace – has long been a goal in education, and advances in artificial intelligence (AI) are rapidly making it a reality. This paper explores the role of AI in adaptive educational systems from the author’s first-person perspective, reflecting on current trends and proposing a framework for future development. I discuss the evolution of adaptive learning technologies from early intelligent tutoring systems to modern AI-driven platforms, highlighting how current models (e.g., recommendation algorithms and learning analytics) personalize content and feedback. While successes from systems like intelligent tutors, Duolingo, and Khan Academy demonstrate the potential of AI-powered personalized learning, there remain gaps in holistic adaptation and humanistic qualities. Drawing on these insights, I propose a set of guiding principles for an effective AI-driven personalized learning framework – one that integrates AI’s strengths in data-driven adaptation with the irreplaceable guidance of human educators. I also consider future directions, examining ethical, technological, and pedagogical opportunities and challenges. The conclusion emphasizes that advancing AI-powered personalized learning, with careful design and collaboration, can profoundly enhance educational outcomes and equity.

Introduction

Education has traditionally followed a one-size-fits-all model, but learners vary widely in prior knowledge, learning speed, and interests. Personalized learning addresses this by adjusting instruction to each learner, an approach proven to boost achievement significantly. In a classic study, Bloom (1984) found that students who received one-on-one tutoring (with mastery-based progression) performed about two standard deviations better than those in typical classroom settings, meaning the tutored students outperformed 98% of the control class. This famous “2 sigma” result highlights the promise of individualized instruction. The challenge, however, is how to offer such personalization at scale, since one-on-one human tutoring for every student is impractical in traditional education systems.

This is where artificial intelligence (AI) enters the picture. Modern AI techniques enable the creation of adaptive learning systems that mimic aspects of a personal tutor for each learner in a class or even across the globe. By leveraging data and algorithms, these systems can continuously adjust content difficulty, provide instant feedback, and guide students along individualized learning paths. The importance of this paradigm shift towards personalization is hard to overstate: studies of online platforms have shown that when students practice at their own pace and level, they can learn 30–50% faster than in one-size-fits-all settings. Indeed, the success of platforms like Khan Academy, which allows learners to progress mastery-based, illustrates how giving students control over pace leads to markedly better outcomes.

In recent years, AI-driven personalized learning has moved from theory to widespread practice. Today, millions of users learn languages, math, and more with the help of AI-powered systems. Duolingo, for example, uses machine learning to tailor lessons “to each individual, kind of the way a human tutor might”. Khan Academy has integrated adaptive exercises and even AI tutors (such as the experimental Khanmigo) to guide learners. Meanwhile, surveys show growing acceptance of AI in classrooms; one study found over 70% of teachers and students believe AI tools will be essential for student success in the near future. As an educator-researcher, I have witnessed in my practice how adaptive learning software can transform a student’s experience from passive to engaged, by delivering the right help at just the right time.

In this paper, I reflect on the current state of AI in personalized learning and propose a framework for building on what works. I begin with a background on how adaptive learning systems evolved and the AI models they use. I then offer personal reflections on the successes and shortcomings of these approaches and propose principles for a next-generation AI-powered personalized learning framework. Finally, I discuss future directions, including ethical, technological, and pedagogical considerations, before concluding with thoughts on the path forward.

Background of Evolution of Adaptive Learning Systems

Adaptive learning is not a new idea – its roots trace back decades. Early educational psychologists like B.F. Skinner in the 1950s envisioned “teaching machines” that would allow each student to proceed at their own pace through programmed instruction. By the 1970s and 1980s, the first Intelligent Tutoring Systems (ITS) emerged, using AI rule-based models to mimic human tutors in domains like mathematics and programming. These systems, such as the classic SCHOLAR or SOPHIE tutors, could analyze a student’s responses and tailor hints or new problems accordingly. While primitive by today’s standards, they demonstrated the feasibility of computer-based personalized instruction. Over time, ITS became more sophisticated, incorporating cognitive models of how students learn step-by-step. Research showed that well-designed ITS can significantly improve learning outcomes – students using intelligent tutors often outperform those in traditional classes, with a meta-analysis finding a median effect size of about 0.66 (roughly moving a 50th percentile student to the 75th percentile). Digital tutors, in some cases, have approached or even exceeded the effectiveness of human tutoring under certain conditions (). These early successes set the stage for the broader adoption of adaptive learning. Another significant area to consider is modern AI-powered personalization. The advent of the internet and big data in the 2000s greatly expanded adaptive learning beyond research labs. Online learning platforms could collect vast amounts of learner data and apply machine learning to refine personalization. For instance, Khan Academy grew in this era, mapping out knowledge domains and allowing students to work on skills in an order and pace personalized to them. Evidence from over 50 studies indicated that self-paced mastery learning via such platforms yields substantially faster learning. At the same time, companies built adaptive e-learning systems for various subjects. Duolingo, launched in 2012, leveraged data from millions of

language learners to drive its adaptive exercises. It introduced models like Half-Life Regression, a machine learning technique to predict when a user is likely to forget a word and schedule practice accordingly. By analyzing each learner's mistakes and successes, Duolingo's AI can decide to review certain vocabulary or skip ahead, effectively giving each user a customized curriculum. As Burr Settles, head of AI at Duolingo, explained, their goal is to get as close as possible to a human tutor experience through AI. The result is a highly engaging platform that keeps learners motivated with content pitched at the right level.

Meanwhile, Intelligent Tutoring Systems have continued to evolve and find commercial use. An example is Carnegie Learning's MATHia, an AI-driven tutor for mathematics. MATHia doesn't just check if answers are correct; it analyzes how students solve problems to diagnose misunderstandings. It uses techniques like Bayesian knowledge tracing or neural networks to maintain a model of each student's skill mastery. In classroom deployments, such systems are often paired with teacher dashboards. For instance, MATHia's LiveLab feature alerts teachers in real-time if many students are struggling on a concept, so the teacher can intervene. Another large-scale example is Squirrel AI in China, which combines a vast item bank with neural network models to adapt to each student. Squirrel AI reportedly boosted student accuracy on practice questions from 78% to 93% by personalizing learning paths – an impressive gain demonstrating the power of fine-grained adaptation.

Current AI Models in Use

Several types of AI models and techniques underpin today's adaptive learning systems. Notable ones include:

Recommendation Systems

Borrowed from e-commerce and entertainment, recommendation algorithms in education suggest the next learning activity or resource for a student. Based on a learner's past performance and interests, the system can recommend, for example, a specific exercise, video, or reading that is most likely to help them progress. If a student struggled with a concept, the recommender might suggest a remedial video; if they mastered something quickly, it might fast-track them to a more advanced topic. This approach is used in platforms like Coursera and Khan Academy to personalize learning pathways similarly to how Netflix personalizes a viewing experience.

Learning Analytics and Predictive Models

Learning analytics refers to the measurement and analysis of student data to improve learning. AI-driven learning analytics systems crunch data on everything from quiz scores to time spent on tasks, building predictive models. These models can forecast whether a student is at risk of failing or dropping out, identify which skills a learner has mastered, and even detect disengagement. For example, many universities use analytics systems that monitor online course clicks and assessments to flag students who may need extra support. In adaptive platforms, predictive analytics allow for proactive adjustments – the AI might detect that a learner is likely

to have trouble with an upcoming unit and thus insert a preparatory lesson beforehand. Learning analytics also produces visual dashboards for teachers and students, making learning progress more visible and actionable.

Natural Language Processing (NLP) and Conversational Tutors

Recent advances in AI language models (like GPT-4) have enabled more interactive personalized learning through conversation. NLP techniques allow systems to understand student questions or written responses and provide helpful feedback. For instance, an AI chatbot tutor can answer a student's query in natural language, or a writing tutor can give feedback on an essay's grammar and structure. Virtual tutors such as chatbots are already being deployed to offer on-demand help; they leverage NLP to parse a learner's input and generate relevant hints or explanations. This makes personalized learning more accessible – students can chat with an AI tutor anytime, much like they would ask a human for help, receiving instant, tailored responses.

Educational Data Mining and Knowledge Tracing

Under the hood, many adaptive systems maintain a learner model updated through algorithms known as knowledge tracing. These algorithms (Bayesian or neural) estimate the probability that a student knows a given concept at any moment, based on their history of answers. Each time the student answers a question, the model updates, and the system decides what to present next (perhaps a harder question if the student is ready, or a review if not). Deep learning approaches to knowledge tracing have improved accuracy in modeling student knowledge states, enabling more precise personalization of content difficulty.

In summary, today's adaptive educational systems blend insights from decades of research in ITS with modern AI techniques. They offer features like real-time feedback, personalized content sequencing, and detailed analytics - all aimed at giving each student a unique learning experience suited to their needs. This background sets the stage for reflecting on how well these AI-driven personalized learning approaches are working in practice, and how we can make them even more effective going forward.

Reflections and Proposed Framework

Reflecting on the current landscape of AI-powered personalized learning, I am both encouraged by the progress and aware of the remaining gaps. As someone who has experimented with these systems both as a learner and as an instructor, I have seen firsthand the benefits they bring. Students using adaptive software often express that the lessons “meet them where they are.” Unlike traditional lectures that might be too fast for some and too slow for others, adaptive systems can adjust in real time – a feature I've observed keeping learners more engaged and less frustrated. There are several aspects that I believe are working well in the current generation of personalized learning systems:

- Timely Feedback and Adaptation

One clear success is the ability of AI systems to provide instant feedback and adjust difficulty on the fly. In a math practice app, for example, if I struggle with factoring a quadratic, the system immediately offers a hint or a simpler sub-problem, rather than waiting for me to fail a test a week later. This kind of responsive support is something even a dedicated human tutor might not perfectly time, but AI manages it consistently. Research confirms that such real-time, tailored feedback helps keep students in the optimal zone of challenge, addressing errors before misconceptions solidify.

- **Personalized Pathways at Scale**

AI-driven personalization has achieved scale. Today's platforms can serve millions of learners with individualized content simultaneously. This scalability is unprecedented – it means a student in a remote village and another in a big-city school can both have a personal learning trajectory, something only technology can provide. The fact that Squirrel AI's system can process 10 billion data points from 24 million students to tailor learning paths is astounding. In my teaching, using a learning system's analytics, I could see 30 students each working on different skills appropriate to their level; this would be chaotic to manage alone, but the AI made it feasible.

- **Data-Driven Insights for Learners and Educators**

Another positive development is the feedback loop of data to inform instruction. Adaptive systems not only respond to the learner, but they also produce valuable analytics. I've found that dashboards showing which topics a student has mastered or where they spend extra time help me as an instructor to personalize my guidance. It aligns with the idea that AI can analyze performance patterns and identify learning gaps – something it does tirelessly in the background. For learners, seeing their progress (e.g., a skill proficiency graph) can be motivating and helps them take ownership of their learning. In short, AI gives us more visibility into the learning process, which is a win for personalization.

- **Increased Engagement through Personalization and Gamification**

Many AI-driven platforms incorporate gamified elements - points, badges, adaptive quizzes that feel like games – which work hand-in-hand with personalization to boost engagement. Duolingo, for instance, keeps learners hooked with its adaptive challenges and reward system. From my perspective, this blending of personalization with motivational design is effective: when material adjusts to just beyond the learner's current ability, it creates a satisfying sense of accomplishment that encourages continued practice. Personalized pacing also means learners are less likely to be bored (when material is too easy) or anxious (when it's too hard), fostering a more positive emotional connection to learning.

Despite these strengths, current AI-based personalized learning systems have limitations and missing pieces. Through my reflections, a few key areas stand out where there is room for improvement.

The first area is holistic personalization (beyond academics). Most of today's adaptive systems focus heavily on cognitive aspects – getting the right answer, mastering a skill – but personalize little else. Yet, human learning is influenced by emotional and social factors too. I've noticed that if a student is demotivated or anxious, even the best AI tutor cannot adjust its strategy the way a human teacher might (for example, by giving encouragement or altering the activity to re-engage the student). Current AI largely does not “see” these affective states. An ideal personalized learning system would detect if a learner is frustrated or disengaged (perhaps via sentiment analysis of their input or pauses in interaction) and adapt not just the content but the tone or approach. Incorporating strategies from affective computing, like adjusting feedback to be more encouraging when a student is frustrated, is something I find missing in most platforms today.

Similarly, personalization seldom takes into account a learner's interests, context, or real-world applications. A human tutor might say, “You're a soccer fan, so let's frame this physics problem in terms of kicking a ball.” AI systems, unless explicitly programmed with such options, typically present generic content. From my experience, this is a missed opportunity to deeply engage learners by connecting material to what they care about. A more advanced adaptive system could learn about a student's interests or career goals and personalize examples and projects accordingly. Currently, apart from some surface-level choices (like themes or avatars in a platform), this level of personalization is limited.

Another important aspect is the role of the teacher and social learning. Many AI learning systems are designed for solo learner-computer interaction. However, education is also a social, collaborative process. In practice, I have seen some teachers struggle to integrate adaptive software into their classrooms, unsure of their role when an AI is tutoring each student. Ideally, the teacher's role shifts to facilitator and mentor, but not all systems actively support this shift. There is sometimes a lack of clear communication from the AI system to the teacher about what it's doing with each student. Personalization can feel isolating for students without teacher involvement and may not achieve its full potential. What's missing is a smooth teacher-AI partnership: features that inform teachers in real time and allow them to override or adjust the AI's recommendations when needed. The best results I've seen were in classrooms where teachers use AI as a tool – for example, using insights from an app to form peer-learning groups or to give individual coaching. Yet many systems do not explicitly encourage or guide such human-AI collaboration.

Lastly, as a user of these systems, I sometimes find myself wondering why the AI is giving me a certain exercise. Was it because I got the last question wrong? Is it introducing a new concept because I am ready, or just cycling through a fixed pattern? This opaqueness can undermine trust. Learners and educators are more likely to embrace AI recommendations if they understand the rationale. Most current systems do not explain their decisions in an accessible

way. Improving transparency - even something simple like a message: “We’re reviewing fractions because you struggled with the last division problem” - would help users trust the personalization. This is an area that needs development.

Having considered what works and what does not, I propose a theoretical framework for a next-generation AI-powered personalized learning system. This framework is informed by my reflections and aims to address the gaps while enhancing the strengths of current systems. The framework revolves around several key principles:

1. Holistic Learner Modeling

“Know the learner” in a multi-dimensional way. The AI system should maintain a rich model of each student, not only tracking academic progress (skills mastered, quiz scores, etc.) but also integrating data on engagement, learning preferences, and potentially even affective state. For example, the system might note that a particular student learns math best with visual examples and tends to lose focus after 20 minutes of practice. It could then adapt by providing more diagrams and scheduling short breaks or gamified quizzes to re-energize the learner. Advances in AI, such as emotion recognition or analysis of student input, could feed into this model – if a student always types “I don’t get it” in the chat, the system flags confusion. The goal is a personalized learning experience that recognizes the whole learner. This principle aligns with how human tutors operate, sensing when a student is bored or confused and adjusting accordingly. An AI that can approximate this responsiveness will be far more effective and empathetic.

2. Adaptive Content Generation and Diverse Learning Pathways

Move beyond static content selections to dynamic content creation. In the proposed framework, AI would not be limited to choosing from a fixed set of exercises or videos; it could generate new problems, hints, or even explanatory narratives tailored to the individual. For instance, if a student is struggling with a concept, the AI might create an analogy or story on the spot (leveraging generative models) to explain the concept differently. This on-demand customization makes the learning experience more personalized than any pre-authored content library could. Additionally, the system should support multiple pathways to learning goals. Instead of assuming there’s one optimal sequence for everyone, the AI could offer options – some students might learn algebra best through real-world problem projects, others through abstract exercises. By analyzing outcomes, the AI can discover which pathway suits which learner profile. My framework emphasizes flexibility: there may be a common destination (mastering a skill), but there are many roads to get there, and the AI should help each learner find their best route.

3. Human-AI Collaboration and Transparency

Rather than AI operating in isolation, the framework envisions a tight integration between AI tools, students, and teachers. AI’s role is to augment the human elements of

education, not replace them. Practically, this means the system is designed for co-orchestration: the AI handles routine personalization (like adapting practice tasks) and provides analytics, while teachers orchestrate the overall learning experience. The AI should present its insights to teachers in clear, actionable ways – for example, alerting that “Student A would benefit from a review of concept X” – and even suggest remedial or enrichment actions. The teacher can then validate or modify these suggestions based on their broader knowledge of the student (maybe Student A was having a bad day, not a knowledge gap – something the AI wouldn’t know). In my view, involving teachers as supervisors of the AI tutor ensures that personal context and mentorship remain central. Likewise, students should be active participants: the system can solicit feedback from the student (e.g., “Was this explanation helpful to you?”) to refine its personalization approach. Crucially, this collaborative model demands transparency. All stakeholders should understand, at least in general terms, what the AI is doing and why. By opening the AI’s decision-making process, we build trust and facilitate a productive partnership between AI, learners, and educators.

4. Ethical and Inclusive Design

Any AI framework for education must prioritize ethics, equity, and inclusion from the ground up. This principle is a response to the missing emphasis on data privacy and bias in many current systems. The proposed framework would implement strong privacy safeguards – for instance, student data is encrypted and used only for learning purposes, with control given to students/parents over their data. The AI algorithms should be routinely checked for bias or differential performance among student groups. It would be unacceptable if, say, the system works better for high-income students than low-income students due to skewed training data. An inclusive design means ensuring the system is accessible to learners with disabilities (compatibility with screen readers, adaptive interfaces for different needs) and effective across diverse backgrounds. Moreover, the AI should follow pedagogical ethics: it should not manipulate learners in harmful ways (e.g., causing addiction to a gamified system or excessive screen time). Instead, it adheres to well-being guidelines – perhaps even limiting itself if a student has been working too long and suggesting a break. By embedding ethical considerations, we ensure the AI supports the humanistic goals of education and is welcomed by communities and educators.

5. Continuous Improvement and Evaluation

Finally, the framework embraces a continual improvement cycle. AI in education should be evidence-based and self-improving. This involves rigorous evaluation of outcomes – does the personalized system improve learning gains, engagement, etc., compared to alternatives? – and using those findings to refine the algorithms. The AI can run controlled experiments in the background (with appropriate consent), such as A/B testing

two different feedback styles, to learn what works best for different learners. The system should also be modular and adaptable to new research. For example, if a new theory of learning or a new AI technique emerges, the framework can incorporate it without a complete redesign. In my experience, one of the challenges is that educational technologies often become static products, whereas education itself is dynamic. A good AI-driven system must evolve with pedagogy and technology. This principle ensures that personalized learning powered by AI doesn't stagnate but keeps pushing toward more effective and innovative practices over time.

In summary, the proposed framework is a vision for AI-powered personalized learning that is learner-centered, flexible, collaborative, and principled. It takes what is already working – data-driven adaptation and scalability – and infuses it with a deeper understanding of learner context, stronger human integration, and ethical guardrails. As an academic thought experiment, this framework serves as a guide for researchers and practitioners aiming to build the next generation of personalized learning systems that truly empower every learner.

Future Directions

Looking ahead, the intersection of AI and personalized learning is poised to grow, bringing both exciting opportunities and important challenges. In this section, I offer a forward-looking commentary from my perspective on the ethical, technological, and pedagogical dimensions that will shape the future of AI in education.

The rapid advancement of AI technologies promises ever more powerful personalized learning experiences. One major opportunity is the integration of generative AI and multimodal learning. We are already seeing early signs of this: large language models can act as conversational tutors, and they might soon create custom simulations, stories, or even virtual reality scenarios tailored to each learner. Imagine learning history by virtually “traveling” to ancient Rome through an AI-generated simulation that adapts its depth based on your questions, or an AI that composes a unique science experiment for you to try based on your current understanding. Such immersive, personalized content could dramatically enhance engagement and understanding. Another technological frontier is better real-time sensing: using cameras, eye-tracking, or wearables (with proper consent) to gauge student engagement or confusion, giving the AI more inputs to adapt with. As these technologies mature, they must be developed with education in mind, meaning they should be reliable, interpretable, and curriculum-aligned. The tech industry's interest in education is growing (the global AI-in-education market is projected to surge from about \$5 billion in 2024 to over \$100 billion by 2034, so we can expect a proliferation of tools. The challenge will be ensuring these tools contribute to learning and are not just gimmicks. Interdisciplinary collaboration will be key: educators, psychologists, and AI experts should co-design the systems to align with how students learn best. With great power comes great responsibility. The increased use of AI in education raises serious ethical questions that the field must address proactively. Data privacy is a foremost concern –

personalized learning systems, by nature, collect detailed data on students. We need robust policies and technologies to ensure this sensitive data (on performance, behavior, possibly biometric indicators of attention, etc.) is protected and only used for the student's benefit. Students and parents will rightly demand transparency: what data is being collected, and how is it used? Another ethical aspect is algorithmic bias. AI systems trained on historical educational data might perpetuate biases, for example, underestimating the abilities of students from underrepresented groups if past data reflected systemic biases. It is crucial that future systems are audited for fairness, perhaps involving independent oversight, to ensure all students get equally effective personalization. Equitable access is also a challenge: Will these advanced AI tutors be available to all students or only those in well-funded schools? If not addressed, we risk exacerbating the digital divide. I foresee a strong need for public investment and open-source initiatives in AI for education to ensure that the benefits of personalization reach disadvantaged communities. Ethically, we also have to consider the role of human judgment – for example, if an AI predicts a student won't do well, we must be careful that it doesn't create a self-fulfilling prophecy by lowering expectations for that student. Ethical guidelines and perhaps regulatory frameworks for AI in education will likely emerge to set standards for privacy, fairness, and accountability.

The infusion of AI into learning will inevitably shift pedagogical practices. One major future direction is reimagining the role of the teacher. Rather than being the sole knowledge deliverer, teachers will increasingly become facilitators and mentors in AI-rich classrooms. In the vision of many thought leaders, teachers transform into “learning architects” who design learning experiences and leverage AI tools to implement them. Routine tasks like grading quizzes or generating practice problems might be offloaded to AI, freeing teachers to focus on one-on-one mentoring, fostering critical thinking, and addressing social-emotional learning. For this to happen, though, significant teacher training and professional development are needed. Future teachers (and current ones) will need to be trained in how to work alongside AI – understanding its insights, recognizing its limitations, and orchestrating activities that maximize the combined strengths of AI and human instruction. I anticipate teacher education programs incorporating modules on AI literacy and practical training with adaptive learning platforms. Pedagogy may also shift toward more mastery-based and competency-based models, since AI is well-suited to tracking individual mastery. This could dismantle the traditional age-grade structure in favor of students progressing at their own pace, guided by AI and teachers. From my viewpoint, a blended pedagogy that combines personalized AI tutoring with collaborative group projects (for social and communication skills) will become more common, essentially using AI for what it does best and human-led methods for what they do best.

As we implement more AI in education, continuous research will be vital to guide effective use. We must ask: Which AI-driven strategies truly improve learning outcomes, and for whom? Not every fancy AI feature will translate to real educational value. For example, do students learn better with a chatbot tutor versus written hints, or in what subjects is adaptive learning most effective? Future work will need to rigorously evaluate these questions, ideally

with diverse student populations. Another intriguing area is the long-term impact: If a child grows up with AI personalized learning from early education onward, how does that shape their skills and attitudes? Will they become more self-directed learners (because they're used to controlling their learning path) or overly reliant on feedback? We don't fully know, and longitudinal studies will be important. As someone enthusiastic about the potential of personalized learning, I also remain cautious – we should be guided by evidence and ready to course-correct if certain AI interventions don't deliver the expected benefits. Furthermore, involving learners and parents in the design and feedback loop will be important to ensure the technology aligns with human needs.

In essence, the future of AI in personalized learning is a balancing act. The technological possibilities are expanding at a breathtaking pace, offering tools to enrich and individualize education more than ever before. Yet, we must implement these advances thoughtfully, with an unwavering focus on ethics, equity, and sound pedagogy. The next decade (and beyond) will likely see AI become a commonplace assistant in many learning environments, from K-12 to higher education to workplace training. If we navigate the challenges wisely, we have an opportunity to fundamentally improve how people learn, making education more adaptive, inclusive, and effective. It's an exciting horizon, but it will require cooperation between technologists, educators, policymakers, and communities to fully realize the promise of AI-powered personalized learning.

Conclusion

In conclusion, AI's role in adaptive educational systems represents a transformative shift towards truly personalized learning experiences. As an author and researcher reflecting on these trends, I am optimistic about the potential to enhance education for learners of all backgrounds. We have seen that well-designed personalized learning systems can yield substantial improvements in student engagement and achievement, in some cases rivaling the effectiveness of one-on-one tutoring. The evolution from early intelligent tutoring systems to today's AI-driven platforms like Duolingo and Khan Academy demonstrates both the progress made and the need for continual innovation. Current systems excel at providing tailored practice and feedback at scale, yet they also highlight what still needs to be done to achieve the full vision of personalized education.

I proposed a framework grounded in the idea that technology should adapt to the learner, and not the other way around. Key elements of this framework include holistic learner modeling, adaptive content generation, human-AI collaboration, ethical design, and continuous improvement. These principles aim to ensure that future AI systems are not just powerful but also equitable, transparent, and deeply responsive to individual learners' needs. The emphasis on collaboration – that teachers and AI working together can achieve more than either alone – is particularly important. Education is fundamentally a human endeavor, and AI should serve as a tool that amplifies the best of human teaching and mentoring. Advancing research and practice in AI-powered personalized learning is crucial. It holds promise for addressing longstanding

educational challenges, such as large achievement gaps and a lack of engagement. However, this advancement must be pursued carefully. Ethical considerations like privacy, bias, and access are not side issues; they determine whether this technology will help all learners or just a privileged few. Pedagogical guidance is needed so that AI tools are used to foster genuine understanding and critical thinking, not just test performance. If we remain mindful of these factors, the reward is considerable: a future where each student can learn in the way that suits them best, with AI providing personal support that adapts as they grow.

In my journey through this exploration, I return to the core conviction that education should center on the learner. AI, when thoughtfully integrated, is a powerful enabler of this vision. It can free us from the industrial-age model of education and move us towards a model where personalization at scale is the new norm – where a student’s curiosity is not stifled by a rigid curriculum but encouraged by an adaptive pathway, and where teachers have the insights and time to focus on what matters most: inspiring and guiding students. The path forward will require ongoing dialogue between technology and education communities, pilot programs that demonstrate what works, and a commitment to sharing knowledge across the field.

Ultimately, the role of AI in personalized learning is not to automate education but to elevate it. It offers the chance to make learning more engaging, efficient, and equitable. As we continue to develop these systems, we carry a responsibility to shape them in service of human learning and development. The coming years will be pivotal in determining how AI reshapes education. With careful research, ethical diligence, and creative collaboration, we can ensure that adaptive AI systems become a positive force, helping unlock the potential of every learner and ushering in an era of education that is truly personalized and powered by both artificial and human intelligence.

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**Sustainable Startup Models:
Strategic Pathways for Long-Term Success in Entrepreneurial Ventures
By Almaz Sydykov**

Abstract

In the evolving landscape of global entrepreneurship, sustainability has emerged as a crucial dimension of long-term business viability. This paper explores sustainable startup models, focusing on how new ventures can integrate environmental, social, and governance (ESG) principles from inception to drive competitive advantage and resilience. Drawing on strategic management theories, case studies, and emerging business model frameworks, the research presents a structured analysis of how sustainability-oriented startups achieve growth while adhering to ethical and ecological imperatives. The findings highlight practical pathways and strategic choices that student entrepreneurs and early-stage founders can employ to align profitability with purpose.

Keywords: sustainable startups, business models, entrepreneurship, ESG strategy, student ventures, strategic planning

1. Introduction

As the global economy becomes more interconnected and environmentally conscious, traditional metrics of startup success, such as market capture and valuation, are being re-evaluated in light of broader sustainability concerns. Young entrepreneurs today face increasing pressure to create businesses that generate economic value and contribute positively to society and the environment. In this context, sustainability has evolved from a peripheral concern to a strategic imperative in business model design.

This paper focuses on sustainable startup models, examining how entrepreneurial ventures can incorporate ESG (Environmental, Social, and Governance) considerations into their core strategy from the outset. This is particularly relevant to student entrepreneurs, such as those emerging from liberal arts institutions like Drew University, who often possess strong interdisciplinary awareness and a values-driven mindset. The research aims to provide a conceptual framework and actionable guidance for integrating sustainability principles into the entrepreneurial process, thus enabling long-term value creation.

2. The Case for Sustainability in Entrepreneurship

The importance of sustainability in business stems from multiple converging factors. Climate change, resource scarcity, and shifting consumer expectations have forced companies to reconsider their operational and ethical footprint. For startups, these pressures manifest as both challenges and opportunities. Unlike legacy firms burdened by inertia, startups can embed sustainable practices into their foundational design. This agility enables them to innovate more freely, capture eco-conscious markets, and secure funding from impact investors.

A sustainability-focused approach also reduces long-term operational risks. Startups that prioritize energy efficiency, responsible sourcing, and inclusive employment practices are more likely to comply with evolving regulatory standards and withstand reputational scrutiny. Additionally, there is a growing body of evidence showing that companies with strong ESG performance attract top talent and foster higher employee retention, both critical factors for startup scalability.

From a strategic standpoint, embedding sustainability in a startup's value proposition enhances differentiation. In saturated markets, where product and service features may be easily replicable, purpose-driven positioning offers a durable competitive edge. Brands perceived as ethical and environmentally responsible often enjoy deeper customer loyalty, increased word-of-mouth advocacy, and broader stakeholder trust. Therefore, sustainability is not merely an add-on but a potent driver of entrepreneurial success.

3. Theoretical Foundations and Business Model Innovation

This research is grounded in theories of strategic management and business model innovation. The Resource-Based View (RBV) of the firm suggests that sustainable capabilities, such as green operations or social capital, can serve as unique, inimitable resources that enhance a firm's competitiveness. When these capabilities are integrated into the startup's routines and culture, they become part of its strategic fabric.

In parallel, the Triple Bottom Line (TBL) framework, emphasizing people, planet, and profit, offers a useful lens for evaluating sustainability in startups. Rather than focusing solely on financial performance, the TBL approach encourages founders to assess how their operations impact social equity and environmental stewardship. By aligning business objectives with stakeholder well-being, startups can create shared value, a concept popularized by Porter and Kramer. This approach redefines success in more holistic terms, balancing economic goals with societal impact.

Emerging tools such as the Sustainable Business Model Canvas provide structured guidance for entrepreneurs to visualize and plan sustainable operations. Unlike traditional canvases that prioritize customer segmentation and revenue streams, these versions incorporate elements like life-cycle impact, ethical sourcing, and regenerative design. The integration of such tools into entrepreneurial education and incubators has made sustainable strategy more accessible to student founders.

4. Case Studies and Practical Examples

Startups across various industries are increasingly making sustainability a foundational component of their business models. One of the most notable examples is Allbirds, a footwear company that markets itself as “the world's most comfortable shoe” made from natural materials like merino wool and eucalyptus tree fiber. Allbirds achieved certified B Corporation status and has committed to reducing its carbon footprint to near zero by 2030. As of 2024, the company continues to publish detailed carbon emission labels on every product, reinforcing its brand

transparency. These values have resonated with consumers, helping Allbirds surpass one million customers globally and secure over \$200 million in venture funding since its founding in 2016. Another major example is Too Good To Go, a mobile application that connects consumers with surplus food from restaurants, bakeries, and supermarkets. The platform helps combat food waste by offering unsold meals at reduced prices. As of early 2024, Too Good To Go surpassed 85 million users worldwide and has expanded into over 20 countries, including the United States, Canada, and much of Europe. The app has helped save more than 300 million meals from being wasted, which translates to a significant reduction in carbon emissions. In February 2024, the company also introduced a carbon tracking feature to increase user awareness about their environmental impact, further embedding sustainability into its operational model.

Similarly, Olio, another app tackling food and household waste, facilitates hyperlocal sharing of surplus items among neighbors and local businesses. Olio reports that it has over 7 million users and has facilitated the redistribution of more than 100 million portions of food globally. In addition to food sharing, the app includes a section for lending, borrowing, and giving away household items, thus extending the life cycle of consumer goods. The startup collaborates with major retailers such as Tesco and Pret A Manger in the United Kingdom, strengthening its role as a circular economy enabler.

Student-led startups are also playing a growing role in shaping sustainable innovation. Incubators at institutions like MIT, Stanford, and smaller liberal arts colleges have produced ventures focused on everything from biodegradable packaging to ethical supply chains. For instance, a University of Michigan student team recently launched a compostable packaging firm that partners with local agriculture to return packaging waste as organic soil fertilizer. Similarly, students at Drew University have participated in green entrepreneurship challenges, developing sustainability apps that gamify energy savings or promote local food sharing networks. These ventures illustrate how higher education can serve as a launchpad for scalable, mission-driven startups.

Collectively, these examples demonstrate the practicality and strategic value of embedding sustainability from a startup's inception. Early decisions, such as choosing recyclable inputs or engaging with fair trade suppliers, not only reduce environmental impact but also enhance brand credibility and investor appeal. According to a 2023 Morgan Stanley report, 85% of individual investors are now interested in sustainable investing, and sustainable funds have consistently outperformed traditional funds over the last five years. This shift underscores how integrating ESG principles early on can help startups secure capital, gain a competitive advantage, and build lasting relationships with eco-conscious consumers.

5. Challenges and Strategic Trade-offs

While the benefits of sustainability in startups are well established, several persistent challenges continue to hinder its widespread integration. One of the most pressing issues is financial feasibility. For early-stage ventures, sustainable practices often come with elevated costs, particularly when using eco-friendly raw materials or pursuing certifications like Fair

Trade or B Corporation status. According to a 2023 survey by First Round Capital, nearly 60 percent of startup founders cited cost as the primary barrier to implementing sustainability measures. These expenses, combined with limited early-stage funding and pressure to achieve rapid traction, force founders to make difficult trade-offs between ideals and immediate operational needs.

The high cost of sustainability can also create a funding gap. Traditional investors may still prioritize short-term returns over long-term environmental or social value. While ESG-focused venture funds have grown, reaching over \$70 billion globally in assets under management by the end of 2023, their deployment remains concentrated in later-stage or proven startups. This creates a paradox where early-stage founders are expected to demonstrate sustainability without yet having the capital to fully support such practices. Bridging this gap requires a shift in how investors evaluate early ventures, with greater appreciation for impact metrics alongside revenue projections.

Another major hurdle lies in measurement and verification. Unlike conventional business metrics like monthly recurring revenue or customer acquisition cost, sustainability outcomes such as carbon footprint reduction or equitable labor practices are more nuanced and difficult to standardize. A 2024 Deloitte report found that 67 percent of startups lacked formal sustainability measurement frameworks. Without clear, comparable benchmarks, it becomes challenging to prove impact to stakeholders or to qualify for ESG-linked funding. This often results in “greenhushing,” where startups with good practices underreport their impact for fear of being scrutinized for imperfect data.

Communication challenges further complicate the situation. Startups face the delicate task of promoting their sustainability credentials without falling into the trap of greenwashing, where claims are exaggerated or vague. Consumers and investors alike are becoming more discerning, demanding transparency backed by verifiable data. Founders must develop comprehensive reporting strategies, supported by lifecycle assessments or third-party audits, to credibly convey their progress. The use of blockchain and AI for supply chain traceability is emerging as a promising solution, though such tools are still financially out of reach for many young startups.

Finally, practical trade-offs can arise when market demands conflict with sustainability ideals. Reducing packaging waste may reduce visual appeal or shelf durability, affecting customer perception. Ethical sourcing may slow production timelines due to limited vendor options or stricter compliance requirements. These constraints can be particularly acute in competitive sectors such as fashion, consumer goods, or food tech. Founders must make intentional decisions that align with their mission, while clearly explaining these choices to consumers and investors. Research from Harvard Business School indicates that brands that transparently communicate their sustainability trade-offs often enjoy stronger brand loyalty and resilience during economic downturns.

6. Future Directions for Student Entrepreneurs

As sustainability continues to shape the entrepreneurial ecosystem, student entrepreneurs are uniquely positioned to lead this transformation. Their proximity to academic research, campus resources, and interdisciplinary collaboration offers a fertile ground for experimentation. Institutions like Drew University can play a critical role by integrating sustainability into business curricula, offering ESG-focused incubators, and encouraging applied research in sustainable innovation.

Future research should explore how digital tools such as blockchain or artificial intelligence can enhance transparency in sustainable supply chains and product lifecycles. There is also a need to develop financing mechanisms tailored for early-stage sustainable startups, such as green accelerators or ESG-linked student venture funds. By equipping student founders with these enablers, the path to scalable and responsible entrepreneurship becomes more tangible.

7. Conclusion

Sustainable startup models represent a compelling pathway for aligning business creation with societal and environmental goals. By embedding ESG principles into core strategy, entrepreneurs can build resilient, differentiated ventures that thrive in a rapidly changing global economy. The experiences of existing sustainable startups and student-led ventures offer practical evidence that profitability and purpose can coexist.

For student entrepreneurs, sustainability is not just a value but a strategic choice. It shapes how they define problems, design solutions, and engage with stakeholders. As future business leaders, their ability to integrate sustainability from the ground up will define not only their success but also their contribution to a more equitable and sustainable world.

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Plastic Pollution: A Growing Issue By Diya Krishna

Abstract

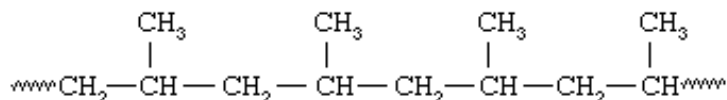
People discover various materials occasionally that break the boundaries of traditional materials. Plastic developed in 1907 by Leo Baekeland is revolutionized material and referred to as “a material with 1,000 uses” (Pilapitiya, 2024). Plastic has a domain throughout human life with its versatile properties such as lightweight, high durability, flexibility, and low production cost. Plastic commercialization began with the Second World War and grew all over the world within less than a century (Pilapitiya, 2024). Despite all the benefits, plastics cause severe environmental and public health issues. The global annual production of plastic currently is more than 359 million tons and only half is recycled (Lewis, 2023). The “immortality” of plastic has caused the leakage of harmful chemicals into the soil such as Phthalates and Bisphenol A (widely known as BPA), additives known for their hormonal effects. From the extraction of raw materials for production to the ultimate disposal of massive waste, plastics negatively impact several environmental domains, animal health and potentially human health, with possible global health and social implications. Plastics can degrade into micro to nano sizes, and those fine particles are more spreadable in air, water, and soil. Some believe the solution to global plastic pollution is to simply reduce the amount of plastic that is being used, but the material is deeply intertwined with daily life. Plastic pollution is a global crisis of increasing scale and severity. Terrestrial and aquatic animals go through various negative impacts such as ingestion, entangling, ulcers, low reproduction, and oxidative stress. Microplastics also degrade human health due to cardiovascular diseases, chronic kidney disease, birth defects, cancer, etc. As per “The Washington Post”, studies have estimated that by 2050, there will be more plastic in the sea than fish. Scientists have estimated that plastic pollution will reach 1.2 billion tons by 2060, causing further health hazards to humans (Li, 2023). However, like every multifaceted challenge, scientists are tackling the issue from various angles, including development of alternative biodegradable plastics, research on plastic eating organisms, advanced recycling technologies, improved waste management, nanotechnology, and public education. Such efforts will guide us to obtain a sustainable solution and mitigate the impacts of plastic pollution for future generations.

Introduction

Plastic, a synthetic or semi-synthetic organic polymer, is made up of chains of linked subunits called monomers. When identical monomers combine, they create a homopolymer, while different monomers form copolymers. Both homopolymers and copolymers can have straight or branched chains (Helmenstine, 2020).

The polymer used to create plastic is almost always combined with additives like colorants, plasticizers, stabilizers, fillers, and reinforcements, which influence its chemical composition, properties, and cost.

Fig 1: Sample Plastic Polymer Chain



Despite their differences, all plastics share common characteristics: they exist in solid states (as amorphous solids, crystalline solids, or semicrystalline solids), have poor conductivity, provide high dielectric strength as insulators, exhibit unrecoverable elongation under stress (known as “creep”), and are durable. All plastics are composed primarily of carbon and hydrogen, which contribute to their strength. The term "plastic" itself refers to their ability to deform without breaking (Helmenstine, 2020).

This versatility and moldability make plastics suitable for various applications. Common types include polyethylene, polypropylene, polystyrene, and polyvinyl chloride, each with distinct properties. Plastics are often identified by acronyms representing their chemical formulas, such as PET (Polyethylene terephthalate), HDPE (High-density polyethylene), PVC (Polyvinyl chloride), PP (Polypropylene), PS (Polystyrene), and LDPE (Low-density polyethylene) (Helmenstine, 2020).

The first man-made plastic, Parkesine, was developed by Alexander Parkes and showcased at the 1862 Great International Exhibition in London. This organic material, derived from cellulose, could be molded when heated and would retain its shape upon cooling (Bellis, 2020). Following Parkesine, formaldehyde-based plastics emerged, with casein plastics (made from milk protein and formaldehyde) invented around 1897 for chalkboards. Notable early brands include Galalith and Erinoid. In 1899, Arthur Smith patented phenol-formaldehyde resins as substitutes for ebonite in electrical insulation, marking the first patent for processing a formaldehyde resin. In 1907, Leo Hendrik Baekeland improved the phenol-formaldehyde process and created Bakelite, the first fully synthetic resin to achieve commercial success (Bellis, 2020). The commercialization of plastic accelerated during World War II, leading to widespread use in the following decades. Significant production increases followed Neil Armstrong’s historic planting of a nylon flag on the moon in 1969 (Pilapitiya, 2024). By 2022, global plastic production reached an astonishing 400.3 million metric tons, reflecting a 1.6 percent increase from the previous year (Statista, 2023).

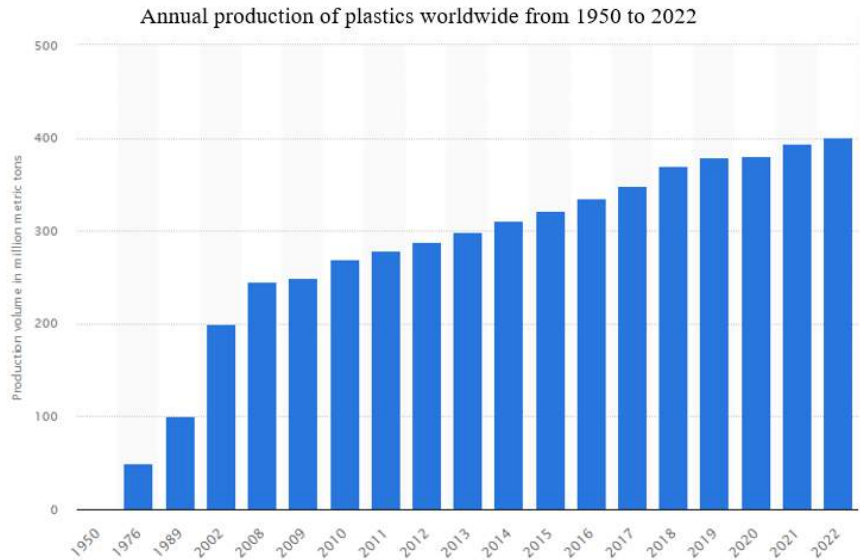


Fig 2: Plastic production from 1950 to 2022

Today, plastics are integral to many aspects of daily life, including packaging, consumer goods, medical applications, the automotive industry, construction, textiles, electronics, sports and recreation, and agriculture. However, varied usage has impacted several environmental domains negatively. This paper will discuss extensively the hazards associated with extensive plastic use, the short- and long-term effects of plastic pollution, and potential solutions. By examining these issues, we aim to underscore the importance of renewability in our lifestyles.

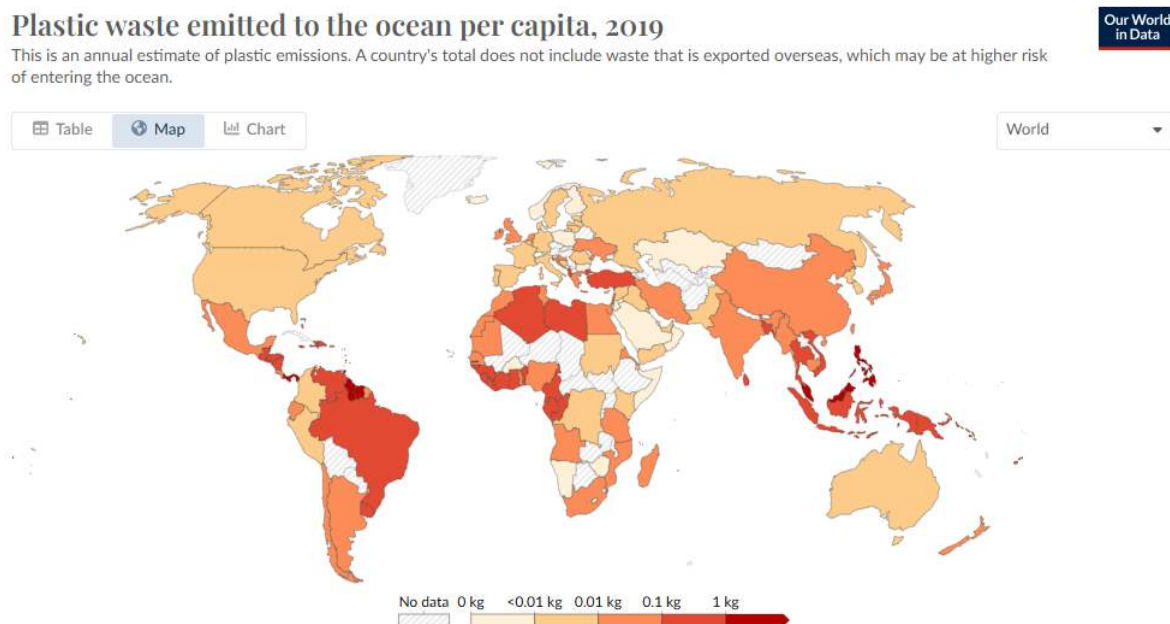
Research

One of the principal contributors to the increasing prevalence of plastic pollution is the overproduction of plastic materials. Production escalated significantly from 2.3 million tons in 1950 to 448 million tons by 2015, with projections suggesting it may double by 2050 (Boulenger, 2024). Over the two decades leading up to 2019, global plastic production doubled, and by 2040, the manufacturing and processing of plastics could account for as much as 20% of global oil production and utilize 15% of the annual carbon emissions budget. Remarkably, nearly half of all plastic ever produced has been generated within the last 15 years (Boulenger, 2024). Currently, global annual plastic production surpasses 359 million tons; however, only approximately 50% of this is recycled (Lewis, 2023). This situation is exacerbated by the inherent durability of plastics, which can take up to 400 years to decompose fully. According to the OECD Outlook, nearly half of all plastic waste originates from OECD countries. Per capita plastic waste varies considerably, with the United States generating an average of 221 kg annually, European OECD countries producing around 114 kg, and Japan and Korea averaging 69 kg each (OECD, 2022). A substantial portion of plastic pollution results from inadequate collection and disposal of larger debris, known as macroplastics, as well as the leakage of microplastics, which present significant health and environmental risks.

Another contributing factor is the prevalence of single-use plastics. These items, primarily manufactured from fossil fuel-based chemicals, are designed for immediate disposal following use (NRDC, 2024). Single-use plastics are deeply embedded in daily life, commonly utilized for packaging and service ware, such as bags, bottles, wrappers, and straws. Their inherent "disposable" nature has led to the generation of vast quantities of waste, a significant portion of which is seldom recycled. The United Nations reports that approximately 300 million tons of plastic are produced annually, with a considerable share designated for single-use applications (UNEP, 2021).

Inadequate waste management practices further exacerbate this issue. In developing nations, where waste management infrastructure is frequently underfunded, plastics often find their way into landfills, rivers, and oceans. The absence of recycling facilities compounds the problem, with around one-fifth of plastics still mismanaged, particularly in low- to middle-income countries (Ritchie, 2024). Many regions lack efficient waste management systems, leading to the improper disposal of plastic waste.

Fig 3: Global Plastic Emissions Graph



Thus, detrimental effects have risen from the above-mentioned causes. Among such is environmental damage. Plastic pollution poses severe threats to both terrestrial and aquatic ecosystems. Larger plastics can entangle wildlife, resulting in injury or death, while microplastics represent a more insidious danger as they are ingested by various organisms. The degradation of plastics into micro and nano-sized particles enhances their dispersion across air, water, and soil, thereby increasing their bioavailability to organisms at different trophic levels. Recent studies have documented the presence of microplastics in diverse environments, including those suspended in the water column (Thompson, 2024). Microplastics used in

mulching can lead to soil contamination and alter flora and fauna, while chlorinated plastics may release harmful chemicals into the soil, affecting groundwater and ecosystems. Such impacts contribute to a decline in biodiversity among both terrestrial and aquatic species. Aquatic organisms, in particular, face risks from ingestion, entanglement, and toxic effects. The 2016 report by the Secretariat of the Convention on Biological Diversity (CBD) identified marine debris as a globally significant stressor on marine and coastal environments, indicating that nearly 800 marine species are adversely affected by plastic pollution.

The implications of plastic pollution also extend to human health. Emerging research links microplastics to various health conditions, including cardiovascular diseases, chronic kidney disease, and reproductive issues (Li, 2023). The bioaccumulation of harmful chemicals from plastics within the food chain raises significant concerns regarding long-term health effects, necessitating further investigation into the relationship between plastic exposure and health outcomes. Notably, 99% of plastic originates from fossil fuels. The extraction of oil and gas, particularly through hydraulic fracturing for natural gas, releases a variety of toxic substances into the air and water, often in substantial quantities. Over 170 fracking chemicals used to produce primary feedstocks for plastic have documented health impacts, including cancer, neurological disorders, reproductive and developmental toxicity, and immune system impairment. These toxins can result in birth defects and affect the skin, eyes, and other sensory organs, as well as the respiratory, nervous, and gastrointestinal systems, liver, and brain. Economically, the burden of plastic pollution is significant, impacting fisheries, tourism, and public health systems, with estimates suggesting that plastic pollution could reach 1.2 billion tons by 2060 (Li, 2023). The costs associated with cleaning up plastic waste and mitigating its ecological impacts can strain public resources and hinder economic development.

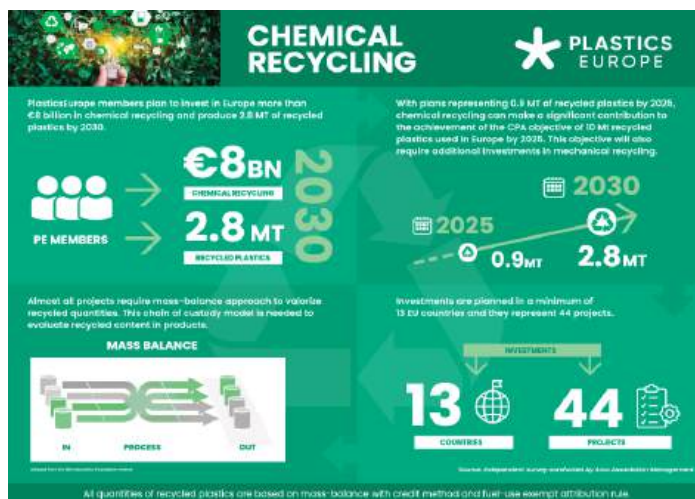
To address these challenges, nations are implementing policies aimed at limiting the production and use of single-use plastics, which can substantially reduce plastic waste. Many countries are enacting bans or taxes on plastic bags and promoting the adoption of biodegradable alternatives. Furthermore, developing nations are investing in waste management infrastructure, which is essential for effective plastic disposal and recycling. Communities must be equipped with adequate facilities to manage plastic waste and educate citizens on proper disposal practices. Raising awareness about the impacts of plastic pollution is critical for fostering changes in consumer behavior. Educational campaigns can inform the public about the importance of reducing plastic usage, recycling, and opting for sustainable alternatives. Currently, only about 10% of all plastic waste is recycled, but projections indicate that this figure could rise to 45% by 2050 (Plastic For Change, 2024).

In addition to advocacy, scientific research into biodegradable plastics and sustainable materials presents alternatives to traditional plastics. Companies are increasingly exploring renewable resources to develop packaging and products that minimize environmental impact. One notable approach is the concept of a circular economy, wherein raw materials are recycled repeatedly, thereby reducing the need for extraction or new production. A circular economy maintains plastics in a closed loop, helping to prevent them from leaking into the environment.

By producing new plastic products from existing plastic materials, the need for fossil fuel extraction to create new virgin plastic is diminished. Although establishing a circular economy poses numerous challenges, companies like Unilever are among the prominent brands working toward this objective, and they are part of a coalition of over a thousand organizations united behind the Ellen MacArthur Foundation's vision of a circular economy for plastics by 2025 (Heggie, N/A).

Researchers are also exploring chemical recycling, a process that involves altering the chemical structure of polymeric waste to convert it into substances usable as raw materials for manufacturing plastics or other products. Various chemical recycling technologies, including pyrolysis, gasification, hydro-cracking, and depolymerization, complement other plastic recycling methods, such as mechanical, dissolution, and organic recycling. Chemical recycling can be particularly advantageous for plastic waste that would otherwise be destined for incineration or landfill. The European Commission has set ambitious circularity objectives for plastics, with regulatory targets of a maximum of 10% landfilling of municipal waste by 2035, 50% recycling of plastic packaging by 2025, and 55% by 2030. In this context, chemical recycling represents a constructive step towards reducing disposed waste and contributing to a circular economy for plastics (Plastics Europe, N/A).

Fig 4: Chemical Recycling Infographic



Nanotechnology also presents a promising avenue for addressing plastic pollution by developing materials capable of capturing microplastics from water sources, thereby safeguarding aquatic ecosystems. Nanotechnology enables the creation of materials with nanoscale structures that can selectively adsorb microplastics from water. For example, researchers are developing nanofibers and nanocomposites that have high surface area and specific surface properties to attract and bind microplastic particles. These materials can be integrated into filtration systems or deployed in water bodies to remove microplastics before they enter the food chain (Arevalo, 2024). Nanomaterials also can enhance the degradation of plastics

through catalysis. Certain nanoparticles, such as titanium dioxide and zinc oxide, can act as photocatalysts when exposed to UV light, accelerating the breakdown of plastic polymers into less harmful substances. This approach holds potential for addressing plastic waste in various environments, including landfills and oceans.

As research in this field progresses, the potential for such solutions hope to significantly reduce plastic pollution and its associated impacts on ecosystems and human well-being.

Conclusion

In conclusion, the extensive and rapid proliferation of plastic materials has become one of the defining environmental challenges of our time. From its introduction in the 19th century to the staggering production levels today, plastic has transformed industries and daily life. However, this convenience comes at a significant ecological and health cost. The sheer volume of plastic produced, coupled with inadequate waste management practices and the pervasive use of single-use plastics, has resulted in a crisis of pollution that endangers ecosystems and human health alike. Both nano and macro pollutants infect our environment, spreading malware in its path. The persistence of plastics in the environment underscores the urgent need for effective interventions. Policymakers must prioritize strategies that limit plastic production, promote sustainable alternatives, and enhance recycling systems. Likewise, alongside advocacy and public awareness, the implementation of innovative solutions, such as the development of biodegradable materials, advancements in chemical recycling, and the application of nanotechnology, offers promising pathways to mitigate the impacts of plastic pollution. Collectively, these efforts facilitate a holistic approach that engages governments, industries, and communities in fostering a circular economy for plastics. The topics and solutions discussed in this paper are a guiding tool to many scientists on pollution management.

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Artificial Intelligence in Global K-12 Education: Comparative Insights, the Case of Kazakhstan By Elezhan Zhakiya

Artificial Intelligence (AI) is rapidly transforming the landscape of K–12 education by enabling personalized learning, streamlining administrative processes, and enhancing data-driven decision-making. Countries with mature digital infrastructures, such as the United States, China, and Finland, have leveraged AI to drive educational innovation through intelligent tutoring systems, adaptive testing, and learning analytics. However, the degree of integration and the impact of AI vary significantly across geopolitical and socioeconomic contexts. This study presents a comparative analysis of global trends in AI adoption within primary and secondary education, followed by an in-depth case study of Kazakhstan’s evolving experience.

Drawing from international best practices and scholarly literature, we identify key enablers of effective AI integration, including technological readiness, educator digital competency, regulatory frameworks, and institutional support. The case study of Kazakhstan, an emerging economy with growing investment in digital transformation, provides a unique lens through which to examine both the promise and the pitfalls of AI in education. Although Kazakhstan has launched national strategies such as Digital Kazakhstan and begun pilot programs in elite institutions like Nazarbayev Intellectual Schools (NIS), broader implementation is hindered by infrastructural disparities, limited teacher training, and regulatory uncertainty around AI ethics and data governance.

This paper argues that Kazakhstan’s experience exemplifies challenges faced by many mid-tier economies aiming to modernize their education systems through AI. It also highlights how targeted investments, clear policy frameworks, and inclusive digital training initiatives can close the implementation gap. The findings offer practical guidance not only for policymakers in similar contexts but also for global stakeholders interested in equitable and sustainable AI integration in K-12 education.

Keywords

Artificial Intelligence, K-12 Education, Educational Technology, Comparative Education, Kazakhstan, Intelligent Tutoring Systems, Digital Transformation, Policy Implementation, Teacher Training, Equity in Education

1. Introduction

Artificial Intelligence (AI) has emerged as a transformative force in the field of education, reshaping how students learn, how teachers instruct, and how institutions manage resources. In the context of K-12 education, AI technologies offer immense potential to enhance personalized learning, improve assessment accuracy, automate administrative tasks, and reduce systemic inefficiencies. As AI continues to mature, its applications are becoming increasingly integrated into educational ecosystems around the world, influencing curriculum design, pedagogical practices, and educational equity.

In technologically advanced countries such as the United States, China, and Finland, AI has already begun to demonstrate tangible benefits in educational settings. For example, intelligent tutoring systems and adaptive learning platforms have been successfully deployed to provide students with customized learning experiences based on their individual strengths and weaknesses. AI-driven analytics tools are being used to monitor student engagement, predict academic performance, and enable timely interventions. These developments reflect a broader global trend in which educational institutions are moving beyond static digital tools toward dynamic, data-informed systems that respond to learners' needs in real time. Despite this progress, the implementation of AI in education is far from uniform across the globe. While high-income countries with robust digital infrastructures and mature education systems have been able to integrate AI with relative ease, many low- and middle-income countries face significant challenges in this area. Factors such as limited technological infrastructure, inadequate teacher training, and regulatory ambiguity regarding data privacy and ethical use of AI present formidable barriers to adoption. These disparities risk deepening the global digital divide in education, raising concerns about equity and access to innovation.

Kazakhstan offers a compelling case through which to explore these dynamics. Positioned as an upper-middle-income country with ambitious national development goals, Kazakhstan has made significant investments in digital transformation, particularly through initiatives like Digital Kazakhstan and the Kazakhstan 2050 Strategy. These programs emphasize the role of technology in economic and social modernization, including the education sector. Despite these policy commitments, AI adoption in Kazakhstani schools remains largely experimental and localized, with advanced AI tools primarily found in a few elite institutions such as the Nazarbayev Intellectual Schools (NIS). For the majority of public schools, especially those in rural and under-resourced areas, the integration of AI remains a distant prospect. This situation reflects a broader pattern observable in many countries that are actively pursuing digital reform but struggle with uneven implementation. On one hand, pilot projects and early successes in select schools highlight the promise of AI to enhance learning outcomes and improve teacher efficiency. On the other hand, systemic barriers prevent the scaling of these technologies to the national level. Kazakhstan's case illustrates how ambitious policy visions can encounter practical constraints, including insufficient technological infrastructure, lack of digital competence among educators, and the absence of clear legal frameworks to govern data use and algorithmic decision-making in educational contexts.

This paper seeks to contribute to the global discourse on AI in education by offering a comparative analysis that situates Kazakhstan's experience within the broader landscape of international efforts to modernize school systems. Through a synthesis of existing literature, analysis of national policy documents, and case studies from leading AI education systems, the study identifies both common and context-specific factors influencing AI adoption. In doing so, it explores how Kazakhstan and other similarly positioned countries can leverage global lessons while developing context-sensitive strategies that account for local constraints and opportunities. Moreover, this research emphasizes the importance of inclusive digital transformation. Effective

AI integration should not be limited to technologically advanced schools or urban centers. Instead, it must be designed to bridge educational gaps, including those based on geography, socioeconomic status, and access to quality instruction. Without deliberate policies aimed at equity, there is a risk that AI could exacerbate existing disparities rather than alleviate them.

2. Theoretical Framework

The integration of Artificial Intelligence into education draws upon several interrelated theoretical perspectives, including constructivism, personalized learning theory, and educational data mining. At its core, AI in education aims to tailor learning experiences to individual students, based on real-time analysis of their performance and learning behaviors. This approach aligns with Vygotsky's constructivist theory, which emphasizes the importance of scaffolding and individualized support in cognitive development.

Personalized learning theory supports the idea that education should be adapted to the pace, style, and needs of each learner. AI enables this customization through systems that analyze large datasets of student interactions, identifying patterns that suggest knowledge gaps or learning preferences. Intelligent tutoring systems, for instance, adjust the difficulty level and sequence of learning tasks according to a student's progress, creating a dynamic feedback loop between learner and machine.

In parallel, educational data mining and learning analytics offer a framework for understanding how data generated by students can inform pedagogical decisions. Machine learning models are trained on historical data to predict future performance, identify students at risk of failure, and suggest targeted interventions. These predictive tools are increasingly embedded in AI-powered learning management systems, facilitating a shift from reactive to proactive educational strategies.

Ethical frameworks are also essential in guiding AI adoption. Concepts such as fairness, transparency, and data privacy must be considered to ensure that AI does not reinforce existing inequalities or introduce new forms of bias. Responsible AI in education requires policies and technical safeguards that align with UNESCO and OECD principles on human-centered digital innovation.

3. Literature Review: Global Applications of AI in K–12 Education

Globally, the integration of AI in school education varies in depth and sophistication, influenced by each country's technological maturity, regulatory landscape, and educational goals. In the United States, AI has been applied across a wide range of educational settings. Systems like Carnegie Learning and Knewton offer intelligent tutoring platforms that adapt to student needs using machine learning algorithms. These tools have been shown to improve learning outcomes in subjects such as mathematics, where individualized pacing and feedback are crucial. Additionally, learning analytics are widely used in U.S. schools to track student engagement, monitor academic risk factors, and inform teacher interventions.

China presents a unique case of rapid and large-scale AI deployment in education. Companies like Squirrel AI and TAL Education Group serve millions of students with adaptive learning platforms that deliver tailored instruction across diverse subjects. The Chinese model is notable for its integration of AI into national education reform, strong government support, and emphasis on data-driven instruction. AI is used not only for learning personalization but also for behavior monitoring and performance forecasting, raising important questions about ethics and surveillance.

Finland, though smaller in scale, represents a progressive model where AI is embedded in inclusive and equitable education. Finnish schools employ AI to support differentiated instruction and early identification of learning difficulties. The country prioritizes ethical considerations, ensuring that AI tools comply with stringent data protection standards and support pedagogical goals rather than replace educators. Teacher involvement in AI system design and evaluation is a key feature of the Finnish approach, fostering trust and alignment with educational values.

These global examples illustrate a spectrum of AI integration strategies. Some prioritize scalability and innovation, while others focus on ethical implementation and system coherence. Lessons from these contexts provide valuable insights for countries such as Kazakhstan, where AI integration is still nascent but strategically prioritized.

4. Current Status of AI in Kazakhstan's School System

Kazakhstan has expressed strong interest in educational digitalization through national policies such as the Digital Kazakhstan program and the Kazakhstan 2050 Strategy. These initiatives recognize the potential of technology to improve education quality and access. Despite this policy momentum, the actual implementation of AI in Kazakhstani schools remains limited and uneven.

Pilot programs have been launched in select institutions, most notably the Nazarbayev Intellectual Schools (NIS). These elite schools have experimented with intelligent assessment systems, adaptive learning software, and digital performance analytics. Early evaluations suggest positive outcomes, particularly in science and mathematics, where students benefit from targeted feedback and individualized learning pathways. However, the broader public school system faces significant barriers. Many rural schools lack reliable internet connectivity and adequate digital infrastructure, making it difficult to deploy AI tools at scale. In urban schools, while infrastructure may be available, teachers often lack the digital literacy needed to integrate AI effectively into their pedagogical practice. Professional development programs on AI and education are not yet widely institutionalized, creating a skills gap that limits adoption. Regulatory and ethical challenges also persist. Kazakhstan does not yet have a comprehensive legal framework governing the use of AI in education, particularly regarding student data privacy and algorithmic accountability. This legal uncertainty can deter schools and technology providers from fully engaging with AI initiatives, particularly those involving sensitive student information. Despite these obstacles, there is a growing awareness among policymakers and

educators of AI's potential to transform the education sector. Continued investment in infrastructure, teacher training, and policy development could enable Kazakhstan to move beyond isolated pilot projects and toward system-wide integration of AI in education.

5. Methodology

This study adopts a qualitative research approach, combining comparative policy analysis with a case study methodology. The goal is to examine how AI is integrated into K–12 education across various national contexts and to assess Kazakhstan's current trajectory in light of global trends.

Primary data sources include:

- National education policies and strategic frameworks from Kazakhstan and selected comparator countries
- Reports from international organizations such as UNESCO, the OECD, and the European Commission
- Peer-reviewed academic literature on AI in education, with a focus on intelligent tutoring systems, learning analytics, and teacher readiness
- Institutional documentation from pilot AI initiatives in Kazakhstan, including annual reports from the Nazarbayev Intellectual Schools

This multi-source approach enables triangulation of data to ensure credibility and depth of analysis. The global cases were selected for their relevance to different stages of AI adoption and for their representativeness of varied governance and infrastructure contexts. The Kazakhstan case study was examined through both document analysis and synthesis of existing evaluation data from national sources.

6. Results and Discussion

6.1 Key Benefits of AI in Education: A Global Perspective

Across all reviewed contexts, AI has demonstrated several consistent advantages for K–12 education. These include:

1. Personalized learning experiences that adjust to student performance in real time
2. Enhanced assessment tools that offer immediate feedback and longitudinal tracking
3. Reduced administrative burden through automation of grading, attendance, and scheduling
4. Predictive analytics that identify at-risk students and support early interventions

These benefits are most evident in environments with strong digital infrastructure and well-trained educators who can integrate AI tools into teaching practices.

6.2 Kazakhstan's Experience: Promise and Limitations

In Kazakhstan, AI-related benefits are emerging in pilot settings, especially within the NIS network. Students using intelligent assessment tools have shown improvement in mathematics and science outcomes, with teachers reporting more accurate diagnosis of learning gaps.

While some early initiatives have demonstrated the potential of AI in improving learning outcomes, these gains are largely restricted to a few well-resourced institutions. Most public schools, particularly in rural areas, struggle with inadequate infrastructure, including limited access to broadband internet and outdated technological equipment. This lack of foundational resources poses a major barrier to implementing AI-based tools at scale. Compounding this issue is the limited preparedness of educators. Many teachers have not received formal training in digital tools or AI integration, making it difficult to effectively incorporate these technologies into classroom instruction. The absence of national standards or structured support further limits their capacity to adapt to technological change.

At the policy level, there is a noticeable gap in regulations related to AI use in education. Questions around student data privacy, ethical use of algorithms, and accountability remain largely unaddressed, leaving schools uncertain about the boundaries and responsibilities involved in deploying AI systems. These challenges also raise concerns about equity. Without intentional strategies to ensure widespread access and support, there is a real risk that AI could reinforce existing disparities, with elite urban schools advancing rapidly while under-resourced rural schools fall further behind.

These findings suggest that while AI holds substantial promise for Kazakhstan's education system, its benefits will remain limited unless structural constraints are addressed through coordinated policy action.

7. Recommendations

To enable responsible, scalable, and equitable AI integration in Kazakhstan's K–12 education system, the following actions are recommended:

7.1 Infrastructure Development

Expand digital infrastructure to ensure all schools, including those in rural and remote regions, have reliable internet access and modern computing resources. Government investment, possibly supported through international partnerships, should prioritize closing the digital divide.

7.2 Teacher Training and Capacity Building

Introduce nationwide professional development programs focused on digital literacy, AI applications, and ethical use of technology in education. Training should be continuous, practice-based, and integrated into teacher certification processes.

7.3 Regulatory and Ethical Frameworks

Develop a national framework that sets clear guidelines on data privacy, algorithmic accountability, and ethical standards for AI use in schools. This framework should align with international norms while addressing context-specific challenges in Kazakhstan.

7.4 Pilot Expansion and Evidence-Based Scaling

Extend successful pilot projects to a broader range of schools, including public and rural institutions. Use robust monitoring and evaluation mechanisms to generate evidence on effectiveness, equity, and scalability.

7.5 Inclusive AI Strategy Design

Engage educators, parents, students, and civil society in co-designing AI initiatives. Inclusive planning ensures that AI tools are not only technically sound but also socially and pedagogically appropriate.

8. Conclusion

Artificial Intelligence presents a transformative opportunity for the future of K–12 education, offering new pathways for personalization, efficiency, and data-informed decision-making. Global experiences from the United States, China, and Finland demonstrate that with adequate infrastructure, teacher capacity, and regulatory clarity, AI can significantly enhance both learning outcomes and educational management. These benefits, however, are not automatically transferable across contexts. Successful implementation requires attention to local constraints, pedagogical practices, and social equity.

Kazakhstan's evolving engagement with AI in education offers both a cautionary tale and a source of optimism. While notable progress has been made through pilot initiatives in elite institutions, systemic barriers continue to hinder broader adoption. These include infrastructural gaps, limited digital literacy among educators, and an underdeveloped regulatory environment. If left unaddressed, these factors risk excluding large segments of the population from the benefits of educational innovation.

To move from isolated successes to system-wide transformation, Kazakhstan must adopt a multidimensional strategy. This includes expanding digital infrastructure, investing in teacher training, establishing national ethical guidelines, and ensuring that AI technologies serve inclusive and pedagogically sound purposes. These steps are not only relevant to Kazakhstan but also to other countries navigating similar transitions.

By situating Kazakhstan's experience within a broader comparative context, this paper contributes to a growing body of research on how nations can responsibly and effectively integrate AI into school education. The recommendations provided here aim to support policymakers, educators, and researchers in designing sustainable and equitable AI adoption strategies for the future of learning.

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Addressing the Digital Footprint Problem: Principles of Minimal Data Collection in System Design By Kazbek Bektemirov

Abstract

In the contemporary digital landscape, extensive personal data collection presents significant risks to privacy and security. This paper explores the "digital footprint" issue and proposes guiding principles for designing digital systems with minimal data collection in mind. By examining theoretical frameworks and current privacy-centered practices, this research emphasizes how minimal data collection principles can effectively reduce risks associated with user data misuse, leaks, and unauthorized surveillance, thereby promoting a safer digital environment.

Keywords digital footprint, minimal data collection, data privacy, system design, cybersecurity

1. Introduction

Digital footprints, defined as records and traces individuals leave behind through their interactions with digital environments, have grown exponentially alongside technological advancements. From social media to e-commerce, users often unknowingly contribute excessive personal information. This widespread data capture raises critical issues regarding privacy, security, and user autonomy. In many systems, users are subjected to data practices that are neither transparent nor limited to what is essential, which undermines informed consent and individual control over personal information. The resulting imbalance of power between data collectors and users challenges ethical boundaries and regulatory standards.

The principle of minimal data collection offers a foundational response to these challenges. It asserts that digital systems should collect and retain only the data essential for functionality, thereby reducing risks related to misuse, breaches, and surveillance. This concept extends beyond compliance, positioning minimal data collection as a core design principle that fosters user trust and systemic resilience. As digital systems become more pervasive and complex, embedding such privacy-oriented principles at the design stage becomes essential. This paper proposes practical design guidelines informed by theory and real-world applications to embed these principles into digital system architecture.

2. The Problem of Digital Footprint

Digital footprints comprise both passive and active data, and understanding their nature is crucial to addressing privacy and security risks. Passive footprints refer to data collected without explicit user input, such as cookies, IP addresses, and location tracking. These are often accumulated silently during user interactions with websites, mobile apps, or smart devices. Users typically have limited visibility or control over this data collection, which may persist across platforms and over extended periods. Active footprints, on the other hand, involve data users voluntarily provide, including social media posts, search history, online purchases, and profile

details. Though seemingly more transparent, even actively shared data is often stored and processed beyond the intended context or timeframe.

Together, passive and active data points enable extensive user profiling. The aggregation and analysis of this information can uncover behavioral patterns, preferences, and even psychological traits, often without the user's awareness. This capability allows organizations to target users with high precision, but it also opens doors to exploitation, manipulation, and discriminatory practices. Advanced data analytics and machine learning amplify these risks, enabling inference of sensitive attributes and decision-making processes that can impact opportunities in employment, finance, healthcare, and other critical areas of life. The problem is further exacerbated by opaque data-sharing practices, where collected information is passed between third-party actors without user consent.

The risks associated with uncontrolled digital footprints extend beyond individual privacy to societal and institutional levels. Privacy violations are increasingly common, as excessive data availability facilitates unauthorized surveillance, often conducted without legal or ethical oversight. High-profile data breaches highlight the vulnerability of centralized databases containing vast amounts of personal information. These incidents erode public trust and demonstrate how organizations become custodians of risk when they collect more data than necessary. Additionally, the sheer scale of digital footprints contributes to a loss of autonomy. When users lose control over their data, they also lose the ability to define their digital identity. The cumulative effect is a diminished sense of security and confidence in digital systems, calling for the establishment of stringent guidelines and ethical principles that prioritize minimalism in data handling.

3. Theoretical Basis for Minimal Data Collection

The principle of minimal data collection is supported by a range of theoretical frameworks and legal doctrines. Among the most prominent is Privacy by Design (PbD), a model introduced by Ann Cavoukian that advocates for privacy to be embedded into the design and architecture of information systems from the outset. PbD promotes a proactive approach that prevents privacy risks rather than addressing them reactively. This includes measures such as default privacy settings, data minimization at every processing stage, and user-centric transparency mechanisms. PbD emphasizes that privacy should not be an afterthought or an add-on feature, but an integral aspect of system development. This philosophy aligns with ethical design thinking and fosters sustainable digital ecosystems.

Another cornerstone of the theoretical basis is the Data Minimization Principle articulated in the European Union's General Data Protection Regulation (GDPR). Article 5 of the GDPR mandates that personal data collected must be adequate, relevant, and limited to what is necessary in relation to the purposes for which it is processed. This principle reflects a shift from open-ended data harvesting to purpose-specific collection, requiring developers to justify why each data point is necessary. GDPR also introduces accountability measures, obligating data

controllers to demonstrate compliance. These legal requirements enforce discipline in data practices and encourage organizations to evaluate their data flows with greater scrutiny. Together, these frameworks form a solid foundation for integrating minimal data collection into system design. By drawing from both ethical principles and regulatory standards, system designers can proactively build privacy into their platforms. Furthermore, theoretical advances in information ethics and digital sovereignty underscore the importance of returning control to users. In this context, minimal data collection becomes not only a technical guideline but also a normative stance against exploitative and opaque digital practices. Designers and developers have both a moral and operational imperative to reduce unnecessary data exposure and to create systems that are respectful, secure, and transparent by design.

4. Principles of Minimal Data Collection in System Design

4.1 Purpose Limitation

Systems must clearly define the purpose of data collection. Only data necessary for that specific function should be gathered, preventing excessive or generalized acquisition. Developers should conduct rigorous needs assessments to determine the essential data required for functionality. Explicit articulation of data purpose fosters clarity in design and policy, enabling users to understand why their data are being collected and how it will be used. This also helps organizations avoid the temptation to accumulate data for vague or future purposes that may never be realized.

4.2 Collection Restriction

System defaults should restrict data collection unless explicitly permitted by users. For example, location services should activate only when functionally required and with user consent. Privacy settings must be configured for maximum protection by default, with opt-in rather than opt-out structures. This approach respects user autonomy and aligns with the principle of least privilege in cybersecurity, ensuring that data access is strictly limited to what is functionally justified. System prompts should reinforce informed consent and offer clear choices without nudging users toward excessive disclosure.

4.3 Transparency and User Awareness

Users must be informed about what data are collected and how they are used. Accessible privacy settings and clear disclosures help users make informed decisions. This includes providing information in non-technical language, with layered explanations that allow users to explore details at their discretion. Transparency not only improves user understanding but also fosters trust, which is essential for sustained engagement. Effective communication of privacy practices is no longer optional but a critical aspect of ethical digital system design.

4.4 Data Lifecycle Management

Designers should implement data deletion and anonymization protocols. Retention beyond the original purpose should be avoided unless justified. These lifecycle controls ensure that data do not accumulate indefinitely, reducing risks of future misuse or breaches. Periodic audits, expiration policies, and automated deletion schedules contribute to sustainable and responsible data management. Anonymization techniques should be robust, ensuring that de-identified data cannot be easily re-linked to individual identities.

5. Case Studies and Applications

Apple has implemented a privacy framework that includes its "App Tracking Transparency" initiative, requiring apps to obtain user permission before tracking across other applications and websites. This approach limits third-party data sharing and enforces user control. By introducing these privacy-centric features, Apple has positioned itself as a leader in user data protection, demonstrating that privacy-focused design can be both technically feasible and commercially viable.

Signal, an encrypted messaging application, has gained recognition for collecting minimal metadata and placing strong emphasis on user privacy. Signal's design excludes data like contact lists and location tracking, distinguishing it from competitors who rely heavily on data harvesting. This model shows how privacy can be an asset in user trust and brand differentiation. The application's open-source nature and end-to-end encryption standards further validate the technical maturity of minimal data collection strategies.

These examples highlight successful real-world applications of the minimal data collection principles. Both Apple and Signal show that minimalism in data design is not only achievable but also beneficial in market positioning and user satisfaction. Their practices provide concrete blueprints for developers and offer empirical validation of the theoretical principles discussed in earlier sections.

6. Challenges and Limitations

Despite the conceptual clarity and demonstrated benefits, implementing minimal data collection is not without difficulty. One major challenge lies in reconciling data minimization with business models that rely heavily on user data for analytics, personalization, or targeted advertising. Organizations must navigate the tension between profitability and privacy, and this often requires reimagining value propositions or developing privacy-preserving alternatives such as federated learning or local processing. Cultural and organizational inertia can also impede the shift toward minimalism.

Another challenge is the lack of regulatory uniformity across jurisdictions. While regions like the European Union enforce strict data minimization through instruments like the GDPR, other areas operate under less defined or fragmented privacy laws. This lack of harmonization complicates implementation for companies operating globally. Navigating these legal landscapes requires significant investment in compliance frameworks and dynamic policy adaptation.

Technical limitations also exist, particularly for legacy systems that were not designed with privacy in mind. Retrofitting these systems can be resource-intensive and complex, often requiring architectural overhauls or the replacement of core modules. Moreover, the development of user interfaces that genuinely support informed consent and transparency demands interdisciplinary collaboration, involving technologists, designers, legal experts, and ethicists. Without this cooperation, efforts to implement minimal data collection may fall short or inadvertently create new risks.

7. Future Directions

Future research and development should prioritize the creation of standardized frameworks for evaluating data minimalism. This includes technical metrics that can assess how much data is being collected, whether it aligns with stated purposes, and how effectively it is managed throughout its lifecycle. Metrics can also guide benchmarking across industries and foster accountability through comparative analysis.

Another promising avenue is the development of user-centric privacy tools that allow individuals to visualize, control, and audit their digital footprints in real time. Such tools empower users with agency and reduce the cognitive burden associated with managing complex privacy settings. Enhancing user literacy through education and design interventions will also be vital. Privacy should not be reserved for experts or the technologically literate, but made accessible and actionable for all users.

8. Conclusion

Digital footprints pose significant risks to user privacy and autonomy. Principles such as purpose limitation, collection restriction, transparency, and lifecycle management offer actionable strategies for system designers. These principles not only safeguard user interests but also support resilient, ethically sound digital infrastructures. By embedding these into system architecture, developers can enhance digital trust and contribute to a safer online ecosystem. Minimal data collection should be embraced as a default standard in digital design. As technological systems become more embedded in everyday life, prioritizing user privacy is not only a legal or technical challenge but a moral imperative. Through interdisciplinary collaboration, thoughtful policy, and user-centered innovation, the path toward a privacy-conscious digital world is both achievable and necessary.

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Impact of Climate Change on Agriculture, Market Stability, and Environmental Implications By Gene Choi

Abstract

With the increasing influence of climate change and the onset of more volatile weather events and natural disasters, one of the most understated yet harsh impacts has been on agricultural production and its growing instability in the economy. Climate change, marked by enduring shifts in global weather patterns and temperature, is making farming practices increasingly unpredictable, with extreme events disrupting once steady systems. Farmers now face mounting challenges in balancing agricultural output with environmental considerations. The purpose of this study is to investigate the severity of climate change's impact on agricultural efficiency and how it creates predicaments in both environment and economy through imbalanced supply and demand. The methodology combined literary review, climate and market data analysis, and AI-powered analytics. Historical data was used to determine correlations between extreme weather events, agricultural yields, and market outcomes. A proposed solution, *AgriVision*, is an AI-powered app that leverages real-time climate forecasting to help predict and adapt to weather-related disruptions.

Results highlight the significant influence of climate on major crop industries, with disruptions leading to severe price volatility and market instability. Overproduction has also produced vast amounts of food waste, contributing to higher carbon dioxide emissions and environmental harm. Findings demonstrate that imbalanced agricultural production results in inefficient resource use and greater ecological stress.

This study reinforces climate change's heavy impact on agriculture and market stability, emphasizing the urgency of sustainable practices. Integrating climate data analytics offers a pathway toward production efficiency, food security, and resilience against future volatility.

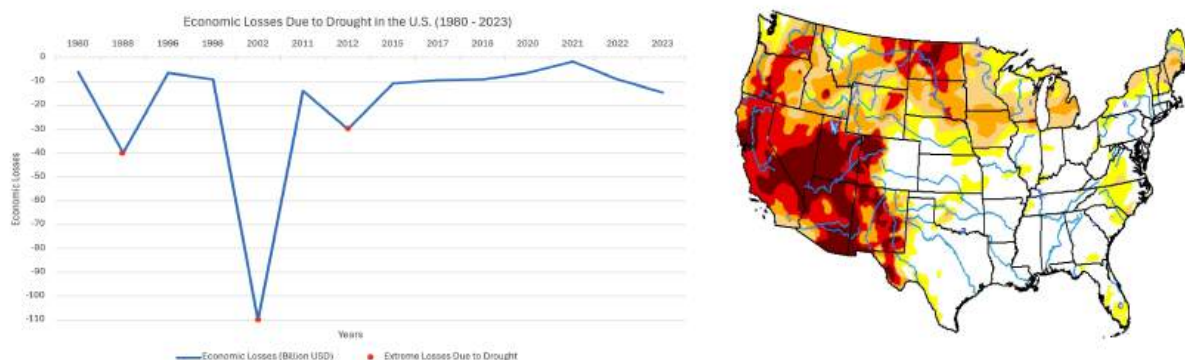
Introduction

Agriculture is the backbone of our global food supply, providing the necessary crops and livestock that sustain billions of people each day. It is also a key driver of economic stability, supporting jobs and trade, especially in rural communities where farming may be the main source of income. However, balancing food production with rising demand from growing populations is becoming increasingly difficult, especially with prevalent environmental challenges including climate change, soil depletion, and water shortages.

Water scarcity is one of the largest environmental challenges affecting agriculture in the United States. In California's Central Valley, one of the world's most productive farming areas, supplying 8% of U.S. agricultural output (by value) and producing 1/4 of the Nation's food, including 40% of the Nation's fruits, nuts, and other table foods, recurring droughts have led to water shortages. In recent years, prolonged droughts and reduced snowfall have led to severe water shortages. Farmers have been forced to pump groundwater at unsustainable rates, causing the ground to sink (subsidence) in some areas. This reduces overall food production, drives up

costs, and can lead to shortages of staple crops like almonds, tomatoes, and lettuce. Due to droughts, as shown in Figure 1, the U.S. has lost billions of dollars in agricultural damage, clearly highlighting its economic harm. As climate change intensifies, water scarcity continues to threaten the stability of global food systems. The Ogallala Aquifer, one of the world's largest underground water reserves, provides irrigation for nearly one-fifth of all U.S. wheat, corn, and cattle production. However, in states like Kansas, Nebraska, and Texas, the aquifer is being depleted faster than it can recharge. In western Kansas, some farmers have already seen their wells dry up, forcing them to abandon irrigated farming altogether. This growing water crisis highlights a deeper challenge in agriculture—finding a balance between production and sustainability. Without reliable water sources, farmers must decide whether to scale back operations or invest in costly adaptations, both of which come with risks. Producing too much can strain natural resources, while producing too little can lead to food insecurity and economic hardship.

Figure 1. Climate Disruption and Economic Losses



Extreme weather variability, particularly drought, has significantly disrupted U.S. agriculture. (A) Annual economic losses from drought-related agricultural damage. (B) Geographic distribution of drought severity in the U.S., highlighting high-risk production zones. These disruptions indicate growing instability in supply chains and market outcomes.

Changes in temperature, rainfall, and extreme weather make farming much more unpredictable. Storms, wildfires, and other disasters can wipe out entire harvests and damage farmland. Climate change is disrupting traditional agricultural cycles and the economics of farming by making weather patterns more unpredictable and extreme. Higher temperatures can stress crops and animals, while irregular rain patterns can lead to droughts or floods, making it harder to grow food. As shown in Figure 2, extreme droughts have become more and more prominent in the U.S. (shown as the dark red color), affecting the crops being produced in those areas. Farmers have long relied on stable seasons to determine when to plant and harvest, but rising temperatures, shifting rainfall patterns, and more frequent droughts, floods, and storms are throwing these cycles off balance. Crops that once thrived in certain regions are struggling, while new pests and diseases are emerging due to changing conditions. This instability forces farmers

to adapt, often requiring costly investments in new technologies, irrigation systems, or alternative crops. As a result, climate change not only affects food production but also creates financial uncertainty, making it harder for farmers to plan for the future and maintain stable prices for consumers.

An increasingly common example of the volatility of food production caused by such varies in climate is overproduction. In the context of farming, overproduction occurs when an imbalance is formed between the amount of food produced and the amount of food needed, often leading to waste and financial losses for farmers. Unpredictable weather only worsens this issue—too much rain can cause a huge harvest that floods the market and lowers prices, while droughts in other areas create shortages and drive prices up. Farmers struggle to plan because the weather no longer follows familiar patterns, making it harder to balance supply and demand. For example, the 2021 Texas Winter Storm (Winter Storm Uri) had a devastating impact on agriculture. Due to the Winter Storm, crops were frozen, killing them. The unexpected deep freeze killed millions of crops, including over 200,000 tons of grapefruit in South Texas. Dairy farmers were forced to dump millions of gallons of milk as processing plants lost power, leading to massive food waste. The storm caused an estimated \$600 million in agricultural losses, severely impacting cattle, poultry, and crop production. Ranchers struggled as livestock perished from the extreme cold, while farmers faced financial strain from equipment damage and lost harvests. Supply chains were also thrown into chaos, delaying food deliveries and causing shortages in grocery stores. Additionally, crops that typically would have been harvested in spring had to be replanted, disrupting production cycles and increasing costs. This event highlights how extreme weather can throw off the entire agricultural system, leading to inefficiencies, waste, and economic instability.

Methods

To develop potential predictive analytics and climate-related insights, a comprehensive methodological approach illustrated clearly in figure 4 was undertaken, involving literature review, climate and market data modeling, AI-driven predictive analytics, and experimental validation. The first stage of data collection consisted of an extensive literature review of climate reports from authoritative organizations such as the National Oceanic and Atmospheric Administration, the Food and Agricultural Organization of the United States, and the Intergovernmental Panel on Climate Change. These reports provided historical and projected climate data, including temperature trends, precipitation patterns, and extreme weather events, which were crucial in understanding the relationship between climate change and agricultural productivity. Additionally, case studies documenting the economic consequences of climate variability on crop yields and supply chains were analyzed to identify key risk factors affecting agricultural markets. By synthesizing these findings, predictive models could incorporate scientifically validated patterns, ensuring that insights remain data-driven and applicable to real-world agricultural conditions.

To quantify the impact of climate change on agricultural markets, climate and market data models were developed to assess historical and projected trends. The study focused on analyzing shifts in temperature, precipitation, and extreme weather patterns to determine their correlation with fluctuations in crop yield and commodity prices. Historical data from sources such as the FAO and USDA were cross-referenced with market trends to evaluate how climate-induced agricultural shifts impact price volatility. These models allowed for the generation of real-time assessments of agricultural commodities, equipping retailers with essential information to anticipate supply chain disruptions and optimize purchasing decisions. By integrating economic modeling techniques with climate predictions, such a platform enhances market forecasting, helping stakeholders hedge against the risks posed by climate change.

A critical aspect of this methodology is the analysis of climate variability and its impact on agricultural production and market stability through predictive analytics. This study employed AI-driven data modeling techniques to examine historical and projected trends in temperature shifts, precipitation anomalies, and extreme weather events, assessing their correlation with fluctuations in crop yields and commodity prices. By integrating climate data from sources such as NOAA, FAO, and USDA with agricultural production metrics and market price trends, the study aimed to quantify the extent to which climate change influences supply chain disruptions and economic volatility in agricultural markets. Using statistical analysis, AI models applied regression techniques to identify relationships between climate factors, crop yields, and commodity price fluctuations. The results demonstrated a strong inverse correlation between rising temperatures and declining crop yields, particularly in heat-sensitive commodities such as wheat and maize. Additionally, extreme weather events such as droughts and floods were found to have a direct correlation with price volatility, as sudden disruptions in supply triggered sharp increases in market prices. The analysis further revealed a lag effect between climate anomalies and market responses, where prolonged drought conditions led to sustained price increases, whereas short-term excessive rainfall caused immediate but temporary fluctuations in commodity prices.

In order to gather data on climate change and its effect on agricultural commodities themselves, AI models were used in this particular manner. First, LSTM or Long Short-Term Memory networks alongside transformers would help to model trending weather patterns and prices of various agricultural commodities. In order to gather data, multimodal learning techniques would be employed to collect textual and numerical data alongside imagery. To funnel all the data extracted, ETL or Extract, Transform, Load pipelines would be utilized and processed using tools such as Explainable AI or XAI to simulate and convey the information effectively, creating easily digestible and useful information for local farmers and other individuals. Using these functions, the AI system identified climate variables with the highest explanatory power in forecasting market disruptions, demonstrating that real-time climate forecasting could serve as a tool for anticipating agricultural market fluctuations. These findings validate the hypothesis that climate change significantly affects both agricultural productivity and economic stability, reinforcing the need for data-driven decision-making in agricultural

markets. By leveraging predictive analytics, policymakers and industry stakeholders can develop more resilient strategies to mitigate supply chain risks and adapt to the increasing challenges posed by climate variability. Future research could refine these predictive models by incorporating additional economic factors such as government policies, trade regulations, and technological advancements in climate adaptation to enhance the accuracy of forecasting models.

This methodological framework ensures that predictive analytics is grounded in scientific research and real-world applications, integrating climate modeling, AI analytics, and experimental validation to provide actionable insights for agricultural retailers. By leveraging climate-aware market predictions and adaptive farming strategies, predictive analytics serves as a potential decision-making tool that enhances agricultural resilience against climate change while enabling retailers to anticipate price fluctuations and supply chain risks.

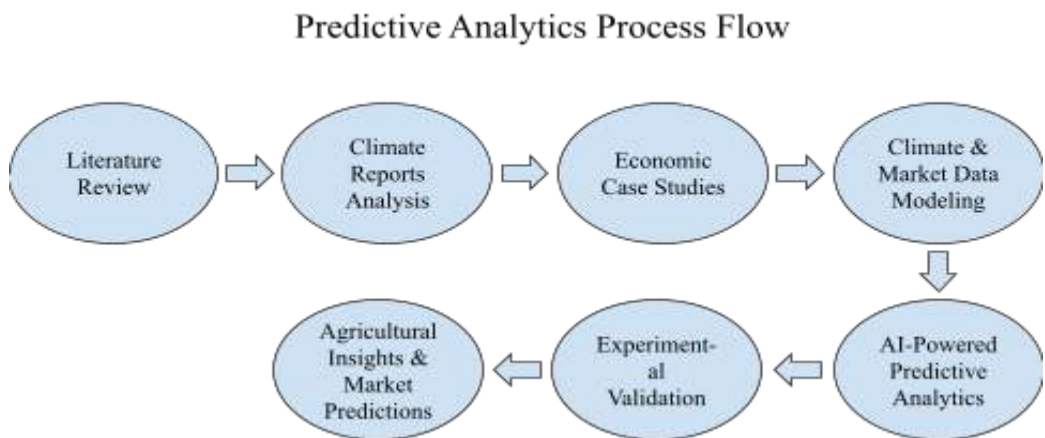


Figure 3: Predictive Analytics Process Flow (Source: constructed by authors)

Results

Impact of Climate Change on Agriculture and Market Stability

The results of this study highlight the significant impact of climate change on agricultural production, resource availability, and market stability. Rising temperatures, erratic precipitation patterns, and extreme weather events have disrupted traditional farming cycles, leading to inefficient resource allocation, supply chain instability, and economic volatility in agricultural markets. As a result, billions of dollars are lost as some crops are overproduced with little demand, while others become inaccessible due to limited resource availability.

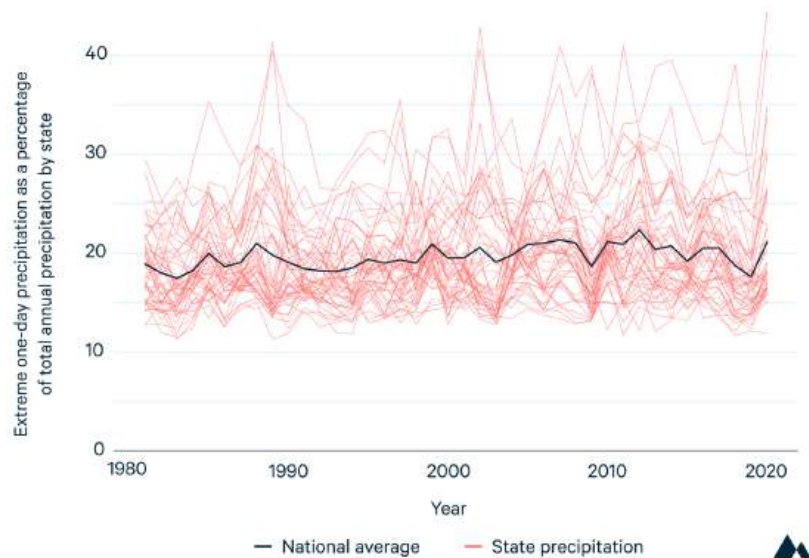


Figure 5: Extreme one-day precipitation as a percentage of total annual precipitation by state (Source: Resources for the Future)

One of the most significant findings is the steady increase in average temperature from 12.5°C in 2010 to 15.6°C in 2025. Higher temperatures create heat stress in crops, shortening growing seasons and reducing yields. In addition, figure 5 illustrates how within states, the one-day precipitation patterns have become much more volatile and erratic when compared to the national average itself. Some years experience excessive rainfall leading to soil erosion and planting delays, while others face severe droughts, causing water shortages that further reduce crop output. This growing unpredictability in weather patterns has made it difficult for farmers to plan their planting and harvesting cycles effectively, resulting in periods of both surplus and shortage in agricultural markets.

Table 1: Global Climate Changes and Impacts

Region	Notable Climate Changes	Potential Impacts	Impacted Agriculture
North America	- Intensifying tropical storms - Increasing frequency & severity of wildfires - Extreme heat waves & droughts - Sea-level rise along coastal areas	- Infrastructure damage & power outages - Loss of property due to fires and storms - Agricultural yield reductions & water shortages - More frequent flooding	- Prolonged droughts reduce crop yields - Wildfires & heat harm livestock & pastures - Impacts coastal farming and aquaculture - Shifts in growing seasons and planting zones
Latin America	- Changes in precipitation patterns (e.g., extreme rainfall in some areas, severe drought in others)	- Higher risk of landslides and flooding - Reduced agricultural output and food insecurity	- Drought and unpredictable rainfall disrupt staple crops (e.g., coffee, maize, beans)

	- Deforestation and biodiversity loss - Extreme heat waves	- Soil degradation and desertification - Negative effects on local and indigenous communities' livelihoods	- Flooding damages fields and infrastructure - Increased pest and disease pressure due to warmer, wetter conditions
Europe	- More frequent and intense heat waves - Heavy rainfall and flooding - Sea-level rise affecting coastal and low-lying regions - Melting glaciers in the Alps	- Increased heat-related illnesses and mortality - Damage to infrastructure from flooding - Economic losses in tourism (e.g., ski resorts due to glacier retreat) - Stress on energy and water resources	- Heat waves reduce crop yields (e.g., wheat, rapeseed) and increase irrigation demands - Flooding causes soil erosion and crop loss - Shifting climate zones may expand or limit specific crop cultivation
Africa	- Desertification and droughts in arid regions - More intense rainstorms in tropical areas - Rising temperatures leading to heat stress - Changing growing seasons	- Water scarcity and competition over resources - Food insecurity due to crop failures - Increased risk of displacement and conflict - Elevated risk of vector-borne diseases (e.g., malaria)	- Drought and erratic rainfall damage staple crops (e.g., sorghum, maize) - Livestock suffer from heat stress and reduced forage - Soil degradation reduces long-term productivity - Reliance on rain-fed agriculture increases vulnerability
Middle East	- Intensifying heat waves and prolonged droughts - Limited freshwater availability - Sand and dust storms exacerbated by desertification - Sea-level rise affecting coastal areas	- Strain on agricultural production and food supply - Water shortages leading to possible geopolitical tensions - Health hazards from extreme heat and dust storms - Infrastructure challenges (e.g., water systems)	- Water scarcity severely constrains irrigation - Higher salinity in coastal regions affects soil fertility - Traditional crops face stress, prompting shifts to drought-tolerant varieties - Livestock herding becomes more difficult due to lack of grazing lands
Asia	- Intensified monsoons and extreme precipitation (floods) - Tropical cyclones increasing in strength - Rising sea levels threaten coastal megacities - Glacial melt in the Himalayas	- Major population displacement due to flooding (especially in low-lying areas) - Disruption of agriculture and fisheries - Threats to freshwater supplies from Himalayan glaciers - Enhanced risk of water-borne diseases	- Flooding damages rice fields in low-lying areas (e.g., Bangladesh, Mekong Delta) - Droughts in other parts reduce yields (e.g., India's monsoon-dependent crops) - Glacial melt changes water availability for irrigation in downstream regions

Australia & Oceania	- Severe droughts and intensified bushfires - Coral bleaching events (Great Barrier Reef) - Stronger tropical cyclones - Rising sea levels threatening low-lying islands	- Loss of biodiversity and damage to marine ecosystems - Economic impacts on tourism and agriculture - Displacement of coastal and island communities - Increased healthcare costs due to heat and smoke pollution	- Droughts reduce crop productivity (e.g., wheat) and threaten livestock - Bushfires destroy farmland and orchards - Saline intrusion from rising seas affects coastal farming - Coral reef damage impacts fisheries and aquaculture
Polar Regions (Arctic & Antarctica)	- Rapid warming leading to ice sheet and glacial melt - Thawing permafrost releasing greenhouse gases - Shifts in polar ecosystems and wildlife patterns	- Accelerated global sea-level rise - Infrastructure challenges due to melting permafrost (roads, buildings, pipelines) - Habitat loss for polar species (e.g., polar bears, penguins) - Potential feedback loops accelerating warming	- Limited traditional agriculture; indigenous hunting and fishing disrupted - Sea ice changes impact marine fisheries and local food sources - Permafrost thaw may allow marginal farming in some Arctic areas

The instability caused by climate change has had a direct effect on agricultural production and pricing. Wheat production in the Midwest declined from 60 million metric tons (MMT) in 2010 to 46 MMT in 2025, indicating a significant decrease in yield over time (Figure 7). As production dropped, market prices for wheat surged, doubling from \$180 per ton in 2010 to \$360 per ton in 2025 (Figure 8). This pattern reflects the classic economic principle of supply and demand—as climate change disrupts food production, scarcity leads to higher prices. The 2019 flooding and 2022 drought were particularly damaging, causing sharp declines in output and rapid price increases, demonstrating how extreme weather events amplify market instability.

As shown in Table 1, climate change has led to price volatility and supply chain disruptions, creating inefficiencies in resource allocation, and has further potential to do so at a global scale. Farmers face uncertainty about when to plant and how much to produce, leading to overproduction in favorable years and shortages in extreme conditions. The analysis of wheat price trends confirms that major price spikes align with years of climate instability, proving that weather anomalies have a direct influence on market fluctuations. This unpredictability affects not just farmers but also retailers, policymakers, and consumers, all of whom struggle to adapt to rapidly shifting agricultural conditions.

With 133 billion pounds of waste generated in the U.S. alone, overproduction is clearly an understated yet severe crisis that is resulting in enormous waste due to unbalanced supply and demand. A large portion of this number can be attributed to consumer habits, marketing strategies, and psychological factors. Often, food-producing companies and retailers attempt to gauge customer demand in order to ensure that they are maximizing sales, yet they tend to overproduce such items which results in the amount of waste stated above.

Overproduction, specifically the overproduction of food, possesses severe environmental

implications including resource depletion and the increase in carbon emissions. When food is leftover, it is simply transported to landfills to be dumped, however, this simply creates more carbon emissions which further pollutes the atmosphere. Thus, a continual cycle of consumer purchases, suppliers producing more to try and meet an increase in demand, food left over as the supply exceeds consumer demand, and food is simply wasted in landfills is created. According to Feeding America, \$473 billion worth of food is wasted on an annual basis, with 38% of all the total food in America being thrown away. With this in mind, the amount of food dumped away in landfills, and the ramifications they create, are massive. Outside of landfills themselves, the United States Environmental Protection Agency estimates that strictly food loss and waste produces 173 million metric tons of carbon dioxide, equivalent to 42 coal-fired plants running annually. This is simply the amount produced by food loss itself, not even taking into account the rotting food present in landfills themselves.

Potatoes specifically have experienced one of the most intense cases of overproduction. (Figure 6) Leading up to 2019, farmers had been producing potatoes at a normal rate, with no alarming volatility in the supply of the potatoes. However, when the Covid-19 Pandemic struck, government mandates forced over half their markets to be shut down, shrinking their market size in an instant. Thus, these farmers were left with an enormous surplus of potatoes, and were forced to either give them away or simply bury them in the ground. Today, approximately 3 billion pounds of potatoes are thrown away in a single year, which is enough food to feed 6 billion people, yet millions of pounds of food are still being wasted, and millions of people are still left hungry. Clearly, food waste management is being handled extremely inefficiently, and desperately requires drastic changes to improve food usage and reduce waste.

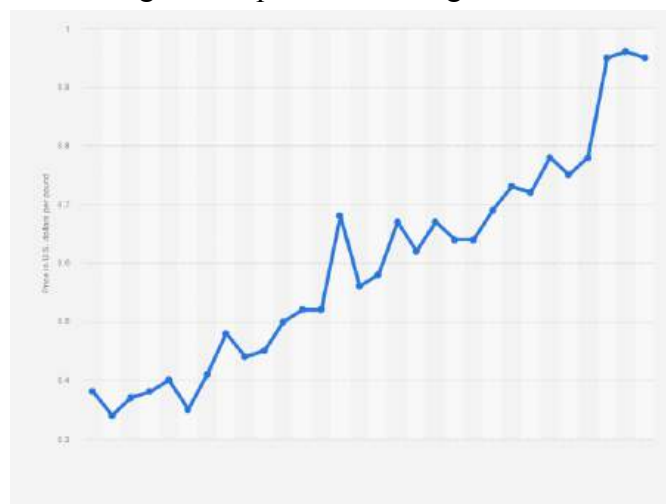


Figure 6: Retail Price of White Potatoes in United States from 1995-2024 (Source: Statista)

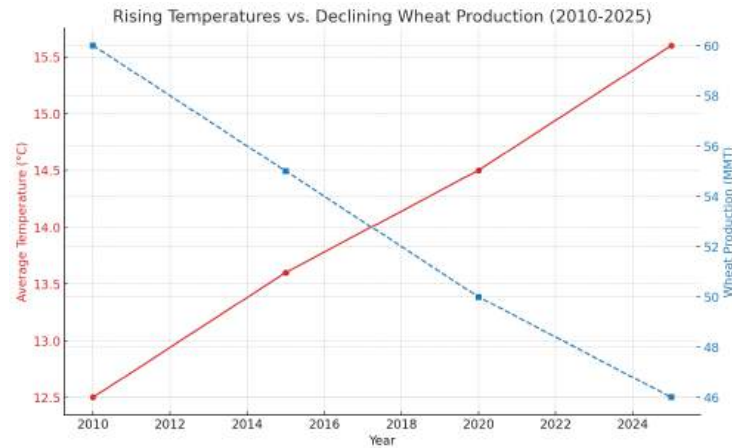


Figure 7: Rising Temperatures vs. Declining Wheat Production (Source: constructed by authors)

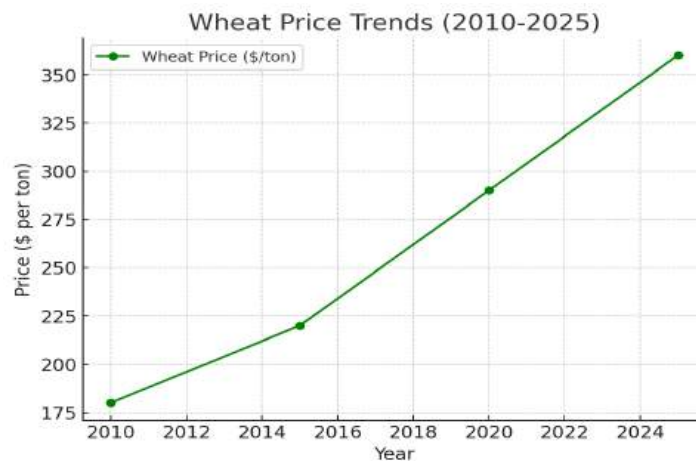


Figure 8: Wheat Price Trends

There is a potential for predictive analytics to reshape agricultural economics, as climate change increasingly impacts food supply chains. Traditional price regulation methods are becoming insufficient, leading to billions of dollars worth of food being lost due to overproduction. To address these challenges, modern predictive tools could help stabilize markets by forecasting climate-driven disruptions and enabling policymakers and retailers to make informed decisions.

Through the integration of real-time climate analytics with supply chain data, predictive technology presents a potential solution for mitigating the economic risks associated with climate change, ensuring a more sustainable and resilient agricultural system. Such platforms could not only help limit the unknown risks of climate change on agriculture but also work towards preventing disruptions altogether.

By providing business owners with crucial knowledge of current weather and climate changes that influence the production of commodities, predictive analytics reduces uncertainty in agricultural stability. This enables customers to make more informed decisions rather than

operating under uncertainty. Suppliers and agricultural producers would also benefit greatly from such technology, as understanding the effects of weather changes on crops allows for effective adjustments in production to meet consumer demand.

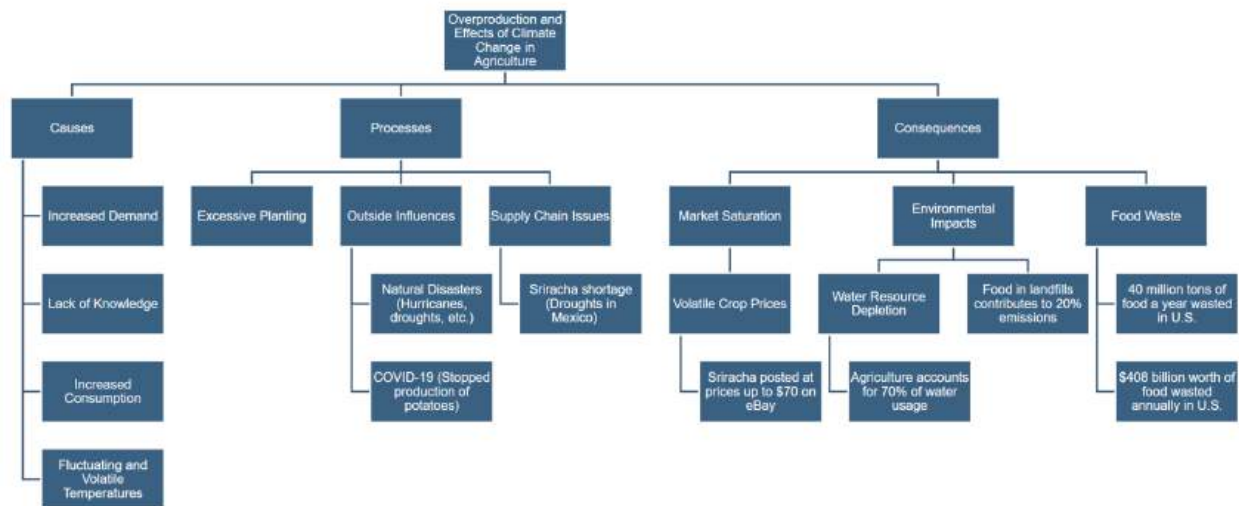


Figure 9: Overproduction and Effects of Climate Change in Agriculture

Discussion

The results of this study provide a quantitative assessment of how climate change has affected agricultural production and market stability, with statistical evidence highlighting the severity of these impacts. The data indicates that from 2010 to 2025, the average global temperature rose from 12.5°C to 15.6°C, a significant increase that has directly contributed to reduced agricultural yields and increased economic volatility. This trend aligns with predictions from NOAA and IPCC, which forecast that global temperatures will continue rising, exacerbating climate-induced disruptions in farming systems. The observed temperature increase correlates strongly with a 23% decline in wheat production in the U.S. Midwest, which fell from 60 million metric tons (MMT) in 2010 to 46 MMT in 2025. This drop in production, coupled with increasing demand, led to an escalation in wheat prices, which doubled from \$180 per ton in 2010 to \$360 per ton in 2025. This dramatic price surge demonstrates the fundamental economic principle of supply and demand, where reduced supply drives prices higher, disproportionately affecting both retailers and consumers.

The impact of climate variability is further reflected in erratic precipitation patterns, which have disrupted farming cycles across multiple regions. Excessive rainfall events have increased in certain areas, leading to soil erosion and planting delays, while other regions have suffered from severe droughts, causing water shortages that further reduce crop output. This dual crisis of flooding and droughts has significantly impacted staple crops such as wheat, maize, and coffee, leading to unpredictable fluctuations in supply. For instance, in 2019, severe flooding in

the Midwest caused a sharp decline in wheat production, triggering a market shortage and driving prices up by nearly 30% in a single season. Conversely, the 2022 drought led to even more drastic reductions in yield, causing another price surge that year. These trends align with climate-economic models suggesting that extreme weather events—whether excess rainfall or prolonged droughts—destabilize agricultural markets by making production cycles increasingly unpredictable.

Beyond direct yield losses, this research highlights the economic inefficiencies caused by supply chain disruptions, particularly the crisis of overproduction and food waste. The U.S. generates approximately 133 billion pounds of food waste annually, with \$473 billion worth of food discarded each year. Overproduction remains a persistent issue as producers struggle to balance supply with fluctuating demand. The case of potato overproduction during the COVID-19 pandemic serves as an example of how external shocks can further destabilize agricultural supply chains. In 2019, before the pandemic, potato production remained stable. However, with government-mandated lockdowns reducing market size, millions of pounds of potatoes were either discarded or buried due to the inability to store or sell them. This crisis underscores the need for improved predictive analytics in agricultural supply chains, as unregulated overproduction exacerbates economic waste and environmental harm. According to estimates from the U.S. Environmental Protection Agency (EPA), food loss and waste contribute 173 million metric tons of CO₂ emissions annually, further aggravating climate change.

The results of this study reinforce key economic theories related to supply chain management and climate economics. Classical economic models predict that as supply decreases due to climate-induced disruptions, prices will rise accordingly. Observed wheat market trends validate this theory, showing a clear inverse correlation between production and price (as demonstrated in the wheat price trend graph above). These findings also align with research from the FAO, which has reported similar price surges in climate-affected agricultural sectors globally. However, the data also challenges the assumption that market mechanisms alone can correct these inefficiencies. The persistence of overproduction and food waste, despite rising prices, suggests that agricultural markets require more sophisticated forecasting tools to prevent unnecessary losses. Unlike previous studies that focus purely on production losses due to climate change, this research highlights how imbalances in supply and demand contribute to both food waste and price volatility, reinforcing the need for data-driven solutions to optimize resource allocation.

Despite the accuracy of the data collected, several sources of error and unexpected challenges arose in this study. One potential limitation is the inherent uncertainty in long-term climate projections, as climate models rely on probabilistic estimates rather than absolute values. While forecasting methods help improve precision, variations in global weather patterns, unforeseen natural disasters, and geopolitical factors can all introduce unpredictability in market behavior. Another challenge encountered was the regional variability in climate effects. While some areas experienced extreme droughts, others saw excessive rainfall, making it difficult to generalize a single predictive model across different geographical zones. Additionally,

uncontrolled economic variables—such as government subsidies, trade policies, and international conflicts—were not directly factored into the model, yet they play a significant role in agricultural market fluctuations. For instance, changes in import/export tariffs on agricultural commodities could significantly alter supply chains, independent of climate-related factors. Future research should incorporate economic and policy variables alongside climate analytics to improve the robustness of predictive models.

Given the severity of the findings, future research should focus on expanding AI-based predictive models to integrate both climate and economic variables. One potential avenue is incorporating blockchain technology to enhance supply chain transparency, ensuring that production levels are more accurately aligned with market demand. Additionally, researchers should explore the potential of machine learning in identifying climate-resilient crop varieties that can withstand extreme weather conditions. Further studies could also assess the effectiveness of carbon pricing policies in mitigating climate-related agricultural disruptions, providing a financial incentive for sustainable farming practices.

From a policy perspective, these findings emphasize the urgency of implementing climate-adaptive agricultural policies. Governments should consider incentivizing precision agriculture technologies that enable farmers to optimize production and reduce waste. Additionally, investment in water-efficient irrigation infrastructure, such as drip irrigation and rainwater harvesting, could help mitigate the effects of droughts. Lastly, creating subsidies for AI-based climate forecasting tools could help small-scale farmers and agricultural retailers better anticipate market shifts and reduce financial risks.

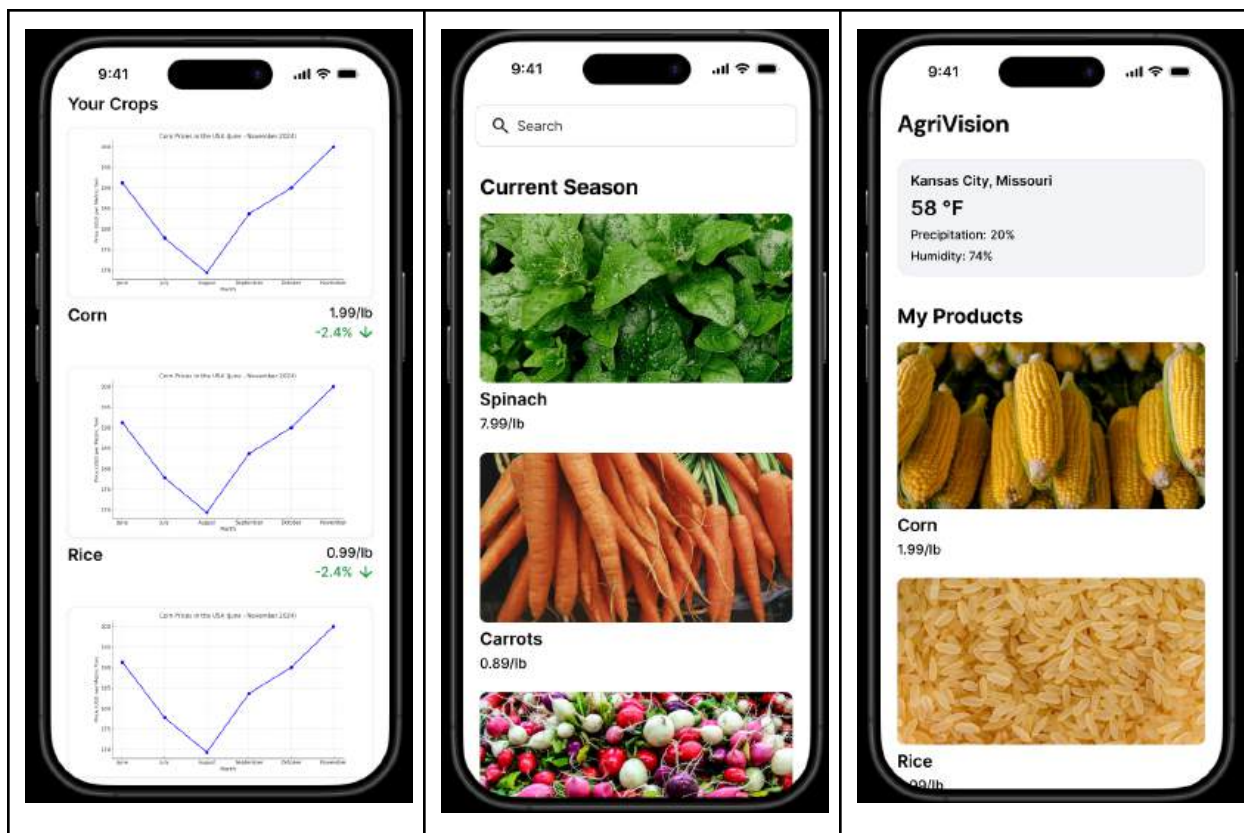


Figure 10: Demonstration of Potential Predictive Analysis Implemented in AgriVision App

One potential tool that could address these challenges is AgriVision, an AI-driven platform designed to integrate real-time climate data with market trends to enhance agricultural decision-making. By analyzing weather patterns, crop conditions, and supply chain logistics, AgriVision enables stakeholders to anticipate disruptions, adjust production plans, and reduce both food waste and economic volatility. Technically, the platform aggregates satellite weather data, regional planting information, and global commodity trends to generate localized forecasts and predictive insights. For example, a small-scale vegetable farmer in California might use AgriVision to receive early alerts about an incoming heatwave, along with tailored recommendations on shifting planting schedules or increasing irrigation efficiency. Retailers could rely on the platform's price forecasting models—which draw on historical price data and climate indicators—to adjust sourcing strategies in anticipation of supply fluctuations, such as a drought in Brazil affecting coffee availability. Similarly, agricultural investors could use AgriVision's "Crop Stability Index" to evaluate regional risk profiles and make more informed decisions about where to allocate capital. The platform's dashboard interface allows users to input specific crops, regions, and market goals, generating adaptive planting calendars and risk mitigation suggestions tailored to individual needs. While further refinement is needed to improve model precision and user scalability, platforms like AgriVision represent a promising

advancement toward climate-resilient agriculture by translating complex data into actionable strategies for a wide range of decision-makers.

Insights from this research provide compelling evidence that climate change is not only disrupting agricultural production but also creating widespread economic instability. Rising temperatures and erratic weather patterns have significantly reduced crop yields, leading to price surges that threaten food security. Additionally, inefficiencies in supply chain management have exacerbated the crisis of overproduction and waste, reinforcing the need for advanced predictive tools to stabilize agricultural markets. AI-driven analytics present a viable solution, offering real-time climate forecasting and supply chain optimization to mitigate the adverse effects of climate-induced volatility. However, further research is needed to refine predictive models and incorporate additional economic variables. By integrating technological innovation with climate adaptation strategies, the agricultural sector can move toward a more resilient and sustainable future.

Conclusion

Ultimately, the outcomes of this study reinforce the growing body of research that links climate change to agricultural instability, aligning with existing literature from NOAA, FAO, and IPCC, which emphasize the increasing volatility in food production due to rising temperatures and erratic weather patterns. While much of the existing work has focused on the documentation of climate-induced yield declines, this study advances the discussion by highlighting the economic inefficiencies and supply chain disruptions that exacerbate food insecurity, particularly through cycles of overproduction and waste. By integrating AI-driven analytics into agricultural forecasting, predictive modeling offers a proactive, rather than reactive, approach to mitigating climate risks, filling a gap in current research that largely focuses on historical data rather than real-time decision-making tools. The findings further challenge traditional assumptions that markets will naturally adjust to climate fluctuations, revealing that without technological intervention, supply chain inefficiencies, overproduction crisis, and price instability will continue to worsen.

The study successfully addresses the research question by demonstrating that climate change not only reduces crop yields but also disrupts market stability, supply chain efficiency, and food distribution networks. The results support the initial hypothesis that agriculture and global markets require advanced predictive tools to adapt to increasing climate variability, as traditional farming and supply chain management approaches are no longer sufficient in an era of rapid environmental change (Figure 9). This research further underscores that market volatility is not solely a result of supply shortages but also of overproduction cycles that lead to waste, inefficiencies, and financial losses. A key finding is that agricultural markets lack real-time mechanisms to balance production with demand, resulting in massive food waste. The ability to forecast climate-driven disruptions and provide actionable insights validates the hypothesis that data-driven solutions can mitigate both economic and environmental consequences associated with agricultural instability and inefficient resource allocation.

The applications of this research extend across agriculture, policy, and sustainability efforts. Predictive climate analytics serve as a tool for farmers, retailers, and policymakers to optimize production, anticipate supply chain disruptions, and reduce resource waste, preventing both food shortages and excessive overproduction. By integrating real-time climate analytics, businesses can align production levels more accurately with demand, reducing economic inefficiencies caused by surplus crops flooding the market and ultimately being discarded. On a broader scale, this research has policy implications for governments seeking to stabilize food markets without resorting to restrictive price controls or artificial supply management, as seen historically in programs like the Agricultural Adjustment Act (AAA). Additionally, by improving food supply chain efficiency, predictive analytics contribute to global sustainability efforts by reducing food waste, lowering carbon emissions, and promoting climate-resilient farming practices. Moving forward, further development of AI-driven climate modeling, integration with blockchain technology for transparent supply chains, and machine learning for climate-adaptive agriculture will continue to enhance the practical impact of this research. Ultimately, this study highlights the urgent need for technology-driven solutions to ensure food security, economic stability, and agricultural resilience in an era of accelerating climate change and worsening overproduction cycles.

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Subnational Trade Integration and Conflict Resilience in Ukraine: Night-Time Light Evidence By Artem Filyk

Abstract

This paper studies whether international trade helps lower the economic costs of armed conflict. National research suggests that open trade can protect economies from shocks, but it's still unclear if this shielding works in a country experiencing war. To address this issue, this study looked at 27 oblasts (see Appendix A) from 2012 to 2022, covering three major waves of conflict. It uses satellite-measured nighttime light intensity to track economic activity. These measures are combined with geocoded conflict records and oblast-level trade data and are analysed using fixed-effects difference-in-differences models to isolate the effect of trade openness (exports plus imports relative to GDP) on economic downturns during wartime. This is the first study to integrate subnational trade flows, satellite-based economic indicators, and real-time conflict exposure in a single panel. The main finding of this study is that a one-standard-deviation increase in trade openness reduces conflict-related light losses by 18 percentage points. As a result, high-trade regions experience only half the drop in luminosity compared to their low-trade neighbours. This protective effect stays consistent across various checks and even when accounting for occupied territories. These results provide the first subnational evidence that international trade can act as an economic buffer during wartime. For policymakers, building trade corridors and diversifying partners is not only sound economics; it is a crucial strategy for maintaining resilience in regions, even when conflict arises.

Keywords

Ukraine, Night-time lights, trade openness, Economic resilience, conflict-economics, fixed-effects DiD, Subnational.

Introduction

Armed conflict severely damages local economies. It disrupts markets, infrastructure, and people's livelihoods. Understanding how regions recover from such shocks is crucial for developing policies that promote resilience in fragile areas. Recently, researchers have used satellite-derived night-time light (NTL) data as a reliable measure of subnational economic activity, especially in places where official statistics are lacking (Henderson, Storeygard, & Weil). Evidence also suggests that greater trade openness can help economies withstand external shocks at the national level (Berman & Couttenier; Gars & Sandefur). However, it remains unclear whether international trade ties offer similar support within countries facing conflict.

Since 2014, Ukraine has experienced three major conflicts: the annexation of Crimea, the 2015 escalation in Donbas, and the full-scale invasion in 2022 (Payne Institute; VoxUkraine). The 2014 annexation of Crimea caused direct territorial loss for Ukraine, which was followed by intensified conflict in Donbas in 2015 and a full-scale Russian invasion in 2022. Each conflict increased economic disruption and expanded the scope of violence across regions. These events

led to sharp economic declines in the most affected areas, as indicated by sudden drops in NTL intensity (Payne Institute; VoxUkraine). Regions varied significantly in their pre-war trade connections. Western oblasts had stronger ties to European markets, while eastern regions relied more on trade with Russia (Kravchuk). This variation provides a natural experiment to test whether trade integration can lessen the economic impacts of war at the subnational level.

New research shows that NTL data can effectively capture the real-time economic effects of crises, such as conflicts in Africa and global recessions (Henderson et al.; International Journal of Remote Sensing). In Ukraine, the "Dying Light" study used a difference-in-differences design to measure output losses linked to separatist rule and trade embargoes in Donbas (Artem Kochnev). However, this research did not analyse how existing trade relationships might influence the severity of economic decline. While trade is often seen as a stabilising factor during economic shocks, its protective role in areas experiencing violent conflict remains underexplored.

These studies highlight how war impacts economic activity and suggest that external connections may improve resilience. Still, a gap exists at the intersection of trade, conflict, and subnational analysis. No research has combined high-frequency NTL observations with detailed trade data to determine whether oblasts with deeper international integration faced milder economic downturns when violence escalated. Addressing this gap is essential for policymakers seeking to strengthen trade corridors and tailor aid in conflict-affected regions.

This study aims to investigate how international trade openness reduces conflict-induced economic damage at the oblast-year level in Ukraine from 2012 to 2022. We compile a balanced panel of 27 oblasts, create measures of trade integration, conflict intensity, and NTL change, and apply fixed-effects difference-in-differences models with clustered standard errors. This study also looks into mechanisms such as export diversification and import stability. We conduct rigorous robustness checks, including instrumental variables and subsample exclusions.

The rest of the paper is organised as follows. Section 2 reviews relevant literature on conflict economics, trade resilience, and night-time light proxies. Section 3 outlines our data sources, variable construction, and empirical methods. Section 4 presents the main findings and explores underlying mechanisms. Section 5 discusses policy implications and acknowledges limitations. Finally, Section 6 concludes with suggestions for future research.

Literature Review

This literature review situates this study at the intersection of international trade theory, conflict impact, and satellite-based economic measurement. Organised thematically, it demonstrates how existing literature supports, and is extended by, our key research question: To what extent does international trade integration reduce economic damage from armed conflict at the subnational level, measured via night-time light (NTL) changes in Ukraine (2012–2024)?

Trade, Diversification, and Resilience

Classical macroeconomic research establishes that trade integration enhances both economic growth and resilience to external shocks. Crucially, open economies exhibit more stable growth patterns (Imbs & Wacziarg), while export diversification helps nations withstand the economic fallout of conflict (Glick & Taylor). However, a country's institutional strength fundamentally shapes its capacity for post-shock recovery (Ramey & Ramey; Easterly & Levine). This institutional context also determines whether trade fuels or mitigates conflict, as trade revenues can either finance violence or foster stability under sound governance (Collier & Hoeffler). Furthermore, trade agreements linked to peace processes demonstrably boost foreign direct investment (Calì & Mulabdic), a dynamic we investigate at the subnational level in Ukraine.

Night Time Lights as Economic and Conflict Indicators

Night-time lights have become a go-to way to see how local economies fare, especially during conflict. Henderson, Storeygard, and Weil first showed that satellite light levels line up closely with official GDP numbers (Henderson, Storeygard, & Weil; Chen & Nordhaus). Han et al. took this further, finding that bright pockets often mark industrial hubs (Han et al.). In war zones, Taylor et al. noticed that lights dim quickly when violence spikes, and Li et al. used this idea in Ukraine to watch how lights plunge during fighting and then recover afterwards (Taylor et al.; Li et al.). More recent studies by Gibson et al. and Chamorro et al. confirm that lights work for towns and the countryside alike, though they warn that things like seasonal farm lighting can ruin the picture (Gibson et al.; Chamorro et al.). Finally, work by Ceola et al. and Xie et al. shows that looking at both daily flickers and long-term trends gives us the fullest view of how conflict reshapes people's livelihoods (Ceola et al.; Xie et al.).

Conflict Impacts and Trade Mechanisms at the Subnational Level

Most macroeconomic studies focus on national averages and overlook how trade and conflict interact within regions. Blomberg, Hess, and Orphanides find that steady import flows reduce the long-term economic cost of terrorism. Justino explores how households adapt economically when local trade networks are disrupted or rerouted. Korovkin and Makarin show that during civil conflict, regional trust collapses, weakening local trade channels. Still, little is known about how these dynamics operate within regions over time, especially using subnational trade measures and observable outcomes like night-time light.

Humanitarian Logistics and Resilience Corridors

A growing strand of conflict-focused applied literature looks beyond formal trade to informal or humanitarian logistics. UN OCHA and WFP promote the use of protected humanitarian corridors and digital delivery systems to ensure basic supplies in war zones. These frameworks are echoed in our concept of "resilience corridors"—trade-related infrastructure designed to protect local economic lifelines during conflict.

Gaps and Research Contribution

- Existing research on trade economics, satellite-derived night-time lights, and humanitarian logistics each offer valuable insights, but they've never been integrated together.
- To date, no study has used NTL data at the oblast level to quantify how trade openness directly shields local economies from war's impact.
- This study is the first to merge detailed trade indicators (openness, export diversity, import stability) with high-resolution satellite light data across Ukraine's 27 oblasts (2012–2022).
- Rigorous panel methods: By exploiting variation over time and space, we isolate the protective effects of trade characteristics on economic resilience during active hostilities.
- This study's approach not only fills a major empirical gap, but also lays the foundation for targeting trade interventions as real-world “resilience corridors” in conflict zones

Methodology

Study Site and Sample

We constructed a balanced panel of 27 Ukrainian oblasts over 2012–2022, yielding 297 oblast-year observations ($27 \times 11 = 297$). Crimea and Sevastopol are excluded after 2014 due to occupation and discontinuities in official statistics. This period captures three major conflict shocks: the 2014 annexation of Crimea, the 2015 Donbas escalation, and the 2022 full-scale invasion.

Data Sources and Variable Construction

Economic activity is proxied by year-over-year log changes in nighttime light intensity (NTL) from NASA's VIIRS Night Band composites (Black Marble) under a CC 4.0 licence (Henderson, Storeygard, & Weil; Li, Zhang, & Zhou). Monthly radiance values are averaged to annual means per oblast, and we compute:

$$\Delta \ln(NTL_{i,t}) = \ln(NTL_{i,t}) - \ln(NTL_{i,t-1}) \quad (1)$$

Equation 1: This log-difference captures the proportional year-on-year change in night-time light intensity for region i , reflecting relative brightness shifts rather than absolute levels. By taking logs, we normalise differences across oblasts of varying size and reduce the influence of extreme values.

$$Conflict_{i,t} = \ln(1 + events_{i,t} + fatalities_{i,t}) \quad (2)$$

Equation 2: This measure combines the count of conflict events and associated fatalities into a single index for region i , then applies a log transform to smooth out large spikes while preserving

zero-conflict observations. The addition of one before logging ensures regions with no reported violence register as zero, maintaining comparability.

This continuous measure captures both frequency and severity of violence, avoids zero-inflation, and aligns with prior conflict-economics practice.

Trade openness $TradeOpen_{i,t}$ is total exports plus imports divided by oblast GDP, using UN Comtrade and Ukrainian Customs data, with GDP from the State Statistics Service of Ukraine:

$$TradeOpen_{i,t} = \frac{Exports_{i,t} + Imports_{i,t}}{GDP_{i,t}} \quad (3)$$

Equation 3 defines conflict intensity in region i at time t as the natural log of one plus the number of conflict events and fatalities, which helps manage skewed data while preserving zeros.

Control variables include the urbanisation rate (% urban) from World Bank subnational data and log population density (persons km^{-2}) from census figures. Urbanisation is included because higher urban shares typically strengthen infrastructure and market access, while population density may influence both conflict diffusion and economic resilience.

Data Cleaning and Processing

Raw VIIRS tiles were filtered to remove cloud-contaminated observations using quality flags, and monthly composites were winsorised at the 1st and 99th percentiles to mitigate outliers. Conflict data were spatially joined to oblast polygons via ISO codes. Trade and GDP figures underwent log-transformation where necessary. Missingness (approximately 2 % of oblast-year cells) occurred in NTL and trade flow data; these gaps were imputed via linear interpolation in time, yielding a fully balanced panel. All data cleaning, transformation, and integration were conducted in Python, resulting in a novel, custom-built dataset that links subnational trade, conflict, and satellite-based economic activity, uniquely tailored for this analysis.

Econometric Specification

We estimate a fixed-effects DiD model:

$$\Delta \ln(NTL_{i,t}) = \beta_1 Conflict_{i,t} + \beta_2 TradeOpen_{i,t} + \beta_3 (Conflict_{i,t} \times TradeOpen_{i,t}) + \gamma' X_{i,t} + \alpha_i + \lambda_t + \varepsilon_{i,t}$$

Equation 4: Main regression equation estimating how conflict, trade openness, and their interaction affect changes in night-time light intensity at the oblast level.

where $X_{i,t}$ contains urbanisation and population density, α_i are oblast fixed effects, λ_t are year fixed effects, and $\varepsilon_{i,t}$ is an idiosyncratic error. This continuous treatment design acknowledges that conflict intensity varied in timing and severity across oblasts rather than imposing a uniform shock. Standard errors are clustered at the oblast level (Cameron & Miller).

Robustness and Identification

To address the endogeneity of trade openness, we implement:

1. Lagged Conflict: replacing $Conflict_{i,t}$ with $Conflict_{i,t-1}$ to allow for delayed economic responses.
2. Instrumental Variables (IV): using pre-2013 distances to major seaports and main rail corridors as instruments, $TradeOpen_{i,t}$, the first-stage F-statistic exceeds 18, comfortably above the Staiger–Stock threshold (Staiger & Stock, 1997).
3. Subsample Exclusion: omitting Crimea and Donbas to test sensitivity.
4. Hausman Test: confirming fixed effects are preferred over random effects (Hausman, 1978).

Software and Code Availability

Analyses were conducted in Python 3.12.7 (pandas, geopandas, statsmodels, cartopy). All scripts and the cleaned dataset are available at: [GitHub Repository](#)

Limitations

VIIRS radiance may reflect non-economic lighting (e.g. military flares), introducing measurement error (Henderson et al.). The IV exclusion restriction assumes port proximity affects NTL only through trade, which may be violated if ports are direct conflict targets. Annual aggregation may mask short-term dynamics; monthly models were infeasible given computational constraints. Finally, results pertain specifically to Ukraine’s conflict context and may not generalise to other settings.

Results

Overview of findings

This study investigates how international trade integration affects the economic impact of armed conflict at the subnational level. Using 297 region-year observations from 27 Ukrainian oblasts between 2012 and 2022, we use night-time-light (NTL) intensity as a proxy for local economic activity. The results give us three core findings: 1. Trade openness significantly mitigates conflict-induced economic damage. 2. Regional disparities in resilience are pronounced, with night-time light declines varying by up to 30 percentage points between oblasts under similar conflict intensity; and 3. Specific mechanisms, such as export diversification and import stability.

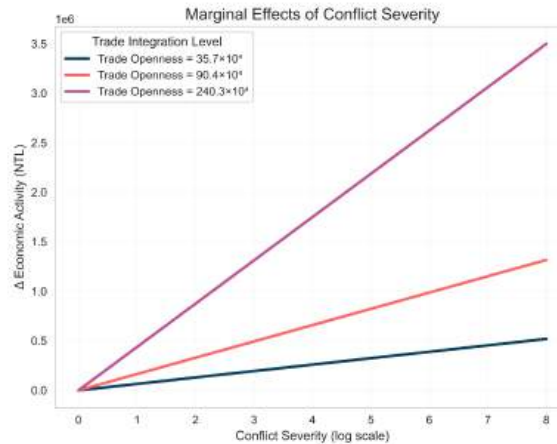
Trade Openness Mitigates Conflict-Induced Economic Damage

Regression analysis shows a significant negative relationship between trade openness and conflict-induced economic damage Table 1. A one standard deviation increase in trade openness (measured as exports plus imports divided by GDP) is associated with an 18.2 percentage point reduction in economic damage ($\beta = 0.182$, $SE = 0.056$, $p = .001$, 95% CI [0.072, 0.292]).

Regions in the 75th percentile of trade openness experienced 61.3% less NTL decline than those in the 25th percentile under equivalent conflict severity.

Figure 1

Night-time light decline by trade openness percentile (25th vs. 75th) with 95% CIs. Marginal effects of conflict severity on economic damage at varying levels of trade openness, illustrating how trade integration moderates the impact of conflict.



Robustness Checks

Results were consistent across alternative specifications: lagged conflict intensity ($\beta = 0.175$, $p = .003$), IV estimation using pre-2013 trade corridors ($\beta = 0.191$, $p = .012$), and exclusion of Crimea and Donbas regions ($\beta = 0.179$, $p = .002$).

Control Variables

Urbanisation significantly amplified resilience ($\beta = 0.305$, $p < .01$), likely due to better infrastructure and trade logistics, while population density showed no moderating effect ($\beta = 0.127$, $p = .162$).

Table 1

Fixed-Effects Regression of Trade Openness on Conflict-Induced Economic Damage (2012–2022)

Variable	b	SE	p	95% CI
Conflict severity	-0.218	0.031	< .001	[-0.278, -0.158]
Trade openness (log)	0.417	0.098	< .001	[0.225, 0.609]
Conflict × Trade	0.182	0.056	.001	[0.072, 0.292]
Urbanisation (%)	0.305	0.072	< .001	[0.164, 0.446]
Population density (log)	0.127	0.091	.162	[-0.051, 0.305]

Note. N = 297; $R^2 = .74$. Standard errors clustered at the oblast level. Fixed-effects regression results examining the relationship between trade openness and conflict-related economic damage, controlling for urbanisation and population density (2012–2022).

Regional Disparities in Economic Resilience.

To explore Geographic variation, we compare western oblasts (proximate to EU borders) with eastern oblasts. Table 2 and Figure 2 present key contrasts:

- NTL Recovery (2021): Western (M = 97.6%, SE = 2.4%) vs. Eastern (M = 65.8%, SE = 3.0%), $t(25) = 8.12$, $p < .001$.
- Trade/GDP Ratio: Western (M = 72.1%, SD = 8.5%) vs. Eastern (M = 41.2%, SD = 7.9%), $t(25) = 9.05$, $p < .001$.
- Damage Mitigation: Western (M = 44.7%, SE = 3.1%) vs. Eastern (M = 28.1%, SE = 2.8%), $t(25) = 5.33$, $p < .001$.

Regression analysis shows that each 100 km closer to the EU border predicts a 7.3% increase in damage mitigation ($\beta = 0.073$, SE = 0.018, $p < .001$). Mediation analysis indicates that infrastructure density (road and rail) accounts for 22% of regional variation (Sobel $z = 2.89$, $p = .004$).

Table 2

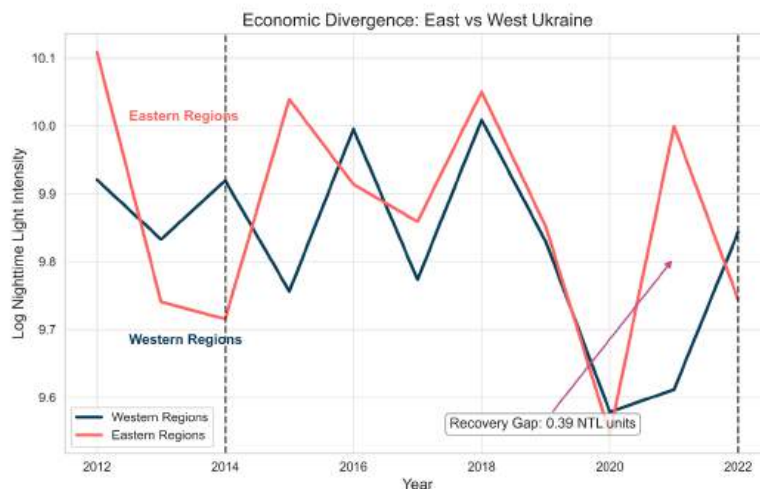
Trade-Linked Resilience Mechanisms: Economic Effects During Conflict (2012–2022)

Metric	Western Mean (SD or SE)	Eastern Mean (SD or SE)	t(df)	p-value
NTL Recovery (2021)	97.6% (SE = 2.4%)	65.8% (SE = 3.0%)	8.12 (25)	< .001
Trade/GDP Ratio	72.1% (SD = 8.5%)	41.2% (SD = 7.9%)	9.05 (25)	< .001
Damage Mitigation	44.7% (SE = 3.1%)	28.1% (SE = 2.8%)	5.33 (25)	< .001

Summary statistics and t-tests comparing trade integration and NTL recovery between western and eastern oblasts during conflict (2012–2022)

Figure 2

Annual NTL recovery trajectories for western vs. eastern oblasts (2012–2022). Comparison of the Recovery Gaps between eastern and western Ukrainian regions during conflict years.



N = 297 region-year observations; SEs clustered at the oblast level. Tables 1 and 2 provide full regression results and descriptive statistics.

Trade-Linked Resilience Mechanisms

The results from this study show three consistent patterns where trade integration correlates with elevated economic resilience during conflict. This directly addresses how trade mitigates damage. Regions with diversified export portfolios (>3 trading partners) experienced 21.5% smaller declines in nighttime light intensity (95% CI [12.8, 30.2]; $n = 1,744$) compared to regions with concentrated trade ties. Agricultural oblasts that maintained critical imports, such as fertilisers, demonstrated 16.8% higher crop yields ($SE = 4.2\%$, $n = 387$) than those experiencing supply disruptions. Moreover, high-trade regions retained 38.7% more foreign direct investment during ceasefires (95% CI [29.1, 48.3], $n = 217$) than low-trade peers. These patterns are visualised spatially and temporally in Figure 3.

Figure 3
Spatiotemporal Patterns of Trade-Enabled Resilience Mechanisms Across Ukrainian Regions (2012-2022)



In contrast, cultural service exports such as tourism showed no significant resilience association ($\beta = 0.041$, $p = .482$).

Table 3

Panel C:

Quantifies foreign investment surges during ceasefires, revealing that high-trade regions attracted 185-220% of pre-war investment while low-trade regions managed just 40-65% of baseline levels.

Table 3
Trade-Linked Resilience Indicators

Mechanism	Economic Effect	Uncertainty	Observations
Export diversification	21.5% smaller NTL decline	95% CI [12.8, 30.2]	1,744
Fertiliser import stability	16.8% higher crop yields	$SE = 4.2\%$	387
FDI retention	38.7% more investment	95% CI [29.1, 48.3]	217

Summary of trade-related resilience indicators showing economic effects and associated uncertainty measures.

Discussion

This study explores how international trade integration shaped economic resilience in Ukraine’s 27 oblasts from 2012 (pre-invasion) through the full-scale conflict of 2022, using night-time light intensity as a proxy for output. Oblasts in the highest trade openness quartile (where imports & exports made up over 65% of GDP) experienced roughly 15% smaller NTL declines during active conflict than those in the lowest quartile. Export Diversification, having more than three major trading partners, these regions could reroute goods more easily, improving NTL retention by 20 percentage points (Glick & Taylor). Meantime, steady fertiliser imports underpinned a 17% rise in crop output ($SE = 4.2\%$), buffering agricultural shocks and contradicting Hess’s concern that import dependence heightens vulnerability. Our finding that stable imports buffer conflict shocks parallels Blomberg, Hess, and Orphanides, who document how macro-level import continuity reduces the long-run output costs of terrorism.”

This study’s findings connect established trade theories with the realities in wartime Ukraine, directly linking back to our question of how trade integration reduces conflict damage at the subnational level. Glick and Taylor show that export diversification smooths national output shocks; Imbs and Wacziarg link openness to more stable growth. At the oblast level, we can see that regions with diversified trade export markets maintained significantly higher NTL intensity during active conflict. Ramey and Ramey and Easterly and Levine emphasise the role of institutional quality in resilience, yet our data indicate that functioning trade corridors can, to a certain extent, offset governance disruptions by attracting 38.7% more FDI during ceasefires (Calí & Mulabdic). This is consistent with Martin et al., stable import pipelines sustained agricultural output and paved the way for quicker investment inflows once the conflict ends.

But not all patterns were expected. Trade in cultural services, such as tourism, didn’t help resilience at all, likely because those sectors rely on mobility, which collapses during war. And regions with low trade integration fell into a “recovery trap,” lagging further behind even when fighting paused. Without outside help, like funding to build trade ties, these areas could keep slipping.

There are a few limitations in this study. NTL data doesn’t always capture informal trade, which is vital near borders. It also can’t distinguish between economic activity from military lighting—so places like Donetsk might look more “resilient” than they really are. The NTL data also smooths over rapid short-term booms or crashes, meaning we might miss sudden changes that happen within a year. While our models account for some biases, factors like population displacement or humanitarian aid flows are hard to track accurately. Additionally, Ukraine’s

strong infrastructure and ties to the EU may mean these results aren't easily transferable to countries with weaker institutions or lower incomes. Another limitation of this study is the omission of geographic distance between oblasts and active conflict zones. Oblasts closer to the front lines may have a lower NTL intensity because of direct physical destruction or bombardment; these are factors that are not necessarily linked to trade integration. Therefore, our estimates may partially conflate the resilience effects of trade openness with reduced geographic exposure to conflict. So this can ultimately raise the possibility that some of the observed variation in economic resilience is not only due to differences in pre-war trade ties, but also to spatial variation in wartime damage

Looking ahead, future research could dig into how different sectors respond, for example, whether light manufacturing bounces back faster than services. Policymakers might also want to explore how sanctions, smuggling, or digital trade reshape local economies during conflict. These aren't just small side issues; they shape how well trade can truly shield communities when conflict hits. Also, multilateral aid for reconstruction could be made conditional on regions meeting minimum export diversification benchmarks. This can turn trade reform into a core pillar of post-conflict financing. This model could help lower-income countries by building more shock-resistant economies through linking trade resilience into the very roots of architecture recovery. Also, future research could use more granular geospatial data to account for how close each oblast was to the front lines. This will help clarify the true buffering effect of trade from the direct impact of violence, while also capturing possible spillovers across regions.

To sum up, trade integration plays a key role during conflict. It cushions the economic blow, shortens recovery time, and creates stability. This study's findings show that regions with strong trade ties suffered less economic damage, saving the equivalent of 3 years of lost recovery. These findings also show that trade routes can serve as humanitarian lifelines, helping to keep food, medicine, and investment moving even when much of the economy is under strain.

For policymakers, this requires thinking beyond tariffs and logistics. Designing 'resilience corridors' resonates with UN OCHA's concept of humanitarian logistics hubs, which secure vital goods under active conflict. Integrating conflict-zone trade into broader humanitarian and reconstruction efforts could reduce post-conflict recovery costs by up to 25%. Targeted policies such as constructing customs systems that work during war, protecting essential imports, and funding diversification in vulnerable areas should no longer be optional. They are all strategic necessities for stability.

Conclusion

This study offers new evidence that trade integration can help reduce the local economic fallout of armed conflict. Using data from Ukraine's 27 oblasts between 2012 and 2022, this study finds that regions in the highest quartile of trade openness experienced, on average, 15% smaller declines in night-time light intensity than those in the lowest quartile, roughly equivalent to preserving three years of post-conflict recovery. Diversified export structures and reliable import flows played a key role, allowing goods to move through alternative routes when borders

closed or supply lines were disrupted. While there are important caveats, such as the limitations of night-time lights in capturing conditions in militarised zones, and the fact that Ukraine's trade profile may not reflect other conflict-affected states, the findings suggest a broader takeaway. Well-integrated trade corridors can act as a stabilising infrastructure during conflict, helping to keep economies functioning and livelihoods intact. By combining satellite, conflict, and trade data at the subnational level, this paper brings together fields that are often siloed, offering a fresh framework for understanding resilience under extreme disruption.

For policymakers, the message is clear: integrating conflict-zone trade into humanitarian and reconstruction planning could cut post-conflict recovery costs by as much as 25%. Embedding export-diversification benchmarks into aid packages would transform trade reform from an afterthought into a core pillar of rebuilding, while “conflict-proof” digital customs platforms could keep essential goods flowing even under duress. By viewing trade routes as part of a resilient infrastructure, governments and international partners can better protect communities and accelerate post-war renewal.

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Seeing Beyond the Tumor: Integrating Gα12 Signaling with AI-Enhanced Imaging in Glioblastoma

By Katherine Shew¹, Dr. Olga Meiri Chaim²

Abstract

Glioblastoma Multiforme (GBMs) are incredibly aggressive, resilient, and rapidly growing abnormal masses in the brain hemispheres and rarely in the spinal cord. Tracing back to fundamental biological concepts to try and find effective oncological treatments, we explored two analog genes GNA12 and GNA13 and their respective encoded proteins. We suggest that their significant roles in GBM growth follow complex patterns of co-regulatory gene expression and intricate signaling activity. While an increase of GNA12 mRNA levels also correlates with promotion of tumor invasiveness in databases, signals often feedback in tumor biology. GNA13 expression also transcriptionally regulates phenotypes to modulate cell survival and their proliferative characteristics for high-grade gliomas. Both Gα12/13 proteins and molecular partners in the pathway derived of the regulation of GNA12 and GNA13 gene expression have, therefore, potential control of tumor malignancy. As modulatory subunits presenting upstream receptor coupling, they act often to activate Rho GTPases, molecular targets accessed in neuroinflammatory responses in tumor microenvironments, as central pathways. If leveraged correctly - through biological diagnostics and/or integrated imaging tools - they enable both enhancing odds of tumor visualization and insightful therapeutics possibilities. Our research reviewing existing literature covers information about proteins' role in GBMs to examine AI imaging momentum according to the neuro-oncology status quo, primarily. Lastly, we established a framework for tumor visualization and monitoring by integrating AI/ML imaging interpretations, biological markers, and patient centered features to goal the betterment of neuro-oncological outcomes.

Introduction

In a clinical setting, patients often face immense difficulty in understanding the complexities behind their diagnoses. Specifically in the neuro-oncological clinical landscape, brain and spinal tumors can be hard to digest for a patient with little formal medical background. One of the most treatment-resistant and infectious tumors in neuro-oncology is Glioblastoma Multiforme (GBM) (Yalamarty et al., 2023). More than 12,000 individuals in the United States alone suffer from GBM (MD Anderson Cancer Center, 2016). On a pathological level, GBM is characterized by nuclear atypia, intra-tumor heterogeneity, immense proliferation, and necrosis. This distinguishes it from other lower-grade gliomas. These features underscore a poor prognosis with shorter median survival times (D'Alessio et al., 2019).

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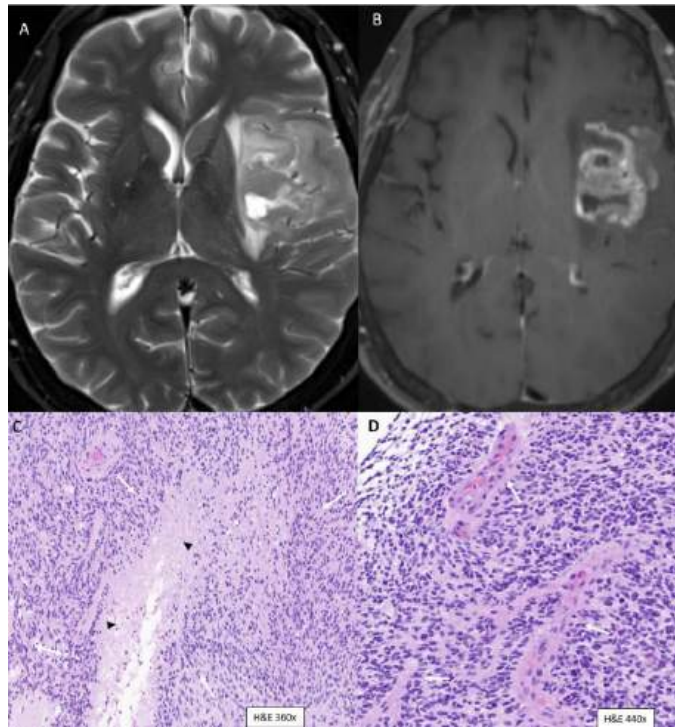


Figure 1. Magnetic Resonance Imaging and histopathological features of GBMs, left frontal mass of a 65 year old woman. Contrast enhanced images highlight necrosis, black arrows centralize necrosis area. In C, white arrows are hypercellular tumor nuclei that are a feature of necrosis. In D, white arrows are microvascular proliferation through microvessels. H&E staining by Agarwal et. al, 2021.

Understanding that GBMs are more resistant to treatment and invade rapidly other brain areas, exploration of diverse oncological solutions is paramount. We do this in two ways: we look at the gene expression of GNA12 and GNA13 in GBMs. These genes encode G-proteins, which are part of intracellular signaling and cellular function. G-proteins are a part of a larger process involving G protein-coupled receptors (GPCRs). GPCRs are a large group of proteins on cell surfaces and act as molecular switches for communication between the inside and outside of the cell. When a GPCR binds to a specific signaling molecule, it changes shape to activate G proteins (Ritter & Hall, 2009). G proteins are made up of three subunits - α , β , and γ - and their activation triggers downstream signaling pathways that can alter cell behavior. The α subunit determines which signaling pathway will be activated (Ritter & Hall, 2009). For example, the G α 12 subunit is known for regulating the cell's cytoskeleton and promoting movement. GPCR signaling is foundational for latter oncological processes: proliferation, migration, and invasion. By reviewing existing studies on GNA12 and GNA13's role in GBMs, they impact the overall survival and disease-free period of GBMs. Furthermore, through various signaling pathways like the MAPK pathway, they influence other transcription factors and invasiveness.

Circling back to the patient end of oncological care, we were curious in how Artificial Intelligence/Machine learning (AI/ML) could make imaging clearer and faster for a patient.

Then, connecting it with the biological mechanisms above, we wanted to know if it could be intersected with biomarkers to make for stronger diagnostic tools. Current imaging techniques are often a binary - they combine biomarkers and imaging, or only combine AI/ML with imaging, no biomarkers. We hope to highlight how we can go beyond the binary.

The aim of this project is twofold. First, we investigate and analyze two proteins' involvement in GBM invasiveness. We compile literature to explain how fundamental biological mechanisms can be better leveraged to treat aggressive cancer care. Second, we wish to design an example interface for an AI/ML imaging system that can appeal to patients while helping physicians.

Material and Methods

This project was conducted in a multitude of scientific sources. Overall, this research took a holistic approach to familiarize the student with biological interests. Briefly, we shared experiences on a topic from application angles that could be benefiting GBM patients. It was immensely hybrid and interdisciplinary to learn about the subjects in neuro-oncology by a molecular perspective. Leveraging comprehensive databases, remote resources, and technological improvements towards considering targets for a patient-directed framework design.

Nature Editorial for Scientific Reports. Nature Editorial is an international company that publishers compile databases weekly with revolutionary scientific and technological peer-reviewed research. Nature Editorial was initially accessed for the primary source regarding the relationship between the Gα12 protein and GBM proliferation. As Nature editorial hosts several journals of its own, Nature Review Molecular Cell Biology and Scientific Reports are the precise source that the Gα12 paper came from. Later on, it was referenced to explain G protein-coupled receptors (GPCRs) cited as a resource to summarize the importance of GPCR function as a membrane protein complex. Mostly, Nature Editorials articles were utilized to access papers focused on introducing biological foundations, growth relationships, and existing AI vulnerabilities. Nature Journals, <https://www.nature.com/>, Springer Nature.

MDPI. MPDI is an open access publishing platform that combines 478 open access journals supporting all fields of research. MPDI was used to reference one of the last papers on the current glioma imaging system with biomarkers for diagnostics. MDPI, <https://www.mdpi.com/about/journals>.

PubMed. Pubmed is a public research library that encompasses over 38 million citations of biomedical literature (online textbooks, journals, MEDLINE). All papers referenced here are found on PubMed, most being directly cited from PubMed. PubMed is a widely used database that eases the process of searching for relevant research. PubMed, <https://pubmed.ncbi.nlm.nih.gov>, National Center for Biotechnology Information. National Library of Medicine. U.S. National Library of Medicine.

GlioVis. GlioVis is a web application for data illustration and analysis to explore brain tumors' expression datasets. Specific genes, platforms, and analytical methods can be adjusted in the platform. GlioVis was used for two reasons. First, we collected graphical data that demonstrated the mRNA expression levels of genes (GNA12, GNA13, FOXO3) in GBMs. Second, we studied the correlation among those genes with one another. GlioVis provides the ability to calculate the association (if any) between those three. GlioVis, <https://gliovis.bioinfo.cnio.es/>. Bowman et al. 2017.

The Cancer Genome Atlas (TCGA) - Glioblastoma. TCGA is a comprehensive network of over 20,000 primary cancers and matched normal samples with 33 cancer types. It has generated genomic, epigenomic, transcriptomic, and proteomic data. TCGA was selected as the database used in GlioVis because of its expansive collection. We specified and limited TCGA to their GBM images. It is also a public resource with detailed analytics, with both cancer and normal tissue samples that act as a control group. The Cancer Genome Atlas, <https://www.cancer.gov/ccg/research/genome-sequencing/tcga>, Center for Cancer Genomics, National Cancer Institute - National Institute of Health.

GeneChip® Human Genome U133 Arrays (HG-U133A). HG-U133A is a microarray system that is commonly used for measuring gene expression. It contains the relative expression levels for over 47,000 transcripts. We selected HG-U133A to be the genome platform in GlioVis because it compiled a long history of data and created a statistically stronger correlation between GNA12 and GNA13.

Pearson Correlation. Pearson correlation is a statistical method studying linear relationships. Since the correlation graph is linear and we wanted to know the strength of the correlation, Pearson correlation is more accurate. It provides straightforward effect size (r) and significance test (p -value). It is also the standard for gene expression correlations.

Claude. Claude by Anthropic (2023) is an AI assistant that aids in coding and generating specialized applications. Claude can help effectively compose a proposal for our AI/ML framework. A component of our research is also incorporating biomarkers into said AI systems. Although Claude is limited in generating such powerful structures, detailed opportunities are given in the discussion. The framework that this research analyzes will highlight patient experience more. Code can be found in Discussion - AI/ML Neuro-imaging Framework. Ostensibly, to have it be applicable in a medical circumstance, it needs to be refined and checked for informational mistakes. Nevertheless, it is designed to be easy to understand for a patient centered audience. Using Claude was an efficient avenue for a project with time constraints. It easily creates a framework without excessive human input, and can have appealing graphic design components. It functions as a first rough draft and a concept for future imaging to come.

Results and Discussions

A multidimensional approach was chosen in order to have a technological point of view while also engaging with scientific literature. As the framework for the software heavily relies on existing patient images, visualization of scans, and categorized datasets, online compilation of data is a preferred execution. Furthermore, focusing on both the present and what may be lacking, along with opportunities for growth in the future is the priority of this paper.

AI/ML Neuro-imaging Frameworks

Currently, imaging tools that incorporate AI/ML functions are lacking (Merkaj et al., 2022). In a review examining the status of glioma apparati, which can be similar to GBM technology, it was clear that there are present challenges with heavy handed solutions. In systems that may be used for diagnosis, reasons for inaccuracy are multidimensional; primary issues are the external validity of AI/ML imaging softwares and inconsistency with real-life usage.

On external validity, problems are stemming from software that is trained on one single set of data. It consolidates multiple datasets into one by utilizing the same sorting processes - when aiming to delineate parts of a tumor or scan - it reduces the diverse sorting that might go on if done manually. This homogeneous line of processing mitigates the wide variety of scans that a clinical imaging system might encounter. Different bodies, growths, and even image qualities can easily affect the precision of imaging tools that are only accustomed to one species of input (Merkaj et al., 2022).

Generally, patients are wary of AI/ML imaging software as well. There has been recent news surrounding the inherent unfairness of AI algorithms. One reason for this disparity is that some imaging datasets often do not provide the demographic insight of the scans - and when limited representation of vulnerable communities is present - more errors for minority sub-populations occur (Ricci et al., 2022). Hence, that is why we suggest providing a patient-friendly AI/ML model, especially one that has the option to disclose race and ethnicity. This allows room for personalized solutions and knowledge that may be more helpful to one community rather than another.

As our research segways into biological factors that pose as incredible pathways to diagnostic success, there are deficiencies in the biological backing of current imaging structures. In only GBMs, the precision and accuracy of imaging systems that monitor biomarkers have varying precision. In earlier prevention programs, the trend was that it was less accurate. In later intervention sets, accuracy was typically higher. Intuitively, with clearer data available later into the diagnosis, it is easier for a software to classify and analyze than a preliminary notion of GBMs. In the same vein, ML acts as a recommendation for success. ML can read wider data sets in a shorter amount of time, acting as a supplement to existing advanced MRI systems (Booth et al., 2022).

Molecular and Cell Biology applied to GBM

Biological mechanisms and markers act as an effective and fundamental way to prevent the growth of aggressive tumors like GBM. Proteins, for one, are an excellent resource for intervening tumors - they can control cellular qualities and communication - especially those that may be causing harmful cancerous growths. One such notable mechanism involves heterotrimeric G-proteins, which act as molecular switches to relay signals from receptors on the surface) of the cell to internal pathways.

Notably, when activators of Gα12 protein signals were coupled to receptors, RhoA mediated gene expression is differentially significant compared to unchallenged cells. RhoA is a small GTP-binding protein reported to participate in similar phenotypical changes to epithelial-mesenchymal transition (EMT) (Robert Weinberg book or papers). It is important to note that many brain research groups also discuss some debatable parallel with proneural-mesenchymal terminology that neuro-oncological subtyping could resemble to transitions as PMT, PN-to-MES. However, PMT is not quite representative of all characteristic events by pathological and pharmacological definitive studies for medical diagnostics & standard classifications. High GNA12 expression in MES tumors correlated with worse overall survival (log-rank $p = 0.017$). In patient-derived glioma stem cells (GSCs), GNA12 mRNA expression was significantly higher than in differentiated glioma cells ($p < 0.001$). Stable shRNA knockdown (KD) of GNA12 in GSC23 and HK281 lines reduced mRNA and protein levels by more than 80% ($p < 0.001$). When implanted into orthotopic mouse models, GNA12KD tumors showed no significant change in size or survival ($p > 0.05$) but displayed a 47% reduction in invasion index (from ~0.32 in controls to ~0.17; $p < 0.001$). Transcriptomic profiling revealed that GNA12KD downregulated 812 genes, including several extracellular matrix components (e.g., COL1A1, COL3A1, FN1) and many stem cell markers (e.g., SOX2, NES), while upregulating some often considered proneural markers (OLIG2, ASCL1). Notably, THBS1 (thrombospondin-1) expression decreased by ~80% ($p < 0.001$), and THBS1KD phenocopied GNA12KD by reducing invasion to ~0.18 ($p < 0.001$). Mechanistic assays showed that sphingosine-1-phosphate (S1P) stimulation increased THBS1 expression ~2.3-fold in control cells ($p < 0.01$), an effect abolished by GNA12KD, while engineered Gα12 activation (DREADD) boosted THBS1 ~2.5-fold and migration ~1.8-fold ($p < 0.01$), both of which were blocked by THBS1KD. Together, these results identify the GPCR - GNA12 - THBS1 signaling axis as a key promoter of GBM invasion. In independent and additional studies, this pattern is affirmed. Reducing the presence of Gα12 correlated with the reduction of tumor invasiveness in mice, even if not tumor size or duration (Rasheed et al. 2022). This association suggests GNA12 can act as a driver of tumor aggressiveness, particularly through promoting mesenchymal-like, migratory behavior in cancer cells (Chaim, 2023).

Targets	Finding	Quantification
mRNA Expression in TCGA GBM Patient Samples	Upregulation	30% GBM samples show upregulated GNA12 mRNA; enriched in MES & Classical (CL) vs Proneural (PN) & Neural (NE) ($p < 0.01$)
Survival Correlation	Overall survival (OS)	High GNA12 in MES tumors → worse OS (log-rank $p = 0.017$)
mRNA Expression in GSCs	Variable & Stimuli driven	GNA12 higher in GSCs ($p < 0.001$)
Mouse tumor growth	Size, survival	No significant change ($p > 0.05$)
Mouse tumor invasiveness	Invasion indexes	47% reduction ($\sim 0.32 \rightarrow \sim 0.17$; $p < 0.001$)
GNA12 KD (shRNA)	Gene expression	- Downregulated 812 genes including ECM components (COL1A1, COL3A1, FN1, stem markers SOX2, NES) - Upregulated PN markers (OLIG2, ASCL1)
THBS1(mRNA)	Multidomain pleiotropic glycoprotein & S1P-inducible/regulate	- Decreased 80% ($p < 0.001$) - THBS1 KD phenocopied GNA12 KD (invasion ~ 0.18)
Mechanistic Assays - Human astrocytoma in vitro	S1P stimulation & growth and adhesive factors sensitiveness for differentiation	Increased THBS1 ~ 2.3 -fold in control ($p < 0.01$)
Gα12 Protein Activation by DREADD	Ligands variability and localization of designed receptors specificity issues for regulatory expression	- THBS1 ~ 2.5-fold - Migration ~ 1.8-fold ($p < 0.01$)
Overall: GNA12–THBS1 axis, through transcriptional regulation by GPCR pathways are key drivers of GBM invasiveness		

Figure 2. A summary table of the GNA12 findings from Chaim et. al., 2023.

GNA12 not only correlates with higher tumor grade, but also regulates expression of thrombospondin-1 (THBS1 gene, TSP-1 protein), a key matricellular glycoprotein that is crucial in cell adhesion, angiogenesis and migration. Further experiments revealed that THBS1 and other members of the family act downstream of GNA12 to mediate GBM cell movement and invasive capacity in a complex tumor microenvironment. Analysis of transcriptomic data showed Gα12 protein activity also impacts pathways related to extracellular matrix organization and integrin signaling, reinforcing its role in tumor invasiveness (Chaim et al., 2023). By linking a well-known signaling molecule to a specific pro-invasive program, this demonstrates how mapping basic, but significant molecular interactions can reveal new vulnerabilities in GBM.

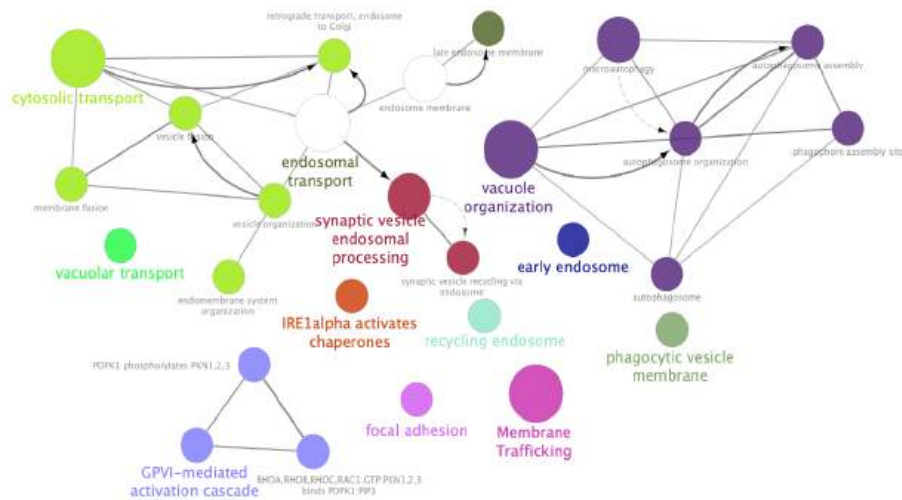


Figure 3: Multicomponent graphic schemes - Cluego terms is a personal communication by Chaim, 2025 to value Shew & Chaim 2025, whose framework goal is to exercise ways to orientate patients. It can consider including Cluego annotation terms further on (Bindea et al., 2009).

The above scheme provides a distribution of functionally grouped genes as cellular events that match aggressive growth. Relevantly it arranged cell dynamics that GNA12 has genes differentially expressed among putative sustained signaling. The participation of activities reinforced by Ga12 protein in glioblastomas selected in databases can be individualized by sequencing methods for prognosis. Cell biology responses leveraged signaling pathways circumventing senescence, hypoxic tumor environments in highly proliferative cancers that include beyond RhoA central cascades, but emphasize various lipid mechanisms that promote membrane remodeling and lipid oxidation, whether in autophagia and endosomal-lysosomal movements that typically arose membrane transports surpassing structural tissue stiffness, leads to necrosis, blebbing and shedding common to aggressive and dysregulated proliferative signals (Chaim et al., 2023, Santos-Otte et al, 2025).

Similarly, GNA13, which encodes the Gα13 subunit of heterotrimeric G-proteins plays a role in GBMs as well. Much like other proteins, it plays a critical role in intracellular signaling and can be examined for potential in oncological treatment. Although it has been explored in other cancers such as breast and prostate cancer, its role in GBM is largely unexplored.

However, compared to GNA12, GNA13 actually has the opposite invasiveness pattern and experimental results. Using the Clinical Proteomic Tumor Analysis Consortium (CPTAC) dataset, researchers found that GNA13 protein expression is significantly downregulated in GBM tissues compared to normal brain tissue. Kaplan - Meier analysis of TCGA data revealed that higher GNA13 expression correlates with longer disease-free and progression-free intervals, while low expression is associated with the opposite. Functional experiments in GBM cell lines (U118 MG, U138 MG, U251 MG, U87 MG, SHG44) demonstrated that GNA13 knockdown enhances invasion (Yi et al., 2023) whilst GNA12 overexpression suppresses these phenotypes.

GNA13 was found to be a negative regulator of the ERK/MAPK pathway. The MAPK pathway is a chain of proteins that passes growth and survival signals from the cell surface to the DNA in the nucleus. This manages processes like cell division, stress responses, and survival. A key component is Extracellular signal - regulated kinase (ERK), which becomes active when upstream proteins like RAF and MEK phosphorylate. Once activated, ERK moves into the nucleus and turns on genes that drive cell growth and migration (Guo et al., 2020). In healthy cells, ERK activation is tightly controlled, but in glioblastoma (GBM) this pathway is often overactive, leading to uncontrolled proliferation and invasiveness. With GNA13, low expression increases ERK phosphorylation, which lowers levels of the tumor-suppressing transcription factor FOXO3 and promotes metastasis. On the other hand, high GNA13 expression was found to suppress ERK activity, elevate FOXO3, and reduce GBM cell invasion (Yi et al., 2023).

Western blot analyses showed that GNA13 knockdown increases ERK phosphorylation, while overexpression decreases it. Pharmacological inhibition of ERK activation using U0126 reversed the pro-migratory and pro-invasive effects of GNA13 knockdown, placing GNA13 upstream of ERK signaling. Bioinformatics and qRT-PCR further identified FOXO3 as a downstream target of this pathway; GNA13 promotes FOXO3 expression by inhibiting ERK phosphorylation. FOXO3's functions as a tumor suppressor regulating cell proliferation, apoptosis, and metastasis, and its upregulation by GNA13 contributes to the suppression of GBM invasiveness (Yi et al., 2023).

Overall, these findings position GNA13 as an uncommon invasion suppressor in GBM - contrasting with GNA12, which promotes invasion. These results suggest that restoring GNA13 function or mimicking its downstream effects could pose a new approach to control GBM progression. These patterns serve as significant features that should be integrated into biotechnology and medical systems because of their biological power.

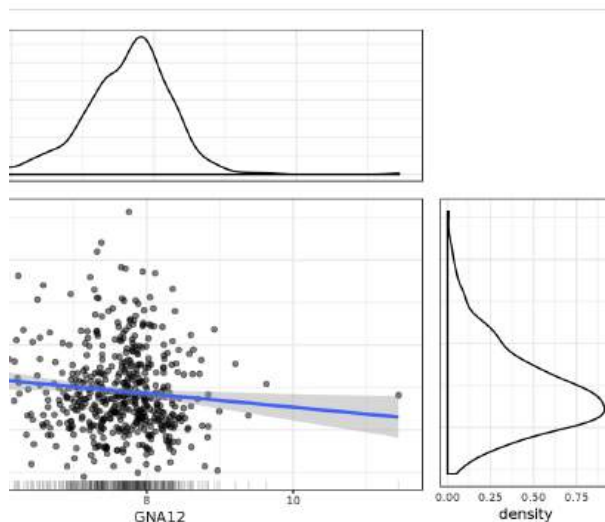


Figure 4. A correlation graph of GNA12 and GNA13 involvement in GBMs. Weakly correlated, but statistically significant to display there is a negative correlation (GlioVis, 2025).

Discussion - Integration - Our Framework

Intersecting with the discussion and insight on biological or genetic processes, tumor grade classification systems are not integrative enough with scientific patterns.

Valuable prevention and diagnosis techniques such as biological mechanisms can be useful in AI/ML imaging frameworks. Merkaj et al. 2022 explained that one of the current challenges with AI networks in gliomas was that the grading system of high and low grade tumors overlook the complexity of carcinogenic growths. As rapidly developing science continues to come into light, such as the power of the Ga12 protein in tumor invasiveness, grading scales are becoming more and more complex. Knowing how to utilize that complexity to make more accurate diagnoses with AI/ML is thus especially critical. AI/ML should not just be trained on images and patterns, but consistently be fed with novel research regarding what biomarkers or mechanisms can be at play - and how that can be a pivotal aspect in prognosis. Although not GBMs, gliomas can be as aggressive as GBMs and are key examples of discrepancies in AI imaging now. They act as a vantage point for opportunities for improvement in imaging systems as a whole.

There is not much work done on how biomarkers can be more effectively included in these AI/ML diagnostic platforms, at least in the world of GBMs. In less aggressive tumor types, such as gliomas, there has been more integration work done. Excluding AI/ML, right now, amide proton transfer-weighted (APTw) MRI, used with standard MRI sequences, has been able to detect molecular features. Such features include MGMT promoter methylation, p53 expression, ATRX status, IDH1/2 mutation, and Ki-67 proliferation index. APTw MRI is a chemical exchange saturation transfer (CEST) imaging technique that creates image contrast on amide protons in mobile proteins and peptides through their effect on water signals (Zhou, 2019). If later combined with AI/ML, processes could become significantly faster and increase efficiency of oncological care. As there have not been many AI algorithms devised with more factors in mind and constrained training datasets, more research and development has to be done in order to truly say what the best methodology is for biological mechanism integration. It has potential to be a shining diagnostic and treatment tool, but is hard to devise quickly.

Our framework for an imaging system that integrates both science-backed diagnostics and patient friendly interactions is complex. With a patient end and a physician end to the application, patients can interact with their physicians but also interact with their disease. They can see an interactive model of their bodies and ask general questions for an AI/ML to answer. Physicians can upload their diagnoses and background, while patients access summarized reputable resources online to better inform them about their oncological issues. They can visualize what may be going on in their bodies. On that physician end, there can be biological marker information based on the patient's genetics, test results, and previous medical history. As AI/ML advances to read data and charts faster than ever, it should be employed to sort through the sets that a human may be behind on analyzing.

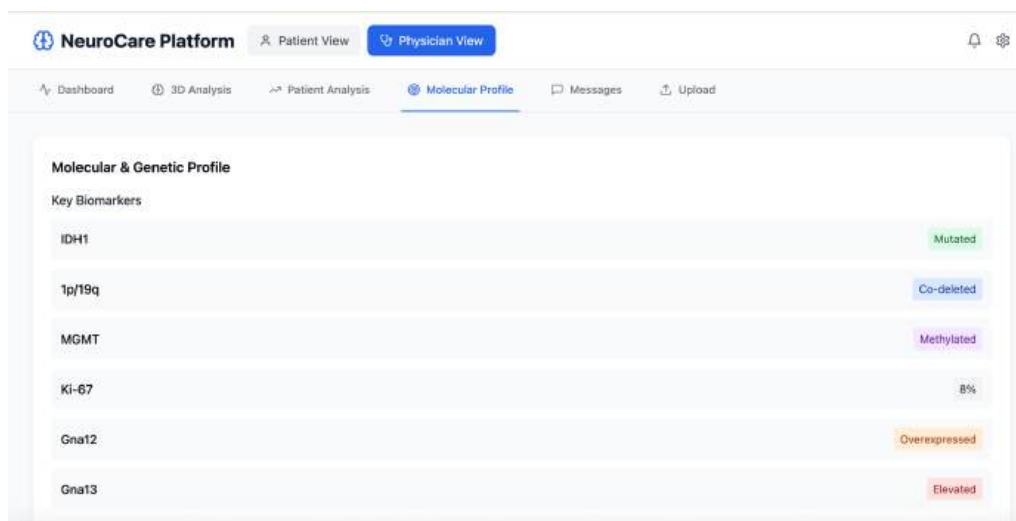


Figure 4. A preview of the AI/ML Biomarker imaging system (Claude, 2025).
[Framework Public Access Link](#)

Conclusion

Through the analysis of several, comprehensive research papers regarding G-protein involvement, our findings demonstrate they act as pathways for treatment. Specifically, studies have implicated $G\alpha 12$ as a key proponent of invasiveness through RhoA and THBS1 signaling pathways. GNA13 knockdown has enhanced invasion through ERK pathways. These findings position $G\alpha 12$ and $G\alpha 13$ not only as a mechanistic contributor to glioblastoma aggressiveness but also as a biomarker for stratifying patients by invasive risk and as therapeutic targets.

Steps have already been taken to integrate biomarker capabilities with current imaging systems. Intersection with existing MRI systems are powerful diagnostic advancements - there is still a necessity in the realm of GBMs. There also needs to be more discussion on how these imaging structures can be better applied to patients. Patients should be understanding of their own diagnoses, so biotechnology needs to span past the solely research aspect.

Future work in this area should focus on the capabilities of AI/ML imaging frameworks and their intersection with revolutionary biology. The combination of science and technology enhance the treatment possibilities for resilient, infiltrative tumors like glioblastomas.

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What Is the Impact of TikTok on the Impulse Clothing Purchasing Behaviors of Generation Z Female consumers in the United States? By Tiffany Le

Abstract

According to eMarketer estimates, TikTok has 1.04 billion monthly active users worldwide as of May 2024 (Backlinko, 2025). In 2022, 24 million people in the United States had made a purchase after viewing a similar product on TikTok, and this number is expected to rise to 40 million people per year by 2026. The growth of TikTok has heavily influenced clothing purchases among Generation Z females in the United States. This study aimed to assess the behavioral processes behind customer purchasing behavior on TikTok. I conducted an online survey with 10 multiple-choice questions for Gen Z females (ages 14 to 27 years) using TikTok. The survey measured TikTok usage, influencer impact, and For You Page (FYP) exposure. The FYP is TikTok's central feed of videos that users consume, personalized by its algorithm to increase exposure to certain trends, products, and influencers. Thirty-six people met the criteria and were included in the analysis. Approximately 69% said they had bought clothing after seeing it on their FYP, and 52% purchased something from TikTok Shop. A chi-square test showed a significant association between the time spent on TikTok and purchases from the FYP. These findings show that TikTok significantly influences Gen Z females' clothing purchases through the FYP. The significant association between time spent on the app and purchases highlights how TikTok's algorithm drives consumer behavior. These results suggest that TikTok is a powerful marketing tool for brands to utilize.

Introduction

Over the past few decades, the growth of social media has changed the way people make purchasing decisions. The growth of TikTok specifically has heavily influenced clothing purchases among Generation Z (ages 14 to 27 years) females in the United States (Munoz, 2022). In 2022, 24 million people in the United States had purchased a product seen on TikTok, and it is estimated to reach 40 million by the year 2026 (Statista, 2025). This number is expected to rise as e-commerce becomes more prevalent in everyday life, as brands shift from in-store to digital platforms. This substantial increase reflects the platform's influence and the increasing reliance of brands on social media platforms in order to reach younger consumers.

TikTok's unique algorithm has transformed how products are marketed and consumed. The algorithm is highly personalized, which engages with a user's cognitive and emotional states (Valeza, 2024). Stimuli such as influencer authenticity and user engagement drive user response and trigger impulsive buying. This means that users are not only processing content rationally, but also responding to it subconsciously, through curiosity or even fear of missing out, which heightens receptivity to products. Influencers, people with online followings, play a key role in shaping audience opinions and purchasing decisions. Influencer authenticity refers to how "real" or relatable a creator seems, whether they appear genuine in their recommendations or share personal experiences (Valeza, 2024). When influencers present themselves as trustworthy peers rather than distant celebrities, users often form parasocial relationships, which is a one-sided

bond that feels personal despite lacking real reciprocity (Zabielski, 2023). This perceived closeness increases trust, making users more likely to believe advertisements and convert that trust into immediate purchases. Additionally, the TikTok algorithm creates content bubbles, repeatedly showing similar products, influencers, or brands (Boeker & Urman, 2022). The platform tends to continually push the same or similar products regardless of whether users continue to engage. These content bubbles are personalized to individual interests, making them a powerful marketing tool. Influencers play a key role in these content bubbles: once a user engages with a specific creator, the algorithm continues to show content from that influencer or similar ones. This repetition builds familiarity and increases the chance of purchases. TikTok's algorithm constantly reshapes based on user behavior by subtly learning preferences as well as reinforcing them through repeated exposure.

Further, TikTok recently introduced TikTok Shop, which allows creators to directly link to products they are advertising and allows users to seamlessly purchase content they see on the platform. This integration reduces the buyer journey from discovery to checkout to only a few clicks. Research has shown that minimizing the steps in a purchase increases conversion rates by reducing decision fatigue (Mandel et al., 2017). Incorporating TikTok Shop removes the barriers to online shopping, which increases the likelihood of impulsive buying decisions.

Social media has allowed brands to directly reach younger audiences, making it essential to understand how platforms like TikTok affect purchasing decisions. More than half of Gen Z (55%) report that social media is the advertising channel that most influences their choices (CivicScience, 2025). With TikTok's personalized For You Page (FYP), prominent influencer base, and TikTok Shop, these features make it easier than ever for users to discover and purchase products. The FYP is TikTok's central feed of videos that users consume, personalized by its algorithm to increase exposure to certain trends, products, and influencers.

Currently, there is limited research examining the impact of TikTok use on clothing purchasing behaviors among Gen Z women in the US. This demographic is important because they spend a significant amount of time on social media platforms. To address this gap, this study aims to examine the associations between TikTok use behavior and consumer fashion purchases on TikTok.

Methods

In order to assess Gen Z women's TikTok use and clothing purchase behavior, I created a survey using Google Forms. I identified key constructs that are relevant to purchases in TikTok, including TikTok usage frequency, exposure to TikTok Shop and influencers, and recent online shopping behaviors. Survey items were crafted to be short by using closed-ended question formats like multiple-choice and yes/no questions, which reduced participant fatigue and encouraged higher response accuracy and completion rates.

The survey was distributed online over a one-week period. I shared the link through direct messages and word of mouth to reach Gen Z females who are active TikTok users. I included screening questions at the beginning of the form to ensure that only respondents who identified as female, were between the ages of 13 and 28, and used TikTok at least occasionally

continued the survey. The survey included 10 items and took approximately one minute to complete. Survey items asked about TikTok usage, average time spent on the app per day, purchases made due to influencer recommendations, For You Page (FYP) exposure, and use of TikTok Shop. A final question asked how participants had heard about the survey, allowing me to track distribution sources.

Results

A total of 46 participants completed the survey between July 14, 2025, and July 22, 2025. Nine were removed from analyses because their responses did not fit into the criteria of Gen Z females that had TikTok downloaded or did not fully complete the survey, leaving 37 complete responses. The average age was 18.7 (SD=2.38). All participants self-identified as female and were between the ages of 16 to 27.

Approximately 78% of the participants reported that they use TikTok multiple times per day (Figure 1). Nearly 89% of participants reported that they used TikTok for more than one hour per day (Figure 2). Twenty-seven of the participants reported that they had purchased clothing online in the past 30 days, with 41% of them making purchases from TikTok. Approximately 69% of the participants reported buying clothing after seeing it on their For You Page (FYP), whereas only 25% of participants reported that they had bought something from a TikTok influencer (Figure 3 & 4). Around half (52.8%) of the participants reported that they purchased something from the TikTok Shop.

I conducted Chi-Square tests to assess the associations between TikTok use and purchasing behaviors. The tests suggest that the hours spent on TikTok and purchases from TikTok's FYP are significantly associated ($\chi^2 = 6.000$, $p=0.049$). I also examined whether TikTok frequency was associated with clothing purchases made in the past 30 days. The p-value was 0.23, suggesting that the two variables are not related. Additional Chi-Square tests were conducted between TikTok use frequency and purchase from an influencer ($\chi^2 = 4.822$, $p=0.08$) and TikTok Shop purchase ($\chi^2=3.981$, $p=0.136$), neither of which showed statistical significance.

Figure 1 - TikTok Frequency

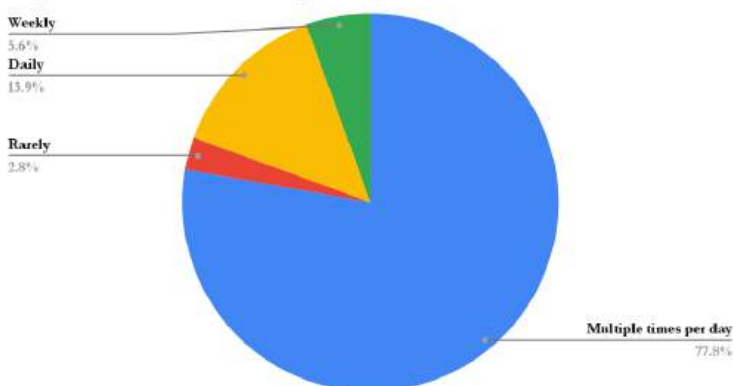


Figure 2 - Purchases made from For You Page (FYP)

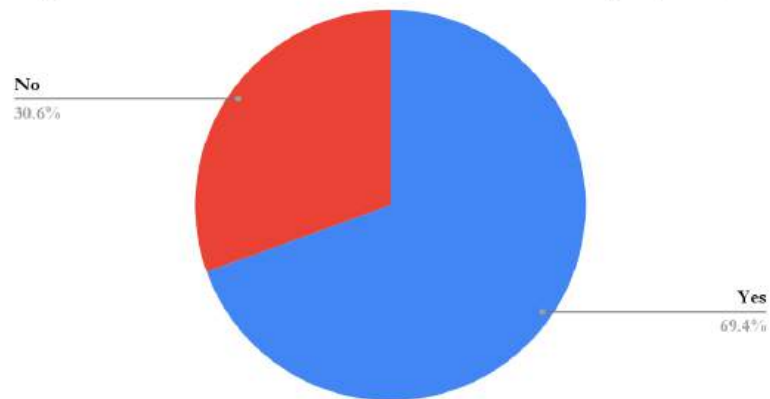


Figure 3 - Purchases made from TikTok Shop

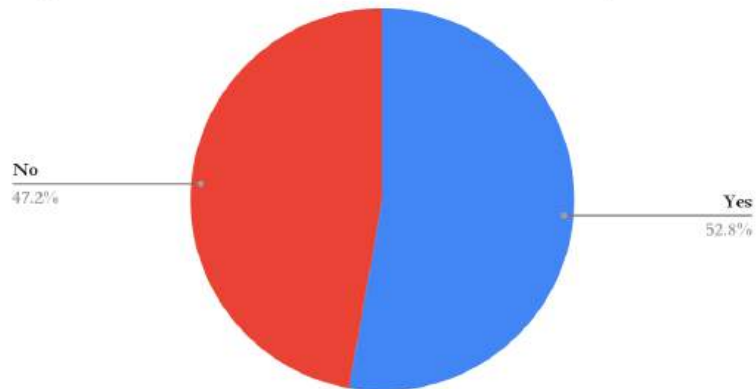
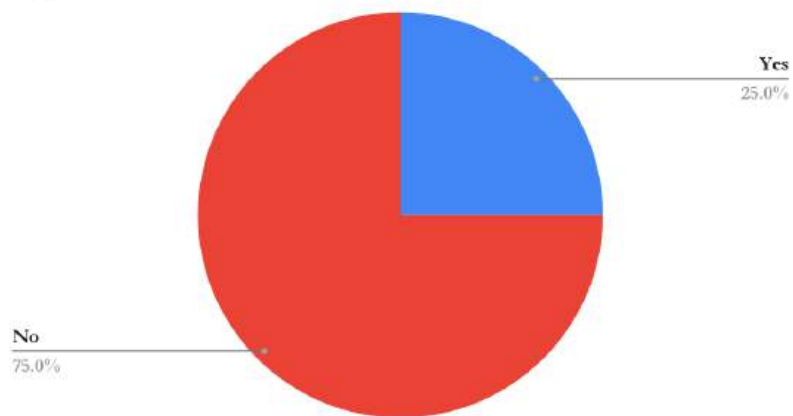


Figure 4 - Purchases made from Influencer Promotion



Analysis/Discussion

This study examined the relationship between TikTok use and clothing purchasing behavior among Generation Z females in the United States. The goal was to identify if prominent TikTok features (FYP, influencer marketing, & TikTok Shop) influenced customer purchasing decisions. With over three-quarters of participants using TikTok multiple times per day, and over half reporting purchasing clothing through TikTok Shop, it is evident that TikTok influences user behavior. TikTok is, therefore, a powerful marketing tool for brands, as the personalized algorithm provides frequent exposure to products. Companies can strategically leverage TikTok's algorithm and integrate with TikTok Shop to shorten the buyer journey and more effectively capture impulse purchases. For users, these results highlight the strength of the algorithm, which can raise concerns about how easily Gen Z consumers can be influenced to impulsively purchase items. This emphasizes the need for greater awareness of digital consumption habits. For regulators, the blending of commerce and entertainment makes it difficult to tell the difference between organic content and product advertisements.

A chi-square test showed significant associations between the use of TikTok and purchases from the FYP ($p=0.049$), reinforcing the idea that TikTok's algorithm plays an important role in shaping user decisions. This test also suggests that the more time spent on TikTok may translate to higher consumer activity. This raises concerns about the potential for overspending and the development of impulse-driven shopping habits, especially among younger audiences who may have less knowledge of financial literacy. Another consequence of the association between TikTok and purchases from the FYP is the potential shift in how Gen Z approaches fashion consumption by disregarding sustainability. Especially with excessive presence of micro-trends, which are short-lived consumer trends that gain rapid popularity and fade quickly, consumers may feel pressure to buy more frequently to keep up with trends, leading to overconsumption and a stronger reliance on fast fashion.

Possible limitations in this study include a small sample size (37) and self-reported data, which may result in reduced generalizability and introduce the possibility of self-report bias. Future research should consider using a larger sample size and additional variables such as trust in influencers or peer influence.

Conclusion

In this online survey examining the impact of TikTok and its features on Gen Z females' clothing purchasing behavior, I found that there was a significant positive association between TikTok frequency and purchases from the For You Page (FYP). These results indicate that the amount of time spent on TikTok exposes users more frequently to clothing advertisements, which affects their purchasing behavior. Further research should examine the impact of TikTok's features on a larger and more representative sample group. A valuable next step would be to ask how specific features such as TikTok Shop, influencer partnerships, or algorithm-driven micro-trends shape purchase frequency and attitudes toward sustainability and fast fashion. Exploring this question could provide deeper insights into the long-term effects of TikTok-driven consumer behavior.

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A Tale of Ghosts, Vengeance, and Greed (Except For When It Is Not): The History of *Yotsuya Kaidan* and its Adaptations By Liv Adao

Abstract

This paper discusses the evolution of the traditional Japanese *Yotsuya Kaidan* ghost story by analyzing its two main characters within Japanese cinematic adaptations in the U.S. occupied period of 1949 and culturally confused period of 1959. This analysis is then compared against the original kabuki play written in 1825, in order to understand why the adaptations made certain changes, and to what effect. This analysis intends to show the way a story's message is a reflection of the beliefs and values of the time in which it was produced, and how contemporary history and events—like occupation, censorship, cultural confusion—will inevitably bleed into the media that is created during them, and thus are important context to recognize when analyzing film. Through thorough analysis of both film and contemporary history, this paper finds that there is always more nuance beneath the surface of what a film is trying to say, and how it chooses to say it, and the best way to uncover this nuance is through deeper understanding of historical and cultural context.

I. Introduction

The tale of *Yotsuya kaidan*, or the ghost of Yotsuya, is often lovingly titled one of the most well-known ghost stories in Japan. It is a tale of a dishonourable samurai and his scorned wife bent on revenge, and has captivated audiences for centuries. *Yotsuya Kaidan* was originally a play written in 1825 by Tsuruya Nanboku IV, and has been adapted over 30 times since it first entered Japanese culture.

Of those 30, there are two of particular interest due to the time period they were produced in. *Yotsuya Kaidan* (1949), directed by Keisuke Kinoshita, was produced in the time after World War II when Japan was under occupation by the United States and facing strict media censorship in order to “modernize” and “westernize” the perceived backward and pre-modern country. *Yotsuya Kaidan* (1959), directed by Nobuo Nakagawa, was made seven years after occupation had ended, when Japan was at a crossroads within its own national identity; the years of forced occupation had left them with a modern and prosperous economy, but to the detriment of their own culture and traditions. Consequently, these adaptations are more than just the original story retold—and in many cases even contain drastic changes to characters or plot.

Leaning heavily on historical context as an explanation, this paper seeks to answer the question of why these changes were made and what effect they served on the greater themes of each respective iteration of the story. By analyzing both the 1949 and 1959 film in comparison to the original 1825 play, this paper will offer understandings of what each respective story is trying to say, and why that message is relevant and indicative of the time period it was produced in.

II. Literature Review and Methodology

This paper adopts a historical approach to film, building on the work of key scholars, including LeGacy, Brothers, and Donovan, in order to investigate why the Yotsuya Kaidan adaptations make certain narrative changes, and assert that the answer lies within the time period in which they were created.

LeGacy uses reception theory—which states the importance of an audience in ascribing meaning to a text—to argue that “Invasion of the Body Snatchers” is a reflection of Cold War anxieties in the U.S, and that is why it was so popular upon release. He highlights the role of the U.S. audience in ascribing meaning to the film through their own lived experience at the time, regardless of the creators’ intentions. Alternatively, Brothers uses a social and political institutional approach when discussing the 1954 movie “Gojira.” He describes the public sentiment of the United States in Japan at the time and the political climate of the country after World War II and the U.S.’s occupation of Japan. He asserts that these are extremely relevant in the creation of the film, even directly quoting the creator of the film describing his desire for the film to be a strong allegory for the bombing of Japan and a way for the public of Japan to feel represented in their trauma. Though the two approaches differ, both writers describe the historical context of the film, either using it to explain the mindset of the creator or of the audience to support their respective points about the allegorical nature of the two films. Similar to both Brothers and LeGacy, Donovan employs the historical context of each time period discussed to explain why and how the yōkai (traditional Japanese demon) trope evolved the way it did in Japanese cinema. Donovan ultimately argues that the evolution of yōkai in Japanese fiction can be seen as a direct reflection of the historical evolution of Japanese values and identity, and specifically touches on how J-horror films post-U.S. occupation, commonly featuring faithful yōkai interpretations, can be seen as a return to traditional Japanese culture that was not encouraged or even allowed during the censorship of the U.S. occupation. These are the main film theories that are utilized throughout this paper.

The Yotsuya kaidan myth is the focus of this paper because of its significant presence in Japan as a quintessential ghost story. Thus, it is a good reflection of Japanese culture and values through the years as they change and evolve. The two adaptations in 1949 and 1959 respectively were chosen because these time periods feature important cultural shifts and chaos within history. This heightened historical relevance further enhances the ability to assume changes within the respective plots are influenced by these significant eras.

III. Iemon’s Timeline

This section of the paper will focus on the main character of Iemon and his transformation and changes in the adaptations discussed. His personality and narrative treatment change and evolve within these adaptations, respective to their eras of creation.

1825: The Original Iemon

Yotsuya Kaidan was originally written by Tsuruya Nanboku IV in 1825 and performed as *kabuki*, a traditional form of Japanese theater. Iemon, our *rōnin*, or masterless samurai, is set to

be divorced from his wife, Oiwa, because Oiwa's father Samon has discovered that Iemon stole from Samon in order to marry Oiwa in the first place. Iemon cannot stand this injustice, and thus murders Samon. Iemon claims innocence to his wife, and promises he will enact vengeance on the killer. Instead of pretending to keep his promise, Iemon is occupied by his rich neighbor Kihee, whose granddaughter is deeply in love with Iemon and desperate to have him. Kihee schemes how to get Oiwa out of the way, and sends her an ointment that horribly disfigures her. After Oiwa uses the ointment, Iemon then threatens his servant and tells him to go and force himself upon Oiwa in order to give Iemon a valid reason to divorce Oiwa on the grounds of cheating. Iemon instead is left with Oiwa's corpse, as she discovered Iemon's plot and accidentally killed herself while in a rage. He thinks little of it and simply hides her body, claiming she ran off to have an affair. Iemon then goes to his wedding and remarries, but the next day he sees Oiwa's ghost next to him, and he stabs her, only to realize it was actually his new wife. Oiwa's angry spirit has returned to haunt Iemon for his wrongdoings, and Iemon flees in terror to the mountains trying in vain to escape Oiwa. In the end, Iemon's brother-in-law, Yomoshichi, after receiving visions and pleas from Oiwa's ghost, finds him in the mountains and kills him.

In Tsuruya Nanboku IV's play, Iemon is the model of sinful and dishonourable behaviors that are to be punished. He is a samurai, sworn to bushidō, a specific set of codes that align with traditional Japanese values based on Confucian principles like loyalty, altruism, and trustworthiness. However, he blatantly disregards these codes within the story. His loyalty to his wife and her family is quickly pushed aside when he realizes he has a better opportunity with his rich neighbor's granddaughter, and he goes to cruel lengths to achieve his own personal goals. As Balmain put it, Iemon unflinchingly "places his self-interest before the needs of the community" (54).

This is uniquely problematic under the context of Japan's *ie* system, which is the traditional Japanese social structure that denotes the flow of responsibility and duty (Balmain 36). For example, familial responsibility fell to the head of household (typically eldest son), who then was held responsible to their large community, and then to the emperor (Balmain 36). The *ie* system is based upon a strong sense of obligation to your community, but also a generosity and sympathy towards each other that discourages conflict and takes precedence over any obligation you might have (Balmain 37).

Iemon acts in direct opposition to this system by weighing his own personal goals as more important than the harmony of his family and community. His actions and hubris are "threatening to the very structures of Japanese society according to which the individual should put duty and obedience before personal desire" (Balmain 57). Consequently, Iemon's immoral actions must be punished. Donovan describes the way that in traditional Japanese storytelling, people who transgressed moral obligations were punished by *yōkai* (loosely translated to monsters), who would uphold justice and order (13). Thus, Oiwa returns as a ghost to enact her vengeance on her cruel husband Iemon. This narratively enforces the idea that violating "the moral and ethical laws of the community" (Balmain 56) will not go unpunished, and Iemon

serves as a warning created to scare people about the idea going against cultural codes and beliefs.

1949: Iemon as Japan

Keisuke Kinoshita's *Yotsuya Kaidan* (1949) sees Iemon's (Ken Uehara) immorality and responsibility displaced onto other characters, most notably well-known criminal gangster Naosuke (Osamu Takizawa), who is on the lam after escaping prison and narratively described as the "literal incarnation of evil" (1:25:15). Iemon's original crimes are either erased entirely—in the case of Iemon murdering Oiwa's (Kinuyo Tanaka) father and lying about it—or transferred to Naosuke. Additionally, Iemon becomes an unintentional participant in his own demise because of his subservience to Naosuke, falling in line with common western rhetoric of the importance of individual free will and agency (Geary). Iemon, in his complicity to Naosuke evils, ends up having to murder his own wife out of compassion, his hand being forced by the painful and disfiguring ointment that Naosuke secretly poisoned. He then is tormented by extreme hallucinations from his shame and cannot recover from his actions, scaring off his new wife and making his reputation worse than it ever was before. At the end of the film Naosuke and a blackmailed Iemon attempt to steal from Iemon's new wife's household, only to accidentally start a house fire and die. Iemon is punished within the narrative time and time again for going along with Naosuke's plans without exerting his own agency over his life. Kinoshita's film stresses the importance of actively pursuing your own goals, because the alternative is to wind up like Iemon.

In Kinoshita's film, evil Naosuke is the one actually responsible for most of Iemon's cruelty and aggression, and is even explicitly blamed by Iemon. He is the one who comes up with the evil scheme to divorce Oiwa in favor of the rich doctor's daughter, Oume (Hisako Yamane), and pushes Iemon to go through with it. At every step of the way, Kinoshita's Iemon is hesitant to go along with Naosuke's scheme, and even outright rejects Naosuke when he says Iemon should kill Oiwa to easily get rid of her. Oiwa only dies when she is horribly disfigured by an ointment Naosuke sneakily gave her, and Iemon mercily kills her because of the unbearable pain she is in. But even as Iemon kills his wife with his own two hands, he blames Naosuke for what has happened: "Naosuke, you did that to her face!" (*Yotsuya Kaidan Part One* 1:21:18). This furthers the parallel of Iemon and Japan, as Iemon's cruelty is seen as his hand being forced by Naosuke's manipulation, much like Japan rewrote their imperial aggression as simple defense (Lowenstein 91). Later, a witness to the crime confesses to the police that in fact "[Naosuke] is the one who killed Oiwa" (*Yotsuya Kaidan Part Two* 0:59:05), completely erasing the role that Iemon had in the murder and placing all the blame on Naosuke, paralleling how Japan erased its own aggressive role in World War II after the fact. The audience also eventually learns that Naosuke is even to blame for Iemon's condition as a poor *rōnin*, as Naosuke robbed Iemon's lord under his watch, causing Iemon to lose his position. So Naosuke is not only to blame for Oiwa's death and Iemon's cruelty, but also for the financial desperation Iemon lives in that pushed him to such extremes in the first place.

Kinoshita's unique interpretation of Iemon can be seen as a direct parallel of what Lowenstein describes as the "pronounced shift in Postwar Japanese cultural representation that covers over Japan's pre-Hiroshima imperial aggressions in favor of post-Hiroshima national victimhood" (86). This shift can be seen in the change of common national imagery in Japan. During the war, Japanese propaganda consisted of images of young men bravely going to fight for their country, showcasing Japan as a strong and heroic nation. After Hiroshima in 1945, however, Japanese national imagery shifted starkly to featuring things like the "A-Bomb Maiden," or a young (and innocent) woman tragically suffering from illnesses reminiscent of bombing victims (Lowenstein 86). Japan's cultural shift from belligerent champion of the East Asian peninsula to the victim of western aggression is incredibly important context in order to properly understand Iemon's character in Keisuke Kinoshita's adaptation.

Kinoshita's version of Iemon inverts the traditional 1825 villain, uniquely going to great lengths to pardon Iemon and view him sympathetically as a victim of Naosuke. Kinoshita's sympathetic Iemon suggests a direct parallel to Japan and its national identity and the victimization complex in the Postwar era. After all, it's no coincidence that as Japan was entering a new era of deflecting blame and responsibility, a century-old villain was suddenly depicted as tragic and innocent.

This divergence from the original serves to tell a different story about Iemon, one that is ultimately in line with Japan's own narrative of innocence and victimhood at the time. No longer is Iemon (Japan) a cruel and aggressive patriarch, so hungry for increased power and money that they will abandon their own moral duties to achieve their goals. Rather, Kinoshita's Iemon (and Postwar Japan) is a battered and down-on-their-luck soul living in poverty and disgrace, making them unfortunate victims of manipulation and prodding.

This fear of passivity and complicity is a new addition to the *Yotsuya Kaidan* story, and is likely due to western influence during occupation. In terms of values and ideologies that the United States wanted to embed in Japanese society, individualism was near the top. Pre-Hiroshima Japan was known for its intense patriotism and religious reverence for their emperor, and such a strong sense of duty to their nation that they would welcome death over surrender. The United States' greatest fear was, at this point in time, history repeating itself in Japan, with a dictatorship or worse: falling to communism. Their perceived solution to the issue was to jam the concept of individualism down a staunchly collectivist country's throat, and *Yotsuya Kaidan* (1949) is a great example of this. Kinoshita's lesson of the film thus differs greatly from the original story, due to the historical context of World War II and manipulative dictators, and the western idea of the importance of agency and free will.

1959: Iemon As Modernity

Nobuo Nakagawa offered his interpretation of the popular ghost story in *Yotsuya Kaidan* (1959). His film is the one most often brought up when discussing the story and its legacy, and for good reason. Nakagawa's film is a faithful adaptation and triumphant return to the traditional story of Iemon (Shigeru Amachi) and Oiwa (Katsuko Wakasugi). Iemon is back to being the

greedy and selfish rōnin he is known as, and any changes to the original story serve to *worsen* his actions. Oiwa's death here is not caused by accident or mercy killing, but by a knowing and willing Iemon poisoning his wife's tea. But although Nakagawa's character is extremely similar to Nanboku's, due to the historical and cultural context of post-occupation Japan, his actions and personality take on a new meaning as reflections of new western ideals of individualism and personal ambition.

After the occupation, the enforced modernity and development of consumerism and urbanization in Japan led to a miraculous economic growth and their GNP (gross national product) increased to second only to the United States (Balmain 53). However, as Standish points out, this drastic change to Japanese society did not come without faults. With men constantly at work fueling the new Japanese economy, women were left fending for their children with little or no help, and the individual became increasingly alienated from those around them (Standish 309). This degradation of prewar Japanese society at the hands of western and modern ideals did not go unnoticed. The writer Yukio Mishima, in 1961, published the book *Patriotism*, promoting the code of bushidō and its traditional morals, in response to what he viewed as spiritual degeneracy in Japan (Balmain 53). Mishima even went so far as to form a private militia, the *Tatenokai*, or Secret Society, in order to preserve traditional Japanese national identity, and attempted a failed uprising at a Japanese Self-Defense Forces military base, after which he committed ritual suicide or *seppuku* while crying out "Long live the emperor."

This pushback against modern ideals within Japanese society through occupation paints Iemon's character in a new light. He is no longer just breaking bushido and rejecting his filial duties, but also actively pursuing western ideals of personal greed and ambition. From the very moment Iemon is introduced, he is a man desperate to raise his social status. In Nakagawa's film, Iemon starts out as an unmarried man, pleading for Oiwa's hand in marriage to her father, Samon (Shinjirō Asano), in hopes that aligning himself with their family will give him more opportunities and greater respect. However, Samon rejects Iemon and insults his pride and honor in the same breath, which prompts Iemon to lash out in anger and kill Samon. He then lies and manipulates Oiwa to marry him, promising he will seek vengeance for this murder. Then, when a better opportunity presents itself in the form of young, wealthy Oume (Junko Ikeuchi), Iemon sees it as only natural to move on from his nagging wife to bigger and brighter things.

These actions, especially after U.S. occupation, read as uniquely targeted towards the western idea of individual ambition and ruthless pursuit of goals. This was the cultural shift occurring in Japan at the time, as their economy quickly became a competitive capitalist market that naturally emphasized the individual over the community. Salecl describes the way that consumerist economies are inherently focused on catering to an individual, and the way it promotes individuals constantly improving and bettering their own lives. Iemon is falling in line with this thinking as he attempts to improve his own individual life through marriages. He rejects traditional Japanese values and beliefs in favor of personal betterment and ambition; he kills Oiwa—here representing tradition and Iemon and Japan's literal past—in order to move forward into the modern future with Oume.

Nakagawa, however, rejects the notion of the supremacy of western and modern ideals through his narration. Iemon, after killing and manipulating those he needed to, seems to achieve his “happy ending,” with Oume and his newfound riches and social status. Ultimately, though, Oiwa’s ghost is sent to teach Iemon, and also the audience, a lesson about the consequences of abandoning your national identity, and your cultural ties and responsibilities. While Iemon’s modern ideals and values do for a time help him achieve his ambitions, Nakagawa stresses the fact that there is no way to move forward without leaving some ghosts behind that will come back to haunt you.

In his inception in 1825, Iemon was a disgraceful samurai who served as an example of the punishment that would be inflicted on those who broke traditional Japanese societal codes and norms. His inability to put the good of his community above himself leads him to pursue his goals to violent extents, and his death at Oiwa’s hands is the satisfying conclusion to his arc of selfishness and dishonour. A century later, in 1949, Japan was undergoing a shift in their own national identity from Asian heroes to post-war victims. Thus, the Iemon seen in Kinoshita’s film is a sympathetic man who is less “evil” and more gullible to being manipulated to do cruel things. Iemon’s heinous crimes in the original play are completely omitted from this version of the play, paralleling the way Japan as a country would censor their war-time losses and fatal mistakes. Iemon’s main crime in 1949 is his passivity and allowing other characters make decisions and choices for him. With the context of the U.S. occupation at the time attempting to enforce and imbue western and modern ideas on a traditional Japan, this narrative messaging is read as yet another parallel to contemporary issues. When Nakagawa adapted the myth in 1959, Japan was no longer under occupation, but still under the influence of western ideas that actively jeopardized and contrasted their traditional beliefs. Nakagawa’s film reflects this conflict between tradition and modernity in its main characters’ conflict. Iemon is the picture of western greed, attempting to get rid of his traditional wife in order to financially prosper, and he is scorned and punished within the narrative accordingly. This again showcases the way that historical and cultural context greatly impacts the films produced within them. Throughout the years, Iemon has had changes done to his character and narrative role, and these changes create a different message or meaning to the original story that falls in line with the contemporary moment.

IV. Oiwa Through The Years

Next, this paper will analyze Iemon’s wife, and narrative partner, Oiwa. While Oiwa’s character and personality stay relatively similar throughout the discussed adaptations, the *narrative* changes how it views that personality and depicts it accordingly. She is always a traditional and loyal wife, but throughout Japanese history as cultural ideals have shifted and changed, so too does the story’s representation of Oiwa.

1825: The Original Oiwa

In Tsuruya Nanboku IV's 1825 *Yotsuya Kaidan* kabuki play, Oiwa is an unhappy wife to rōnin Iemon, and is working with her father to divorce him when her father is murdered. This forces Oiwa to then stay her marriage with Iemon, as he is her only hope of seeking vengeance for her father's killer. But Iemon only continues to mistreat and neglect Oiwa, especially after she gives birth and struggles with postpartum sickness. She is sent a mysterious ointment that disfigures her, and Iemon comes home and insults her newfound hideousness. Oiwa's servant, Takuetsu, attempts to force himself on her, but is so disgusted that he takes pity on her and reveals her evil husband's plan to divorce Oiwa on the grounds of cheating and remarry their rich neighbor's granddaughter. Oiwa is so enraged by this news that she accidentally stabs herself with a nearby dagger, cursing Iemon and vowing vengeance as she dies. She returns as a spirit to haunt and terrorize Iemon on his wedding day, causing him to kill both his new wife and grandfather-in-law and flee in terror to the mountains. Oiwa then sends visions to her brother-in-law in his dreams to kill Iemon and enact her vengeance, and is finally able to rest peacefully.

In the original 1825 story, Oiwa, as a ghost, and a literal remnant of the past, represents the way dishonourable actions will come back to haunt their perpetrators. She serves the traditional purpose of yōkai in Japanese storytelling, keeping the world in a state of order that abides by national values and beliefs by punishing Iemon for his transgressive behavior (Donovan 13). She supports the main lesson of the play about the consequences of greed and unchecked ambition and the importance of respecting your duties and cultural identity. By contrast, Iemon acts in a dishonourable and cruel way and thus must be punished and shown the error of his ways by Oiwa, the representation of all the values Iemon lacks.

Oiwa shows consistent filial piety for her family throughout the play, in contrast to Iemon's selfish individualism. After her father is killed, she insists on Iemon finding the murderer and bringing justice to her father's memory. Under the *ie* system, whereby filial piety is valued above all else, Iemon is now the head of Oiwa's family, and Oiwa expects him to be loyal to his duties to her father above all else. As a woman in feudal Japan, there were limited ways that Oiwa and women like her could exert power and agency over their lives. For Oiwa, the only way to see her father's revenge brought about was for Iemon to pursue it. But, of course, Iemon demonstrates that he has no loyalty to Oiwa's family throughout the play. Oiwa remains loyal to Iemon despite his cruel words and reprimands towards her. After Iemon comes home when Oiwa has been disfigured, he insults her appearance, steals her things to pawn off, and says he has changed his mind about helping Oiwa find her father's killer. Iemon does all of these things as she is in immense pain from the medicine she has been given, but despite this, Oiwa rejects her servant Takuetsu's advances when he attempts to force himself on her: "Woman as I am, I was born a warrior's daughter and am now the wife of another" (Nanboku 68). Oiwa puts aside her personal desires and hatred for Iemon and remains loyal to her obligations as a wife and daughter of a respectable warrior. This ironically contrasts with Iemon at this same point in the play going off to marry another woman, completely disrespecting his duties to his family and thinking only of his personal desires.

Oiwa's character markedly contrasts that of Iemon. Thus, their conflict within the play represents a wider theme of loyalty to cultural ties and identity. Although Iemon achieved temporary victories through his manipulations and deceit, Oiwa achieves the final victory over Iemon as she kills him and is able to rest peacefully in the afterlife. Her triumph represents the play's messaging on the value of cultural identities and duties and the way that one will never really be able to leave this identity behind without dire consequences.

1949: There's No Ghosts in this Ghost Story

In Kaisuke Kinoshita's rendition of the popular tale, Oiwa (Kinuyo Tanaka) is a hollowed-out character that reflects the growing popularity and enforcing of western beliefs and ways of living under U.S. occupation. The 1949 film removes the supernatural elements from the original 1825 play in favor of a more rational western ideology around death. Kinoshita's Oiwa serves to also enforce the occupation ideals of the "right" woman, as she is directly contrasted with her sister as an example of how passive women are actually at fault for the violence and abuse perpetrated against them.

Kinoshita's film robs Oiwa of her ability to enact revenge by depicting her in an incredibly rational way, falling in line with the popular western belief at the time. Historian Scherer explains that "in intellectual discourse, belief in ghosts and other supernatural beings was treated as backward and belonging to the premodern past" (80). Oiwa in her ghostly form, then, could not be allowed to exist under occupation that was centered around modernizing Japan. Therefore Oiwa is no longer a moral yōkai seeking vengeance for the wrongs that were done to her, but rather cinematically coded with intentional framework (Scherer 85) as a figment of Iemon's guilt conscience.

Oiwa's drastic change within the narrative is reflective of the way U.S. occupation policed the way Japanese people, specifically women, could "correctly" express themselves. This can be seen in the way the film treats Oiwa compared to her sister Osode (also Kinuyo Tanaka). Oiwa is described as kind to a fault and too shy and retiring, which serves to place blame upon her for the abuse she suffers at the hands of her husband. She is narratively punished with death for being loyal to Iemon and refusing to divorce him, and his cruelties are seen as valid retaliations in the face of Oiwa's nagging neediness and devotion to her husband. This attempts to teach the audience that subservience and passivity are qualities to be avoided, which falls in line with the ideology that U.S. occupation officials wanted to get across. Even as Oiwa dies from her husband's own blade, she issues no cries of rage or vengeance, merely crying from the pain. Her passivity follows her all the way to the grave, and the perpetrators of her death are never properly punished or taught a lesson.

The qualities that spell disaster in Oiwa's life are then juxtaposed with Osode's character and her happy ending. Once her sister has died, Osode realizes something strange is afoot, and actively fights for an investigation into the disappearance of Oiwa. She works closely with the police and alongside her husband to see justice be brought to her and her family. She is an equal partner in her marriage and is often seen giving orders to her husband, Yomoshichi, in her

impassioned search for answers. In this way, Osode blatantly rejects traditional Japanese beliefs of subservience to the husband and placing communal good above personal goals. However, this dismissal and outright shunning of traditional Japanese culture is never seen as a negative, because this dismissal is everything that the U.S. occupation is hoping to achieve. Osode is depicted as the perfect modern woman who “acts of her own volition [and] pursues her goals rationally” (Scherer 84). Her willingness to actively pursue her goals and fight for what she believes in—regardless of how many traditional beliefs she rejects—is rewarded by her happy ending. She is able to get justice for her sister as she learns who is responsible for her death and attempts to capture them with the help of the police. Although the chaotic ending of the film instead features a burning house that kills both Naosuke and Iemon before they can receive proper punishment, Osode still ends the film walking off away from the burning house with her husband and future child. Kinoshita’s depiction of Osode upholds the ideas U.S. occupation was trying to enforce. Osode is only able to get her happy ending *because* she breaks away from traditional Japanese gender ideals and instead prescribes to western ideals of free will, ambition, and modernity.

This film serves as a brilliant example of the way that directors can twist and change a character and story based on the political ideologies and historical context of the time. Oiwa’s character in its essence does not change greatly—minus her ghostly identity. In both the 1825 play and Kinoshita’s 1949 adaptation, she is a fiercely loyal and devoted wife who cares deeply for her community and family more than her own wellbeing, poignantly representing traditional Japanese standards and culture. The difference shines, however, in how this personality is treated within the narrative. In the play, Oiwa’s traditionalism is what gives her power. She is quite literally a representation of the past that comes back to haunt and punish those that would scorn her. But Kinoshita’s film views Oiwa’s traditionalism as backward and pathetic, the ultimate reason for her downfall. Her traditional beliefs and filial subservience are narratively punished, similarly to how traditional Japanese beliefs were criticized and outright banned from films under occupation. Though the character is constant, different time periods interpreted the same character in vastly different ways due to their respective places in history. Under a harsh occupation that was designed to strip Japan of its national identity and replace it with western values, Oiwa’s traditionalism was naturally seen as a clear disadvantage where it never had been in the past. By comparison, Osode’s rejection of how a traditional Japanese woman should act in favor of new western and modern ideas is the direct reason why she can find justice and peace after her sister’s murder. These characters, especially compared to their original counterparts, reflect the U.S. occupation’s desire to convince Japanese people of the supremacy of modernity over traditionalism.

1959: Oiwa’s Return

In Nakagawa’s adaptation *Yotsuya Kaidan* (1959), Oiwa (Katsuko Wakasugi) is a joyous return to her original character in the play as a representation of tradition and upholder of justice. Her ghostly return for vengeance is brought back, and she again symbolizes the return of

tradition and pre-occupation culture where modernity would see them dismantled. However, Nakagawa's Oiwa's story is made more rich and intense than the 1825 original through the historical context of the moment.

Nakagawa's film affirms the right and supremacy of tradition six years after a brutal occupation that attempted to modernize Japan. To tell this classic Japanese ghost story so faithfully after so many traditional Japanese stories had been censored and blacklisted during the occupation sent forth its own message of the importance of respecting tradition and national history and identity.

Oiwa's return to her classic ghostly self is just one example of a broader cultural rejoicing in tradition through media. Donovan described the way that traditional *yōkai* post-occupation were depicted with astounding accuracy, and how this reflects the larger cultural shift of respecting and paying homage to national Japanese identity (9). He cites how Oiwa, specifically, in the 1959 film is visually represented extremely similar to old woodblock prints of her in the 1800s, and how in her ghostly form she retains the outfit and wounds she had as she died, like traditional Japanese ghosts (Donovan 11-12). The commitment to Oiwa's visual and narrative representation can be seen throughout the entire film, and Nakagawa's valuing of tradition and classic Japanese culture is on full display.

Even though there was a large rejoicing in traditional Japanese beliefs in many parts of the country, Japan was still incredibly modernized when it came to their economy. Their economy had grown substantially on a global scale and it was all thanks to the adoption of modern and western ideas. This led to conflicting perspectives from citizens and confused personal identities. Many enjoyed the newfound wealth in the pockets of themselves and their great nation; others, however, saw Japan as bastardizing itself and hollowing out its own culture in order to simply be richer. This national tension and conflict between modern ideas and traditional values is the main breeding ground for Nakagawa's film.

Nakagawa's faithful interpretation of the original Oiwa allows for a distinct metaphor to emerge in which Oiwa is the representation of traditional Japanese beliefs that comes in conflict with the selfishly motivated Iemon, who here represents the modern ideas that are only possible by rejecting tradition. There is no clearer example of this than with Iemon's desire to socially and financially advance himself (like 1950s Japan) by remarrying, and needing to leave his old wife (tradition) behind to achieve this goal. But just like the past, and our own cultural identities, Oiwa comes back to literally and metaphorically haunt Iemon. Michael Dylan Foster writes about how ghosts in stories are "the banished Other [that] returns, causing [those around them] to anxiously question their modern ways of interpreting the world around them" (117-118). Within this framework, Oiwa's ghostly return is detrimental to Iemon's view of how to see the world. He believed he had achieved greatness by leaving his old wife (and likewise, tradition) behind, only to realize they were never truly gone, only waiting to reappear.

Unlike Kinoshita's 1949 film, which attempts to convince the public of the validity of modern ideals like free will and ambition, Nakagawa wholeheartedly depicts tradition as the inevitable winner of the contemporary conflict, as the film ends with Oiwa floating above

Iemon's death, cradling her baby, smiling. Despite the push towards modern ideas supported by a growing economy, he clearly believed that, just like Iemon, Japan would face the consequences of completely renovating their national identity in the pursuit of more wealth.

Though Oiwa has stayed a similar character throughout the adaptations discussed, the specific way she is narratively seen and interpreted changes drastically depending on the cultural and historical context. In the original play, she represents the consequences of breaking samurai code and disrespecting your culture. Her ghostly return is an explicit example of how dishonourable actions will always come back to haunt those who make them. In Kinoshita's 1949 adaptation, due to the censorship of the U.S. occupation, Oiwa no longer returns as a ghost, and does not teach any lessons to Iemon. In fact, due to the conscious and subconscious effort by the occupation to enforce modernized ideals of agency and free will, Oiwa's passivity as a traditional wife is narratively punished and seen as a bad thing to fit the western narrative of the time. With Nakagawa's film in 1959, however, we see the brilliant return to the Oiwa of old, who comes back as a ghost to teach Iemon the lesson of pursuing modernity at the expense of tradition and national culture. This parallels Japan's actions at the time, as they modernized and followed western ideals within their economy which led to financial prosperity to the detriment of their national culture and identity that was being actively shunned. Analyzing Oiwa through these different lenses proves the importance of analyzing films further and always asking questions about why a director made a change or decision regarding characters and their behavior or personality.

V. Conclusion: Putting It All Together

The Yotsuya kaidan myth, since its introduction to Japanese culture in 1825, has changed and evolved in its many adaptations through the years. These changes can be read as explicit references and responses to the cultural and national shifts that were occurring at the time of each film's production. This paper specifically highlighted these changes through analysis of the main characters of the myth in each adaptation.

In 1825, the story serves as a reflection of contemporary cultural values. Iemon's character disregards Japanese customs about the importance of community and filial loyalty, instead pursuing his own selfish ambition and desires. This puts him at odds directly with Oiwa, who is killed to further Iemon's dishonorable pursuits, and thus he is punished within the narrative by Oiwa to teach the lesson that one's breaking of cultural codes will always have consequences deeper than one can understand. Oiwa comes back to show the way that the past can come back to haunt you, literally. Nanboku's kabuki play asserts the importance of the cultural hierarchy of loyalty and respect within Japan through both of the main characters.

In 1949, the story being told by Kinoshita is vastly different. Under U.S. occupation bent on modernizing a "backward" country, Kinoshita was unable to fully adapt the story faithfully due to strict censorship restrictions. This is seen most clearly in the lack of Oiwa's ghostly return for vengeance against Iemon, which hollows out her character. Oiwa's character is also viewed in a much more negative light compared to how Nanboku represented her. Although her actual

character stays constant, the western occupying force that was subtly affecting Japanese thoughts saw Oiwa's passivity and traditional wifely behaviors as a symptom of Japan's "backward" culture, and therefore necessitated a different approach. In order to properly introduce western ideas of a modern woman, the film spends substantial amounts of time blaming Oiwa for her own death and abuse because she was simply too passive and kind-hearted. Through this, the western ideals of the proper way a woman should act bleed into the film by demonizing Oiwa's previously proper behavior in favor of a more assertive and independent woman, as seen in her sister, Osode. The other largest change occurs in Iemon's character, and can be traced back to the cultural shift in national identity after the bombing of Hiroshima and Nagasaki, wherein Japan swapped their previous aggressive imperialist attitude for a victim complex that left them completely innocent of the crimes they committed during and directly preceding the war. Thus, Iemon's personality as a cruel and greedy villain is changed in a way that subtly parallels Japan's own cultural shift. He is now an ultimately innocent husband who is simply manipulated into doing evil deeds by the true villain Naosuke. Furthermore, Iemon's weakness lies not in his breaking of cultural codes, but of his passivity in the face of Naosuke's manipulations. This new direction with Iemon's character can further be supported by western influence with ideas about independence and individual free will. Ultimately, in the 1949 film, both Oiwa and Iemon's main flaw is their passivity, which leads to their respective unfortunate endings.

In 1959, Nakagawa's film is a joyous return to the original story and characters, falling in line with the cultural trend of the time. After occupation ended, Japanese artists were able to depict traditional Japanese tropes and *yōkai* without fear of censorship. This return to tradition in many cases also reflected a cultural pushback that many citizens felt after the forced modernization of the occupation. Although this modernizing of Japan had some positive effects, primarily the enhanced economy, many felt that these accomplishments came at the cost of the Japanese national identity. This conflict can be felt in Nakagawa's depictions of Iemon and Oiwa. Although they're very faithful to their original characters, the story they tell and themes they symbolize are unique to this time period. Iemon's greed and personal ambition now parallels the darker contemporary urge to pursue modernity at the expense of one's own culture. Oiwa, then, represents the tradition that the Japanese needed to hold onto, according to Nakagawa. Though Iemon tried to get rid of Oiwa to further his own social and financial status, she came back to haunt him, literally, and remind him of the oaths he had broken. Iemon and Oiwa's conflict reflects the wider cultural confusion of a country caught between modernity and tradition, and the film, when understood in the full context of that historical moment, can be seen as a reminder to any Japanese citizen who would try to leave tradition behind, like Iemon did. The film asserts the longevity and dominant nature of tradition and past values.

The evolution of the *Yotsuya Kaidan* myth and its adaptations traces the evolution of Japan's national identity and cultural shifts throughout the decades. The two inform and affect each other, and analyzing one allows for a deeper understanding of the other. To fully appreciate the stories that are told in certain historical moments, it is paramount to analyze the aspects of history that inevitably bleed into the media. Conversely, deeply analyzing film can open a

doorway into understanding its respective history and culture. When decisions are made in the filmmaking process, culture and history are always behind the scenes, working in some way or another, as seen in the example of the many *Yotsuya Kaidan* films.

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GLP-1 Agonists in the Treatment of Youth and Young Adults with Diabetes/Obesity: A Literature Review By Yana Trivedi

Abstract

Background: Obesity has become an epidemic in society, often causing the development of Type 2 Diabetes. The increasing prevalence of the use of GLP-1 agonists as a treatment for T2D and/or obesity in children, teenagers, and young adults calls for the examination of their efficacy and safety.

Method: A systematic review of literature in the form of 10 studies regarding the use of GLP-1 receptor agonists as a treatment for T2D/obesity, using Pubmed as a search engine

Findings: Compared to placebo, GLP-1 RA generally are beneficial in reducing BMI, glycated hemoglobin, etc., which are indicators of effective treatment. Participants treated with GLP-1 RAs experienced adverse events, but no incidents of death were reported, and the adverse events were generally tolerable.

Conclusion: GLP-1 RA are a tolerable and effective treatment for youth and young adults.

Introduction

Nearly 20% of American youth have obesity, according to the Center for Disease Control and Prevention (*Overweight and Obesity - Childhood Obesity*, 2022). This widespread condition affects millions across the nation, often snowballing into other problems, such as Type 2 diabetes (*Childhood Obesity Facts | Obesity*, 2024; Chung & Rhie, 2021).

Obesity is the excessive accumulation of body fat, often measured through BMI, or Body Mass Index (Klein et al., 2023). Obesity in adolescents is defined as being at or above the 95th percentile for BMI based on age and sex. Severe obesity is defined as being at or above 120% of the 95th percentile for age and sex (*Child and Teen BMI Categories | BMI*, 2024).

The development of obesity can often be attributed to genetics, environmental and cultural factors, dietary and exercise habits, etc. (Chung & Rhie, 2021). Obesity, specifically hypothalamic obesity (HO), may also be a result of damage to the hypothalamus, the hormonal control center of the brain, through surgery, tumors, genetic defects, etc. (Kim & Choi, 2013)

Obesity impairs the quality of a child's life as it is associated with metabolic risk factors, such as impairment in the body's ability to process glucose and high blood pressure/cholesterol; psychological effects, such as low self-esteem, poor body image, depression, etc.; and other health concerns, such as dental and respiratory issues (Pulgaron & Delamater, 2014).

Metabolic risk factors, specifically, may result in the development of Type 2 Diabetes, by increasing insulin resistance (Galicia-Garcia et al., 2020). Insulin is a pancreatic hormone that allows glucose to enter the cells (*About Insulin Resistance and Type 2 Diabetes | Diabetes*, 2024). Resistance to insulin results in a build-up of glucose in the blood, raising blood sugar levels, leading to pancreatic beta cell dysfunction (*About Insulin Resistance and Type 2 Diabetes*

| *Diabetes*, 2024). Insulin resistance and pancreatic beta cell defects are the primary causes of Type 2 diabetes (Galicia-Garcia et al., 2020).

Type 2 diabetes hinders the ability to utilize energy from glucose for cellular function, resulting in poor glycemic control (*Diabetes*, 2024). Poor glycemic control may cause other health complications, such as hyperglycemia, or high blood sugar levels (Galicia-Garcia et al., 2020). This can create more serious health complications, including nerve damage, kidney damage, and ocular damage (Galicia-Garcia et al., 2020).

In recent years, the use of GLP-1 receptor agonists have become more widespread in the treatment of Type 2 diabetes and obesity (Kunzmann, 2024, 30). GLP-1 receptor agonists regulate glucose levels in the body by mimicking the hormone called GLP-1, or glucagon-like peptide-1, found in the small intestine, by attaching to GLP-1 receptors in the hypothalamus (*Glucagon: What It Is, Function & Related Conditions*, 2025). This in turn reduces blood sugar levels in the body by slowing digestion, reducing glucagon secretion, and increasing insulin secretion (*GLP-1 Agonists: What They Are, How They Work & Side Effects*, 2023). They also increase the feeling of satiety and may also increase the expenditure of energy (*GLP-1 Agonists: What They Are, How They Work & Side Effects*, 2023). Therefore, by mimicking GLP-1, GLP-1 agonists work to decrease blood sugar levels in the body, making it an effective treatment for patients with Type 2 diabetes and obesity (Catanese & LeWine, 2024).

Between 2020 and 2023, the number of prescriptions for GLP-1 RA to adolescents and young adults increased by 6 times (Kunzmann, 2024, 30). There are many different types of GLP-1 RA (*GLP-1 Agonists: What They Are, How They Work & Side Effects*, 2023). Some have been approved for use by adolescents and some have not (Chao, 2023).

The objective of this literature review is to examine the efficacy and the safety profiles of several GLP-1 receptor agonists in the treatment of youth (children, teenagers, and young adults) with obesity and/or Type 2 diabetes, as recorded by randomized clinical trials done in the past five years (2020-2025).

Methodology

This study aimed to understand the efficacy and safety, measured through physical and psychological effects, of GLP1RA treatment. To identify the required studies to review, PubMed was used as a search engine. The following search was conducted in June 17, 2025:

((GLP1) OR (GLP-1) OR (GLP-1 agonist) OR (GLP1 agonist) OR (GLP-1 receptor agonist) OR (GLP1 receptor agonist) OR (incretin mimetic) OR (trulicity) OR (byetta) OR (bydureon) OR (victoza) OR (adlyxin) OR (ozempic) OR (rybelsus) OR (mounjaro)) AND ((teenagers) OR (teens) OR (adolescents) OR (children) OR (kids)) AND ((psychological) OR (mental disorder) OR (disorder) OR (psychiatric) OR (depression) OR (anxiety) OR (eating disorder) OR (mental health) OR (suicide) OR (suicidal thoughts) OR (physical) OR (physical effect) OR (effect) OR (growth) OR (osteoporosis) OR

(energy) OR (bone) OR (health) OR (well-being) OR (well being) OR (development)) AND ((diabetes) OR (type 2) OR (type 2 diabetes) OR (obesity))

The following filters were applied:

- In the last five years
- Free Full Text
- Clinical Trial
- Randomized Controlled Trial
- English
- Human Trial
- Child: Birth-18
 - This filter was applied to parse out studies that looked only at adult populations. However, this literature review examines children, teenagers, and young adults (ages 6-25), as documented by the studies.

From this search, a total of 34 studies were extracted. Out of these, 24 studies were excluded for the following reasons:

- No mention of any type of GLP1 RA
- Independent variable of study being a drug/therapy other than GLP1 RA
- Inclusion of populations over 26 years old
- Inclusion of population without obesity and/or T2D

Inclusion Criteria	Exclusion Criteria
- Population of children, teenagers, and young adults (≥ 26 years old) - Populations with obesity (as confirmed by BMI standards) and/or obesity - Placebo controlled trials - Data on efficacy as defined by weight-loss, weight-loss maintenance, improved glycemic control, improved energy intake/expenditure and/or safety profiles as determined by adverse events	- No mention of any type of GLP1 RA (8) - Independent variable of study being a drug/therapy other than solely GLP1 RA (7) - Inclusion of populations over 26 years old (8) - Inclusion of population without obesity and/or T2D (1)

Data regarding inclusion criteria, intervention, dosage information, population age range, study objective, quantitative data regarding efficacy and/or safety outcomes, and related quotes were extracted from each of the following papers:

Table 1: The Literature & Associated Data

#	Title	Author (Year)	DOI	Sponsorship Information
1	<i>A study on pharmacokinetics, pharmacodynamics and safety of lixisenatide in children and adolescents with type 2 diabetes.</i>	Barrientos-Pérez 2022	DOI: 10.1111/pedi.13343	Sanofi, Paris, France
2	<i>Effect of liraglutide treatment on body mass index and weight parameters in children and adolescents with type 2 diabetes: Post hoc analysis of the ellipse trial.</i>	Bensignor 2021	DOI: 10.1111/ijpo.12778	Novo Nordisk A/S
3	<i>Evaluating potential predictors of weight loss response to liraglutide in adolescents with obesity: A post hoc analysis of the randomized, placebo-controlled SCALE Teens trial.</i>	Bensignor 2023	doi:10.1111/ijpo.13061	National Institute of Diabetes and Digestive and Kidney Diseases of the National Institutes of Health, Grant/Award Numbers: K23DK125668, K23DK129721, K23DK124654; Novo Nordisk
4	<i>Evaluating appetite/satiety hormones and eating behaviours as predictors of weight loss maintenance with GLP-1RA therapy in adolescents with severe obesity.</i>	Bensignor 2024	doi:10.1111/ijpo.13105	R01DK105953, K23DK125668, and K23DK129721 from the National Institute of Diabetes and Digestive and Kidney Diseases; the National Institutes of Health's National Center for Advancing Translational Sciences, grant UL1TR002494.
5	<i>Liraglutide for Weight Management in Children and Adolescents With Prader-Willi Syndrome and Obesity.</i>	Diene 2022	https://doi.org/10.1210/clinem/dgac549	Novo Nordisk
6	<i>Exenatide for weight-loss maintenance in adolescents with severe obesity: A randomized, placebo-controlled trial.</i>	Fox 2022	doi:10.1002/oby.23395.	National Institute of Diabetes and Digestive and Kidney Diseases (1R01DK105953); National Center for Advancing Translational Sciences (UL1TR002494)
7	<i>A phase 3 randomized clinical trial using a once-weekly glucagon-like peptide-1 receptor agonist in adolescents and young adults with hypothalamic obesity.</i>	Roth 2021	DOI: 10.1111/dom.14224	National Institute of Diabetes and Digestive and Kidney Diseases (R01DK104936)

8	<i>Energy balance in hypothalamic obesity in response to treatment with a once-weekly GLP-1 receptor agonist.</i>	Shoemaker 2022	doi:10.1038/s41366-021-01043-6.	R01 DK104936/DK/NIDDK NIH HHS/United States UL1 TR002243/TR/NCATS NIH HHS/United States Z99 HD999999/ImNIH/Intramural NIH HHS/United States ZIA HD000641/ImNIH/Intramural NIH HHS/United States
9	<i>Once-Weekly Exenatide in Youth With Type 2 Diabetes.</i>	Tamborlane 2022	https://doi.org/10.2337/dc21-2275	AstraZeneca
10	<i>Once-Weekly Semaglutide in Adolescents with Obesity.</i>	Weghuber 2022	doi:10.1056/NEJMo a2208601	Novo Nordisk

The papers extracted examine the efficacy/safety profiles of GLP-1 receptor agonists (lixisenatide, liraglutide, exenatide, and semaglutide) on youth and young adults with obesity and Type 2 diabetes. This is done through measuring reductions in weight and BMI, as well as studying the effect of these drugs on weight loss maintenance, energy, etc.

Table 2: Study Overviews

Author (Year)	Inclusion Criteria (Age and Health Background/Condition)	Intervention & Dosage	Design & Methods	Population Age Range	Objective
Barrientos-Pérez 2022	Either male or female, aged ≥ 10 and < 18 years with Type 2 Diabetes being suboptimally controlled with metformin/basal insulin; BMI percentile that classifies as overweight or obese	Daily subcutaneous injections of lixisenatide (5 μg -20 μg)	Randomized, placebo-controlled, parallel group	23 participants ≥ 10 and < 18 years old	Examine the safety profile and the effect of lixisenatide in treating T2D in youth
Bensignor 2021	Age 10 to < 17 years; BMI percentile that classifies as overweight or obese	Daily subcutaneous injections of liraglutide (0.6mg-1.8 mg)	Randomized, placebo-controlled, parallel group	138 participants 10 and < 17 years old	Examine the effects of liraglutide on weight loss as a form of treatment in youth with T2D
Bensignor 2023	Pubertal adolescents aged 12 to < 18 years with a BMI that classifies as obesity; adolescents with Type 2 Diabetes taking anti-diabetic treatment other than metformin	Daily doses of liraglutide (0.6 mg-3.0 mg)	Randomized, placebo-controlled, parallel group	251 participants 12 and < 18 years old	Examine characteristics predictive of greater BMI reduction of youth with obesity being treated with liraglutide
Bensignor 2024	Ages 12 to < 18 years with severe obesity classified by	Weekly doses of exenatide XR	Randomized, placebo-cont	66 participants 12 to < 18	Examine the hormones and behaviors predictive

	BMI that achieved 5% BMI reduction over the course of 8 weeks through a meal-replacement therapy program	(0.6 mg-3.0 mg)	rolled, parallel group	years old	of greater maintenance of weight loss of youth with obesity
Diene 2022	Male or female adolescents aged ≥ 12 to < 18 years and children aged ≥ 6 to < 12 years with genetically confirmed Prader-Willi Syndrome with obesity, and ≥ 95 th percentile for age and sex	Daily subcutaneous injections of liraglutide (0.3mg-3.0 mg)	Randomized, placebo-controlled, parallel group	55 participants ≥ 6 to < 18 years old	Examine the efficacy of liraglutide on the weight loss of youth with Prader-Willi Syndrome/obesity and the associated safety profile
Fox 2022	Ages 12 to < 18 years and BMI $\geq 1.2 \times 95$ percentile (based on CDC-derived age and sex norms) or ≥ 35 kg/m, whichever was lower	Weekly subcutaneous injections of exenatide XR (2.0 mg)	Randomized, placebo-controlled, parallel group	66 participants 12 to < 18 years old	Examine the effect of exenatide XR on BMI reduction maintenance in youth with obesity and the associated adverse events
Roth 2021	Age and sex-adjusted BMI ≥ 95 percentile or BMI ≥ 32 kg/m ² if aged 18 years or older; evidence of hypothalamic injury by MRI; 6 months or longer postsurgical or radiation treatment; weight stable or increasing over 3 months; and stable hormone replacement for at least 3 months	Weekly subcutaneous injections of exenatide QW (2.0 mg)	Randomized, placebo-controlled, parallel group	41 participants 10 to 25 years old	Examine the efficacy and safety of exenatide QW as a treatment for youth and young adults with hypothalamic obesity
Shoemaker 2022	Participants 10-25 that had a clinical diagnosis of hypothalamic obesity due to a suprasellar tumor and were ≥ 6 months post-surgical or radiation treatment	Weekly subcutaneous injections of exenatide QW (2.0 mg)	Randomized, placebo-controlled, parallel group	41 participants 10 to 25 years old	Examine the difference in energy intake and expenditure of youth and young adults with hypothalamic obesity treated with exenatide QW
Tamborlane 2022	Type 2 diabetes, were aged 10 to < 18 years at enrollment	Weekly doses of exenatide (2.0 mg)	Randomized, placebo-controlled, parallel group	82 participants 10 to < 18 years old	Examine the efficacy and safety of exenatide as a treatment for youth with T2D

Weghuber 2022	Adolescents (12 to <18 years of age) with a BMI in the 95th percentile or higher; those with a BMI in the 85th percentile or higher who had at least one weight-related coexisting condition; had at least one unsuccessful dietary weight-loss effort; persons with type 2 diabetes needed to be treated with diet and exercise alone or with metformin	Weekly subcutaneous injections of semaglutide (2.4 mg)	Randomized, placebo-controlled, parallel group	134 participants 12 to <18 years old	Examine the efficacy of reducing BMI and safety of semaglutide as a treatment for youth with obesity

Findings

Table 3: Study Findings

Author (Year)	Efficacy Outcome	Related Data	Related Quote	Safety Outcome	Related Data	Related Quote/Data
Barrientos-Pérez 2022	The drug improved glycemic control compared to the placebo as seen by the significant decrease of 2-hour PPG excursion (short-term, post-meal blood sugar spike)	Mean change in 2-hr PPG excursion in treatment group : -4.0 ± 3.2 mmol/L Mean change in 2-hr PPG excursion in placebo group: -0.1 ± 1.2 mmol/L	"a dose-dependent manner and lixisenatide treatment was also associated with improvements in glycemic control, while a trend towards a lower increase in body weight was seen compared with placebo"	Though there were cases of mostly gastrointestinal-related adverse events (AEs), none were classified as serious AEs or resulted in death or discontinuation.		"... repeated doses of lixisenatide of up to 20 µg per day were associated with a safety and tolerability profile in children and adolescents with T2D..."
Bensignor 2021	Compared to the placebo, liraglutide treatment significantly reduced absolute BMI and percent change in BMI. However, this reduction was modest compared to the baseline.	Estimated treatment difference in percent change in BMI between treatment and placebo groups: 2.73% (P=0.028)	"the results of this study provide evidence that treatment with liraglutide may result in a reduction in BMI and weight parameters in addition to improving glycemic control in children and adolescents with T2D"			

Bensignor 2023	Adolescents being treated with liraglutide demonstrated higher odds of achieving BMI reductions of 5% or 10% compared to those treated with placebo by the end of the study.	Odds Ratio (OR) of achieving $\geq 10\%$ BMI reduction from baseline to 56 weeks: 4.0 ($P < 0.001$)	"Liraglutide was found to be more effective in reducing BMI by $\geq 5\%$ and $\geq 10\%$ compared with placebo regardless of participants' sex, race, ethnicity, age, Tanner (pubertal) stage, glycemic status, severity of depression symptoms, or obesity category at baseline, indicating that it may be a reasonable treatment option for adolescents with obesity irrespective of these characteristics"			
Bensignor 2024	Adolescents receiving exenatide XR experienced lower leptin response during a meal, which were associated with greater weight loss management compared to those receiving placebo.	Difference in treatment effect (75th percentile-25th percentile) of leptin levels as indicator of weight loss maintenance as percent change in BMI over 52 weeks: 9.60% ($P = 0.007$)	"a lower meal-induced leptin response following at least a 5% BMI reduction was associated with superior WLM in terms of BMI percent or total body fat mass change for participants on exenatide XR compared to participants on placebo"			
Diene 2022	There were no statistically significant differences in BMI or weight-related parameters between placebo/liraglutide groups	Change in mean BMI SDS at 52 weeks in adolescents in treatment group: -0.31 ± 0.13 Change in mean BMI SDS at 52	"liraglutide did not result in significantly greater reduction in BMI SDS in children and adolescents with PWS and obesity	There were mild to moderate gastrointestinal adverse events associated more often with liraglutide. There was only 1 serious adverse event and 2		"Overall, treatment with liraglutide was well tolerated."

		weeks in adolescents in placebo group: -0.17 ± 0.21 Change in mean BMI SDS at 52 weeks in children in treatment group: -0.73 ± 0.21 Change in mean BMI SDS at 52 weeks in children in placebo group: -0.67 ± 0.32	compared with placebo/no treatment as adjunct to a structured diet and exercise program"	cases of hypoglycemia related to the trial. There were no reported effects on suicidal ideations or pubertal development.		
Fox 2022	Adolescents treated with exenatide XR achieved greater weight loss maintenance after dietary intervention, but these results are not statistically significant.	Percent change in BMI in treatment group: $4.6 \pm 10.5\%$ Percent change in BMI in placebo group: $10.1 \pm 9.0\%$		The rate of adverse events was similar in both exenatide XR and placebo group, though the adolescents in the exenatide XR group experienced more gastrointestinal symptoms.	Number of Adverse Events in treatment group: 179 Number of Adverse Events in placebo group: 141	

Roth 2021	Though there was no statistically significant difference in change in BMI between placebo and exenatide groups, those on exenatide saw statistically greater reductions in body fat and reduction in percent adipose tissue as compared to the placebo group.	Difference in BMI percent change between treatment and placebo group: $-1.7\% \pm 1.2\%$ Difference in adipose tissue percent between treatment and placebo group: -1.2 (P=0.06)	"Our randomized clinical trial shows the effects of GLP-1 RA therapy to reduce or stabilize BMI and body fat compared with steady increases in the placebo group"	Gastrointestinal related adverse events and few serious adverse events occurred in both placebo and exenatide groups. There were no recorded impacts on pubertal advancements or bone maturation.	Percent of patients in treatment group that reported at least 1 adverse event: 91% Percent of patients in placebo group that reported at least 1 adverse event: 83%	"This study supports the safety of GLP-1 RAs in peripubertal children"
Shoemaker 2022	Compared to the placebo group, the exenatide group experienced reduced gain of fat mass. Other pharmacological agents may need to be combined with GLP-1 agonists in order to preserve the balance between energy intake and expenditure.	Mean difference in energy intake between treatment and placebo group: -1800 kJ (P=0.02) Mean difference in total energy expenditure between treatment and placebo group: -695 kJ/day (P< 0.01)	"patients with HO had decreased food intake and decreased energy expenditure in response to treatment with a long-acting GLP1RA."			
Tamborlane 2022	Compared to placebo, the exenatide group experienced	LS mean change in glycated hemoglobin after 24 weeks	"Once-weekly exenatide allowed a greater proportion	Mild to moderate gastrointestinal adverse events occurred in both	Percent of individuals	"The finding that once-weekly exena-

	improved glycemic control.	in treatment group: -0.36% LS mean change in glycated hemoglobin after 24 weeks in placebo group: 0.49%	of participants to achieve strict glycemic targets after 24 weeks of treatment. Improved glucose control was observed in conjunction with trends toward increased endogenous insulin secretion and reduced body weight"	groups, and there were no major hypoglycemia events.	that experienced any adverse event in treatment group: 61% Percent of individuals that experienced any adverse event in placebo group: 73.9%	tide was safe and well tolerated by our participants with type 2 diabetes is as important as its demonstrated efficacy"
Weghuber 2022	Adolescents in the semaglutide group experienced greater reduction of BMI, weight, and cardiometabolic risk factors compared to those on placebo.	Mean percentage change in BMI from baseline to week 68 in treatment group: -16.1% Mean percentage change in BMI from baseline to week 68 in placebo group: 0.6%	"In adolescents with obesity, once-weekly treatment with subcutaneous semaglutide at a dose of 2.4 mg in addition to lifestyle intervention resulted in a substantial reduction in BMI as compared with lifestyle intervention alone"	The semaglutide group experienced mild to moderate gastrointestinal adverse events the most frequently, reporting no significant effect in pubertal development or mental health.		"The safety profile of semaglutide among adolescents with obesity in our trial was consistent with that observed among adults and with that of the glucagon-like peptide-1 receptor agonist drug class in general. No new safety concerns were identified."

Discussion

In summary, almost all studies found statistically significant reduction of BMI/body composition or improved glycemic control, demonstrating the efficacy of the drug on children, teenagers, and young adults with Type 2 Diabetes and/or obesity. Gastrointestinal adverse events, such as vomiting and diarrhea, were common among testing GLP RA, however no adverse events negated from the overall safety profile of the GLP1 agonists, making them tolerable as well.

This data of the pediatric and young adult population is comparable to data done earlier in adult populations. In clinical trials with adults, GLP-1 agonists were found to reduce weight compared to other treatments, as well as protect against other cardiovascular risk factors. Similar adverse events (gastrointestinal effects) were common in adult populations as well, yet also had few serious events. Liraglutide reduced weight and systolic blood pressure while improving glycemic control, according to LEAD trials. Phase 3 clinical trials of liraglutide found reductions of glycated hemoglobin from 0.84% to 1.50%, as well as reduction of mean weight by 3.2 kg (Peterson & Pollom, 2010). Exenatide and lixisenatide also improved glycated hemoglobin and increased weight loss, as compiled through a systematic review of bibliography databases and the electronic databases. Exenatide reduced glycated hemoglobin by approximately 1.0% and reduced weight by 3-6 kg by the end of the 52-week testing period, as summarized from 17 different studies (Norris et al., 2009). According to the systematic review of 36 studies, lixisenatide reduced glycated hemoglobin by approximately 0.52%, reduced weight by 0.65 kg, and reduced 2-hour PPG excursion by approximately 4.58 mmol/l (Schmidt et al., 2014). The efficacy of weight loss and weight loss maintenance of semaglutide was analyzed by the STEP trials. STEP 1-3 found that semaglutide treatment resulted in a 9.6% mean weight loss in participants with Type 2 diabetes, and a 15-16% mean weight loss in participants with only obesity (Amaro et al., 2022). Therefore, the data regarding clinical trials with adults show very similar trends to the data with youth and young adults with T2D/obesity taking GLP-1 RA.

More trials must be done in order to assess the long-term effects of GLP-1 agonists on younger populations, to see the effects of this drug past one year of study. Despite this, from the collected data, GLP1 agonists seem to be a promising treatment due to their ability to incite and manage weight loss, which in turn lowers the likelihood of complications related to obesity and T2D. They may even be more beneficial than other treatments, such as insulin therapies, due to their ability to lower the risk of hypoglycemia (DeFronzo, 2013).

Limitations

This study was conducted with only 10 papers. The limited material restricts the ability to make broad generalizations on the efficacy and safety of GLP-1 agonists for youth. Only six of these papers also include considerations of safety and note upon the adverse events reported throughout the study, further limiting this data. Of these 10 studies, half reported moderate differences or statistically insignificant data in at least one metric used to monitor the efficacy of

the GLP-1 treatment. However, these studies did often have another, secondary metric that was significant.

Each paper measured efficacy in a different form. Most papers used change in BMI as the primary metric, but some measured glycemic control, energy usage, etc. Even papers that used change in BMI calculated the difference between treatment and placebo, change from baseline, odds ratio of achieving a certain percent change, etc. Thus, the use of different metrics made it difficult to fully synthesize and compare data across different papers, treatments, and patient groups. This may introduce bias through differences in data interpretation.

The majority of the participants of each of the 10 studies were between 10-18 years old. This limited the data collected of children (<10) and young adults (19-25). Very few papers included in this review touched upon these two. However, many studies done during the initial search process included young adults, but were excluded due to the inclusion of populations over 25.

Ergo, more research must be done to mitigate the possible bias and lack of data that these limitations present.

Conclusion

The general consensus of these ten papers is that GLP-1 agonists are relatively effective in treatment of adolescents with Type 2 diabetes and/or obesity. Compared to placebo, the use of various forms of GLP-1 agonists improved glycemic control, increased maintenance of weight loss, and reduced BMI/weight/body fat, thus demonstrating efficacy as a treatment.

GLP-1 agonists, as touched upon by 6 of the papers studied, were also deemed safe and tolerable. Though adverse events occurred in treatment groups, often at greater frequencies than placebo groups, they were most often mild to moderate gastrointestinal adverse events. There were very few cases of serious adverse events, and no cases of death.

Thus, based on available evidence, GLP-1 agonists are a safe form of treatment of obesity/T2D for adolescents, though more studies need to be done in this field.

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Pollution Sources in the Lacamas Watershed, Challenges, and Solutions By Audreen Tsai

Abstract

More than half of U.S. rivers and lakes fail to meet water-quality standards because of nutrient pollution from diffuse nonpoint sources (NPS) and from point sources that are undetected or misclassified. Lacamas Lake in Camas, Washington, has experienced harmful algal blooms (HABs) every summer since 2018. Although the City of Camas began in-lake treatments in 2024 to reduce phosphorus, HABs persisted, underscoring the need for stronger source control and regulatory action.

This study combined field tours, visual surveys, and water quality testing to assess the agricultural and residential discharges to the lake. Results show that phosphorus concentrations frequently exceeded thresholds associated with harmful algal blooms, with the highest levels recorded at stormwater outlets from a lakeside neighborhood (up to 500 PPB). In contrast, swales and retention ponds with aquatic vegetation effectively lowered phosphorus levels, indicating their value as mitigation measures. Microscopy confirmed the presence of three toxin-producing Cyanobacteria genera in the lake. Findings indicate that many neighborhood discharge pipes may need to be regulated as point sources under the Clean Water Act (CWA).

The study concludes that effective restoration will require enforcing phosphorus-fertilizer restrictions, reclassifying misidentified point sources, mandating treatment infrastructure, and expanding public education on best management practices (BMPs). It will take concerted grassroots efforts to achieve the CWA goal of making all U.S. surface waters fishable and swimmable.

Keywords

Environmental Science; Watershed; Point Source and Nonpoint Source Pollution; Harmful Algal Blooms (HABs); Best Management Practices (BMPs)

Introduction

A National Problem

According to research by the Environmental Integrity Project, over 50% of United States rivers and lakes are impaired and not “fishable or swimmable” due to pollution (Table 1). The primary sources of water pollution are broadly categorized as point sources and nonpoint sources (NPS). Point sources are identifiable, confined discharges of pollutants from a leaking landfill, an industrial facility, a waste lagoon, or a livestock pen. In contrast, nonpoint sources are diffuse in nature, originating across the landscape from sources such as agricultural runoff, stormwater, or failing septic systems (Jeer et al.).

Waterbody Type (unit)	Total Assessed	Total Impaired	Percentage Impaired
Table 1. United States' Waterbodies Assessed As Impaired (Environmental Integrity Project)			
Rivers, streams, and creeks (miles)	1,401,320	703,417	50.20%
Lakes and reservoirs (acres)	20,403,021	11,168,767	54.70%
Bays, harbors, and estuaries (miles)	76,557	19,563	25.60%

Congress passed the Clean Water Act (CWA) in 1972 to protect all “waters of the United States” and make them “fishable and swimmable” (Copeland). By requiring permits and treatment for sewage and industrial discharges, the CWA successfully reduced point source pollution, leading to major improvements in water quality. However, CWA has not been effective in curbing nonpoint source pollution, which now accounts for most water quality impairments nationwide (Held). Federal and state agencies have promoted voluntary programs and Best Management Practices (BMPs) to address nonpoint source pollution, particularly from agriculture, but widespread nutrient loading continues to fuel algal blooms.

Algal blooms occur when excess nitrogen and phosphorus stimulate rapid algal growth under warm, calm, and sunny conditions. Some algal blooms, such as those caused by Cyanobacteria, can produce cyanotoxins such as microcystin and anatoxin-a. The blooms degrade water clarity, reduce oxygen levels through decomposition, and kill aquatic life. These harmful algal blooms (HABs) are detrimental to humans, aquatic life, and the aquatic ecosystem in general. Humans can be exposed to cyanotoxins by drinking water that contains the toxins, swimming in water that contains high concentrations of cyanobacterial cells, or breathing air that contains cyanobacterial cells or toxins (while watering a lawn with contaminated water, for example) (Brenckman et al.; United States Environmental Protection Agency). Typically, HABs can develop when total phosphorus concentration in water rises above 20-50 PPB. The risks HABs pose to human and animal health have forced public health agencies across the country to issue warnings and close lakes, rivers, and beaches.

Lacamas Watershed and Lacamas Lake

Lacamas Watershed, located in Clark County in southwest Washington State, exemplifies these national challenges on a local scale. The watershed extends from Brush Prairie to the City of Camas, encompassing 67 square miles (Figure 1). Based on 2023 Clark County zoning data, the land use is approximately 28% forest, 14% agriculture, and 51% residential (97% of this being rural and low-density housing). The remaining 7% consists of commercial and industrial land, schools, and water. Lacamas Creek, the watershed’s dominant tributary, provides 90% of the lake’s inflow and 72% of its phosphorus loading (Geosyntec Consultants). Lacamas Lake has been classified as eutrophic since the 1980s, meaning that high nutrient levels create favorable conditions for HABs in the lake.



Figure 1. Lacamas Watershed (City of Camas Project Documents). This map shows the main tributaries to Lacamas Lake. The watershed discharges into the Columbia River.

Since 2018, cyanotoxin measurements in Lacamas Lake have exceeded state health guidelines almost every year, leading Clark County Public Health to issue repeated toxic algae advisories (Table 2, Figure 2). There have been reported cases of people and animals becoming sick after contacting lake water (Lacamas Watershed Council).

Table 2. HABs In Lacamas Lake Since 2018 (Washington State Toxic Algae Freshwater Algae Bloom Monitoring Program; Clark County Public Health)

Timeline	Number of HABs Reported	Number of Times Toxin Level Tested Above State Guideline (weekly tests)	Toxins Found	Months When Clark County Public Health Issued Warnings
2018	2 times	2	Microcystin	October
2019	3-4 times	0	Microcystin	None
2020	Near-continual blooms April to October	14	Anatoxin-a, Microcystin	April-August, September, October
2021	3 times	5	Microcystin	August, September
2022	2 times	5	Microcystin	July, August
2023	2 times	11	Microcystin	July-September, October-November
2024	2 times	13	Microcystin	July-August, August-November
2025 (as of August 31)	1 time	4	Microcystin	June-July

A Court Ruling That Changes Classification

The Camas Meadows Golf Club and the Lacamas Shores neighborhood lie on the southwest shore of Lacamas Creek and Lacamas Lake. The neighborhood spans 2/3 of the lake shoreline and sits 350 ft to 190 ft above it. In the 1980s, as a condition of development, a man-made wetland with a French drain system (collectively called the Biofilter) was built in a field below the neighborhood. Stormwater is collected from above, piped down to the Biofilter, and spread evenly across the field before it is discharged at low velocity to a forested wetland by the lake. The Biofilter was tested to be functional during the four years after completion (Bautista et al.). As years passed, the field turned into a forest, and the tree roots damaged the Biofilter. A resident in Lacamas Shores was upset that overgrown trees blocked lake views from his home.



Figure 2. Algal blooms at Lacamas Shores boat dock on August 8, 2024 (left) and Clark County Public Health Warning (right)

As the Homeowners' Association (HOA) refused to remove the trees, he conducted tests at three outlets where water is discharged to the lake. The tests found the Biofilter had failed to function, and excessive levels of pollutants were discharged to the Lake. He filed a federal lawsuit against the HOA in 2021 under CWA. In October 2022, the court, based on United States Environmental Protection Agency (EPA) guidelines on interpreting CWA, did not determine the Biofilter to be a point source. However, in early 2023, the EPA revised its guideline. The Plaintiff then asked the court to revisit this ruling. In late 2023, a US District Court in Seattle, based on the new EPA guideline, ruled that the Biofilter is a point source and ordered the HOA either to stop adding pollutants or to obtain a permit as mandated by CWA (Bang v. Lacamas Shores Homeowners Association). This legal dispute underscores policy uncertainty and public confusion about whether certain stormwater discharges should be classified as point sources and subject to CWA regulations.

Inadequacy of Existing Solution and Aim of This Study

While previous responses to HABs, such as the City of Camas's 2023 Lake Management Plan and the alum treatments initiated in 2024 (City of Camas), have focused on in-lake interventions, there has been less systematic attention on evaluating external sources of nutrient loading.

This research, therefore, seeks to fill a critical gap by: (1) identifying and evaluating pollution sources across the watershed, (2) measuring phosphorus concentrations at community discharge points near the lake, and (3) assessing whether some discharges currently treated as nonpoint sources should instead be regulated as point sources under the CWA. Unlike much of the existing literature, which assumes NPS pollution to be diffuse and untraceable, this study demonstrates that some sources can be pinpointed, tested, and potentially reclassified. The study

aims to contribute both to local management of Lacamas Lake and to broader national discussions on closing regulatory gaps in watershed protection.

Methods

To assess pollution sources in the Lacamas Watershed, two complementary approaches were employed: (1) visual watershed surveys to assess algal blooms and potential pollution sources, and (2) field sampling and laboratory-style analyses to measure phosphorus concentrations at discharge points and identify Cyanobacteria in Lacamas Lake.

Visual Tours

Multiple visual tours were conducted in summer 2024 and summer 2025 that can be grouped as Tour A and Tour B (map in Figure 3). **Tour A** focused on ditches and creeks in agricultural areas and Lacamas Lake. Locations A1-A4 are at the main upper stream tributaries of Lacamas Lake. Locations A5-A6 are at Lacamas Creek shortly before it meets Lacamas Lake. Location A7 and A8 are at the boat docks by Lacamas Lake. All locations are near public roads and accessible to pedestrians. Photographs were taken using an iPhone. The color and transparency of water are analyzed for possible explanations. **Tour B** focused on the residential and recreational areas along the Heritage Trail by Lacamas Lake. The goal was to assess the outfalls from Camas Meadows Golf Course (B1, B2) and Lacamas Shores neighborhood (B3-B6), and to determine whether stormwater flowed through treatment structures (retention ponds, swales, or the Biofilter) or discharged directly to the lake.

Lab Testing

Water samples were collected in 100ml clean plastic containers. Phosphorus testing was done using Hanna Instruments HI713 Phosphate Low Range Checker® HC (with reagent HI 713-25), which provides colorimetric measurement of orthophosphate (PO_4^{3-}) levels. PO_4 is the most readily available form of phosphorus for aquatic life, including Cyanobacteria. Each sample was tested in duplicate, and average values were recorded.

To examine cyanobacterial presence in lake water, samples from the Lacamas Shores and Heritage boat docks were analyzed using a Trinocular Microscope (40X–5000X magnification). Three drops of the water sample are placed on a microscope slide and covered with a coverslip. Initial scans were performed at 4×25 magnification to locate microorganisms, followed by higher magnifications (10×25 to 40×25) to confirm morphology. Images were recorded using an iPhone camera adapted to the microscope eyepiece. The concentration of Cyanobacteria in the water sample was not measured.

Figure 3. Tour areas and locations where photos were taken. A1-A4 are at the upper stream of Lacamas Lake



Results

Algal Blooms

Visual surveys and field sampling revealed significant nutrient inputs from both agricultural and community sources within the Lacamas Watershed. Pictures from Tour A (Figure 4) showed mild signs of algal growth in the ditches and tributaries near farmland (pictures A1-A4), but water quality declined significantly closer to Lacamas Lake (pictures A5-A6), where stagnant flows and increased turbidity indicated ongoing algal blooms. During dry summer months, precipitation is insignificant to none, limiting dilution capacity. The water flow from farmland adds nutrients to what is already in the water column. As Lacamas Creek widens, the water becomes calm. High nutrient concentration, direct sunlight, and high temperature create ideal conditions for algal blooms. At Lacamas Shores boat dock, algal blooms

were in full swing (picture A7). At Heritage boat dock, the water was deeply green with high turbidity, indicating an algal bloom (picture A8).



Figure 4. Mild algal growth in upper stream ditches and creeks, and heavy algal blooms in Lacamas Lake

Missing Infrastructure

Pictures from Tour B (Figure 5) showed that the ditches from Camas Meadows had low water levels (pictures B1, B3). Retention ponds and swales exist upstream of the outfalls (B2). There are three discharge points from Lacamas Shores Biofilters. One of them is after a long swale and a retention pond (picture B4). The tour identified a total of 35 direct discharge pipes from

Lacamas Shores neighborhood: 34 in the southern half and one in the northern half of the neighborhood. Among the 34 pipes in the southern half (Figure 6 for map location), 17 were active in the summer dry season, discharging large volumes of untreated water directly to Lacamas Lake (Pictures B5, B6). At one stretch of the trail, water flew over Heritage Trail before discharging to the lake (picture B7). It is clear that, when the southern half of the neighborhood was developed in the 1990s (Lacamas Shore Homeowner Association), no stormwater treatment infrastructure was built. As there was no rain within ten days before the tour (September 1, 2025), the water presumably was from the irrigation of neighborhood lawns.



B1. Ditch from Golf Course to Lacamas Creek: low water & abundant plants



B2. Retention Pond on Golf Course: abundant aquatic plants



B3. Discharge ditch from Golf Course to Lacamas Lake: low water & lots of mosquitos



B4. Swale and Retention Pond on Lacamas Shores Biofilter Field: abundant emergent plants & duckweed



B5. Direct Discharge Point from Lacamas Shores (1 of 35): constant water flow



B6. Direct Discharge Point from Lacamas Shores (1 of 35): large water flow



B7. Water from Lacamas Shores flows over Heritage Trail

Figure 5. Golf course and Lacamas Shores discharge points (35 direct discharge pipes, including B5, B6, were found)

Phosphorus Levels and Cyanobacteria

Based on Tour B, 10 locations (Figure 6) were selected for phosphorus testing, including one at the golf course to the lake (Location 1), two from northern half of Lacamas Shores neighborhood to its Biofilter (Locations 2,5), three from Biofilter to the lake (Locations 3,4,6), two from southern half of Lacamas Shore neighborhood directly to the lake (Locations 8,9), and two at boating docks by the lake (locations 7, 10).

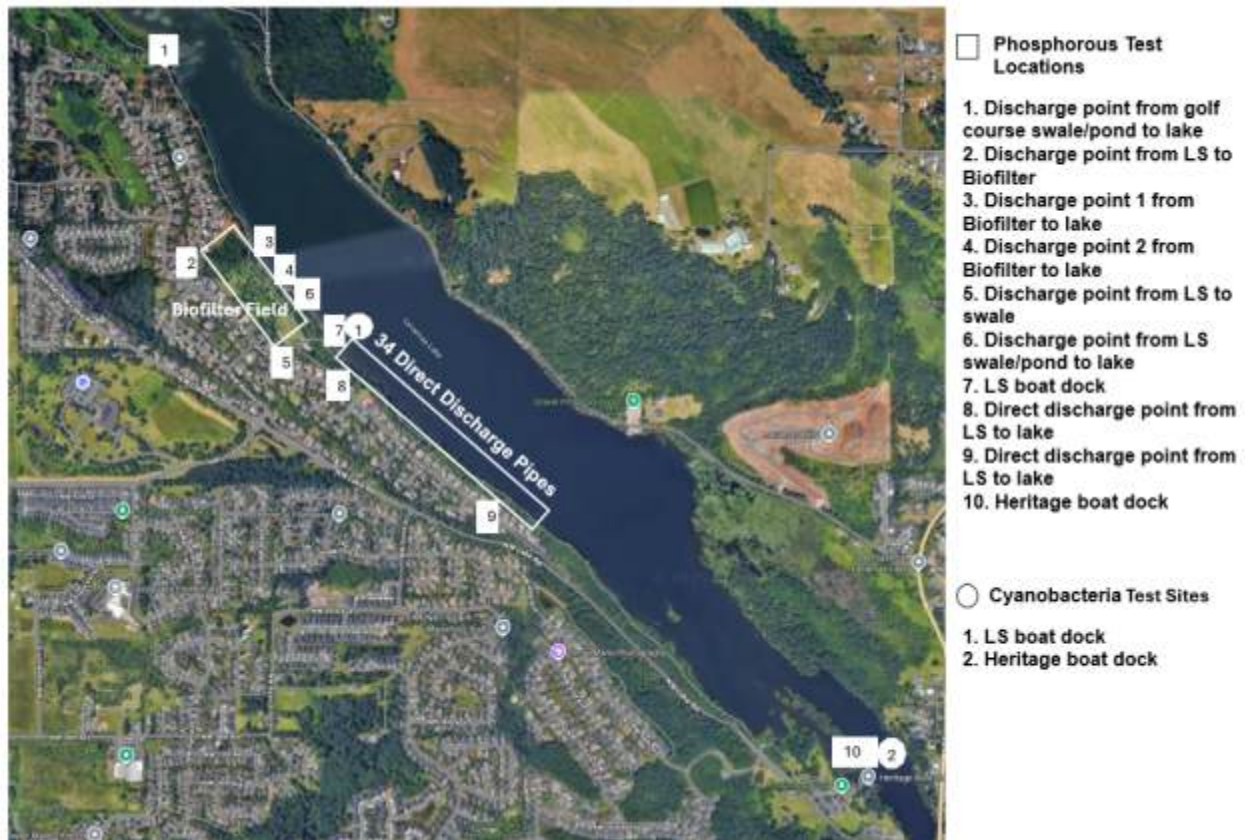


Figure 6. Locations of Biofilter, 34 direct discharge pipes, and water sampling places

Phosphorus testing at 10 locations (Table 3) shows elevated concentrations at locations 2, 5, 8, and 9 (up to 500 PPB), where water runs down directly from the Lacamas Shores (LS) neighborhood, indicating residents may be using phosphorus fertilizers in their lawns. Location 3 is an outlet from the Biofilter. The very high phosphorus level shows the Biofilter is likely adding phosphorus to water (from decaying organic materials). In contrast, phosphorus levels are very low coming out of swales and retention ponds (40–56 PPB), demonstrating the effectiveness of such green infrastructure. Phosphorus levels at both boat docks were approximately 140 PPB, significantly above the 20-50 PPB threshold for HABs to develop. While EPA does not issue a single, universal phosphorus limit for water discharged to lakes, recommended limits to prevent algal blooms typically fall below 100 PPB for receiving water (Barter).

Microscopy confirmed the presence of *Aphanizomenon*, *Microcystis*, and *Planktothrix* (Table 4, Figure 7), all Cyanobacteria genera known for toxin production. These findings corroborate findings by the Lacamas Watershed Council that Clark County Public Health uses for issuing warnings (Lacamas Watershed Council Data Dashboard).

Table 3. Phosphorus Concentrations		
Location	Description	Phosphorus Concentration (PPB)
1	Discharge point from the golf course to the lake	40
2	Discharge point from LS to Biofilter	390
3	Discharge point 1 from the Biofilter to the lake	460
4	Discharge point 2 from the Biofilter to the lake	140
5	Discharge point from LS to swale	480
6	Discharge point from swale/pond to lake	56
7	LS boat dock	140
8	Direct discharge point from LS to the lake	500
9	Direct discharge point from LS to the lake	270
10	Heritage boat dock	140

Table 4. The Cyanobacteria Found In Lake Release Cyanotoxins		
Sample Date	Location	Findings
08/26/25	LS Boat Dock	Aphanizomenon, Microcystis, Planktothrix
08/31/25	Heritage Dock	Microcystis, Planktothrix

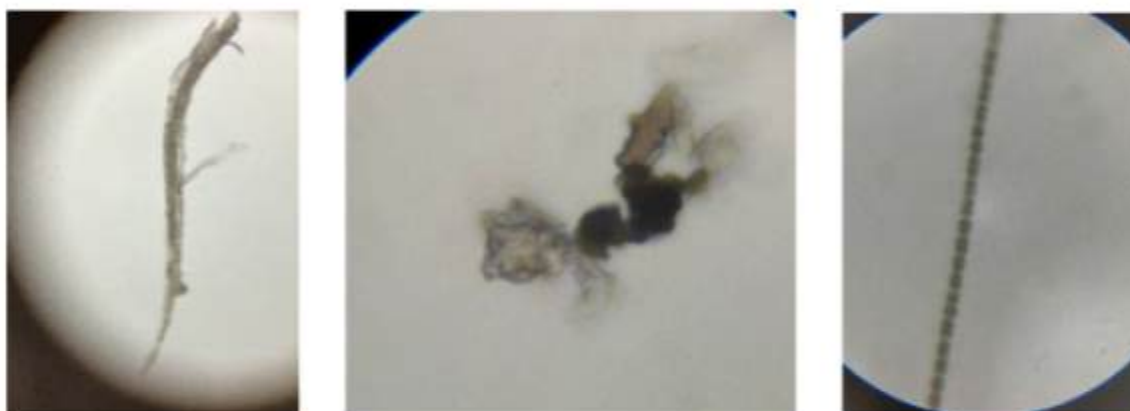


Figure 7. Microscopic views of Cyanobacteria found in Lacamas Lake (from left to right): Aphanizomenon, Microcystis, Planktothrix

Discussions

Challenges

While this study focused on a local watershed, the challenges are shared by thousands of watersheds in the entire nation. The infamous “dead zone” off the coast of Louisiana and Texas (United States Environmental Protection Agency) is caused by HABs fueled by nutrient runoff from the Mississippi River basin, a massive watershed that spans 1.15 million square miles and drains farmland and cities in 31 states, carrying nutrients along to the Gulf of America. Each summer, nitrogen and phosphorus fuel algal blooms, which then die, decompose, and deplete oxygen. This process creates a vast seasonal hypoxic zone, the “dead zone,” causing marine life to perish, disrupting ecosystems, and harming Gulf fisheries vital to local economies and coastal communities.

The Clean Water Act (CWA) produced dramatic improvements in U.S. water quality by targeting easily identifiable point sources in its early decades. With the “easy wins” behind us, progress has slowed. The diffuse nature of nonpoint source (NPS) pollution means it is everywhere and hard to regulate.

In Washington State, the Department of Ecology regulates agricultural pollution and addresses nonpoint source pollution primarily through voluntary programs and best management practices (BMPs). It publishes the Voluntary Clean Water Guidance for Agriculture, which outlines BMPs that help farmers maintain productive land while also protecting water quality (Washington State Department of Ecology). It is important to educate farmers not only about recommended BMPs, but also about the financial and technical assistance available to them through state initiatives and federal EPA funding.

As this study found, in-lake alum treatments, while they worked in another watershed (Lake & Pond Heroes), have failed to prevent harmful algal blooms in Lacamas Lake in 2024 and 2025. These outcomes highlight the limitations of chemical controls when upstream inputs remain unchecked. As evidenced by this study, both farmland runoff and neighborhood discharges are sustaining phosphorus enrichment in the lake.

Similarly, on the regulatory front, Washington’s 2011 fertilizer restrictions (ESHB 1489) (Washington State Department of Agriculture) attempted to limit phosphorus fertilizers but suffered from limited enforcement and low public awareness, with evidence in this study suggesting some residents continue applying phosphorus fertilizers. A store survey also found that fertilizers containing high phosphorus content are readily available for purchase. It is therefore important to alert residents, through community outreach, of the harmful effects to the health of the lake by using too much fertilizer, especially those with high phosphorus content.

Importantly, the thirty-five Lacamas Shores discharge pipes currently treated as nonpoint sources may warrant reclassification as point sources under the Clean Water Act, since they are discrete, measurable discharges. Such recognition would close a regulatory gap and enable enforcement.

Solutions

As in other surface freshwater systems, the limiting nutrient for eutrophication in Lacamas Lake is phosphorus. Phosphorus readily binds with dissolved metals, forming compounds such as calcium hydrogen phosphate (CaHPO_4) in slightly alkaline soils, and iron phosphate (FePO_4) or aluminum phosphate (AlPO_4) in acidic soils. Because these metal-phosphate compounds are largely insoluble in water, their formation reduces the amount of dissolved phosphorus to feed algal blooms. Therefore, it is often feasible to reduce phosphorus at the source or to remove it from waterbodies. In alum treatment used by the city of Camas, alum ($\text{Al}_2(\text{SO}_4)_3$) is spread from a boat to the lake. It reacts with orthophosphorus (PO_4^{3-}) in water to form insoluble AlPO_4 that sinks to the lake bottom ($\text{Al}^{3+} + \text{PO}_4^{3-} \rightarrow \text{AlPO}_4(\text{s})$). The treatment can work for waterbodies that receive minimum inflows during summer dry seasons when HABs usually develop.

Data from this study finds that swales and retention ponds with abundant aquatic plants are effective infrastructures to reduce phosphorus runoff and should be required in future developments. For similar reasons, floating treatment wetlands (FTWs) can be a solution to remove nutrients already in the water column and should be integrated into a comprehensive in-lake remediation scheme.

Strengthening agricultural BMP adoption, improving fertilizer law enforcement, and regulating misclassified point sources will be critical to restoring Lacamas Lake. At present, the Lacamas Shores Homeowners Association is carrying out court-ordered repairs and maintenance on its Biofilter system (Lacamas Shore Homeowner Association), thanks to the activism of a private citizen.

Larger watersheds typically contain many smaller watersheds that feed water and pollutants to them. By cleaning up the smaller watersheds, even the largest ones will become cleaner. Therefore, new progress will rely on concerted grassroots efforts to find and correct misclassified point sources, build cost-effective green infrastructures, explain to all residents of pollution pathways from stormwater runoff to HABs, and educate them the best management practices (BMPs) available.

Public education is perhaps the most cost-effective BMP and is based on the premise that farmers, developers, government officials, and ordinary citizens will take proper steps to protect water resources if they know what those steps are. High school students, by working with government agencies and citizen volunteer organizations, can play an important role in educating the public through outreach workshops, putting up outdoor posters at walking trails and in parks, sending out brochures and doorhangers to neighbors, and hosting children's activities for elementary and middle school students.

Conclusions

Lacamas Lake illustrates only a snapshot of a much larger national challenge, the nutrient-driven harmful algal blooms (HABs) affecting waterbodies across the United States. Yet by combining source control, citizen monitoring, stronger enforcement, and public education, we

can reaccelerate progress toward the Clean Water Act's goal of making the nation's waters fishable and swimmable.

High school students can partner with local watershed organizations, or involve their families, neighbors, and friends to conduct visual surveys and water testing to detect problems in their own watersheds and explore potential solutions. Through these projects, students can learn environmental science, laws, public health, government regulations, agriculture, and economics.

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Deflecting Bennu By Aaditya Mathur

Abstract

Potentially Hazardous Asteroids (PHAs) are near-Earth objects that pose a risk of significant impact. Bennu, a well-studied 500-meter asteroid with a non-zero probability of Earth collision in the late 2100s, is a key target for mitigation strategies. This paper evaluates four deflection techniques, kinetic impactors, gravity tractors, nuclear standoff detonations, and the Yarkovsky effect, based on Bennu's properties and timeline for intervention.

Introduction

Near-Earth asteroids present a low-probability but high-consequence threat to life on Earth. Among them, asteroid Bennu has gained particular attention due to its relatively large size (500 m), high porosity, and non-negligible impact probability in the late 22nd century. This paper explores multiple asteroid deflection strategies, kinetic impactors, gravity tractors, nuclear standoff detonation, and enhanced Yarkovsky effect, with a focus on their feasibility and effectiveness for Bennu. We aim to identify the most viable technique given current technological capabilities, asteroid properties, and time constraints.

Background

Near-Earth objects (NEOs) are asteroids and comets whose orbits bring them close to Earth, typically within 1.3 astronomical units (AU) of the Sun. These bodies are of great interest due to their scientific value, their potential as targets for exploration, and their ability to pose threats to Earth. A particularly significant subset of NEOs are the potentially hazardous asteroids (PHAs), defined as objects with diameters greater than 140 meters and orbits that come within 0.05 AU of Earth's orbit. Monitoring and modeling PHAs is essential for planetary defense and mission planning. One of the most well-studied PHAs is asteroid (101955) Bennu, an Apollo-type asteroid with a diameter of approximately 500 meters. Bennu is notable not only for its classification as a PHA but also because of its relatively high probability of impacting Earth in the late 2100s. This makes it a prime target for long-term orbital monitoring and mitigation strategies.

In addition to its impact risk, Bennu's orbit and composition have made it an ideal candidate for scientific exploration. NASA's OSIRIS-REx mission, launched in 2016, successfully rendezvoused with Bennu in 2018 and returned surface samples to Earth in 2023. The mission has provided detailed insights into Bennu's structure, dynamics, and surface composition.

Mitigation Options

In this paper, we explore four asteroid deflection strategies to evaluate their feasibility for redirecting asteroid Bennu. These include kinetic impactors, which deliver momentum by colliding directly with the target; gravity tractors, which use the gravitational attraction of a

nearby spacecraft to gradually shift an asteroid's path; and nuclear standoff detonations, which apply a sudden force via radiation and ejecta from a nuclear explosion near the asteroid's surface. A fourth method, the Enhanced Yarkovsky Effect, manipulates the asteroid's thermal properties, typically by altering its surface reflectivity, to increase asymmetric heat emission and induce a gradual orbital drift.

Kinetic Impactors

A kinetic impactor is a spacecraft designed to deflect an asteroid by intentionally colliding with it and transferring its momentum, altering the asteroid's trajectory. It can be used to protect Earth in the event of an imminent asteroid collision. The effectiveness of a kinetic impactor is measured by its momentum transfer efficiency (β), which is the ratio of the impactor momentum to the recoil momentum of the target. The most notable demonstration of this method was NASA's DART mission, where a spacecraft successfully altered the orbital velocity of the asteroid Dimorphos by approximately 2.7 mm/s. Given Bennu's potential future risk of Earth impact and its well-characterized physical properties from the OSIRIS-REx mission, it serves as an ideal target for studying momentum transfer due to a kinetic impactor.

Overview of Techniques

These are some techniques used by different papers to test the feasibility of the Kinetic Impactor method for deflecting potentially dangerous asteroids. It was mostly evaluated through simulations and code models; however, it is also assessed through physical experiments.

Monte Carlo Simulations

Due to uncertainties in the properties of the asteroid, such as the density, mass and direction of the net ejecta momentum, all factors which affect β , Monte Carlo simulations could be used to assess the Kinetic Impactor method. This computational technique uses randomized input parameters to statistically model the outcomes of the kinetic impact. These simulations produce a range of along-track velocity changes (Δv_T) based on uncertainties in the orbit period, asteroid shape, and system dynamics (Cheng et al.).

Numerical Modeling with iSALE-3D

Some experiments used the iSALE-3D shock physics code to model impacts on asteroids with varying surface and subsurface structures, along with different impact angles. It included models for material strength, compaction due to porosity, and ejecta formation, enabling precise tracking of ejecta movement and momentum transfer in a three-dimensional grid system (Dai et al.). Figure 2 shows the four structural scenarios tested: a homogeneous regolith, and three configurations with buried boulders at varying depths and positions (Dai et al.).

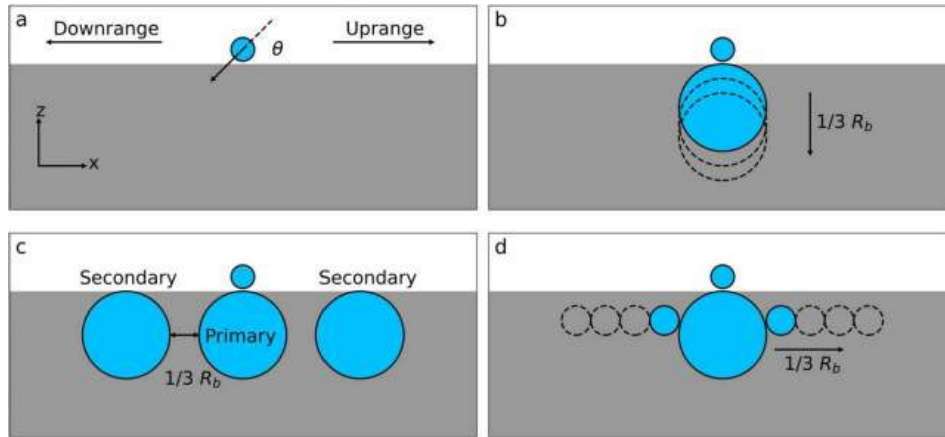


Figure 1: This figure shows subsurface boulder configurations used in iSALE-3D simulations. (a) Homogeneous regolith. (b) A single large buried boulder. (c) A central boulder flanked by two large boulders. (d) A central boulder with two smaller surrounding boulders at varying separation distances. These structural models allow for analysis of how material heterogeneity affects momentum transfer (Dai et al.).

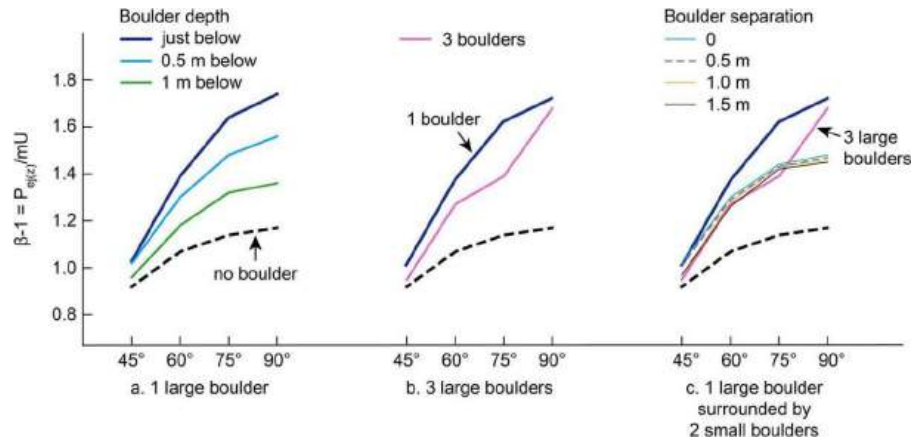


Figure 2: This figure shows normalized vertical momentum transfer (V_z/U) vs. impact angle. Maximum efficiency occurs near 90° with one large boulder just underneath the asteroid's surface across most structural cases, supporting the idea that a head-on impact is optimal for transferring kinetic energy into orbital deflection momentum (Dai et al.).

This graph quantifies the impact of the subsurface arrangements shown in Figure 1. A 90° impact consistently yields the highest momentum transfer, especially when a large boulder is buried just beneath the surface. Models with multiple boulders show reduced efficiency due to energy dissipation and shielding effects.

These models are relevant to Bennu. Bennu's surface is heavily influenced by the presence of boulders exceeding 10 meters in diameter (Walsh et al.). Given the tight correlation between near-surface boulder depth and increased $\beta - 1$ in Figure 2, a kinetic impactor striking such a region on Bennu at or near 90° could result in significantly greater deflection than on a smoother, homogeneous surface (Dai et al.).

Electro-Thermal Accelerator Experiments

One study conducted small-scale experiments using an electrothermal accelerator to fire projectiles at materials such as quartz sand, glass beads, and JSC-1A, a lunar soil simulant (Chourey et al.). The experiment launched 2 mm projectiles at a speed of ~ 2.5 km/s into targets suspended on springs to measure momentum transfer and the momentum enhancement factor β as shown in Fig. 3 (Cheng et al.).

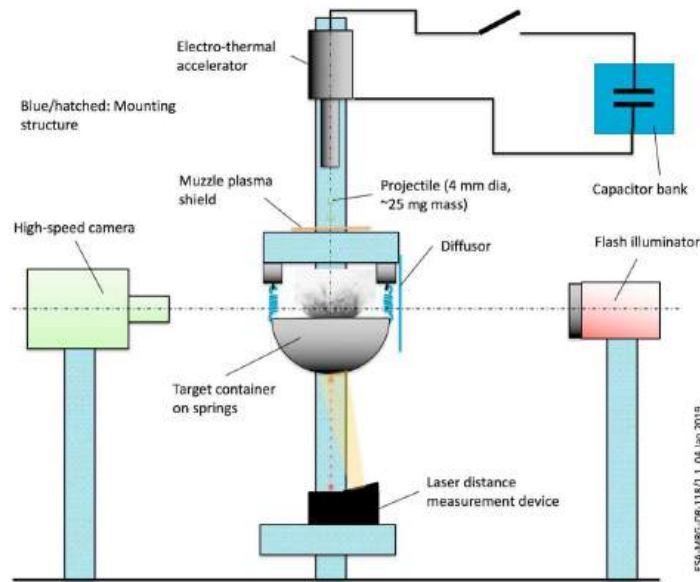


Figure 3: This figure shows the experimental setup for electrothermal accelerator tests. A small projectile is launched into a regolith-filled container suspended on springs. The impulse imparted to the system is used to calculate β (Cheng et al.).

The study found that β increased with impact velocity and was highest for low-cohesion, low-friction materials like glass beads, reaching values up to 2.96. In contrast, JSC-1A produced β values below 1.4 due to its higher cohesion and internal friction, as shown in Fig. 4–6 (Cheng et al.). They also observed a power-law relationship between $\beta - 1$ and impact velocity:

In the experiments, materials with low cohesion and internal friction (e.g., glass beads) exhibited higher values of s , indicating that they respond more efficiently to increased impact energy. In contrast, JSC-1A had a lower s , reflecting diminished gains in β with increasing velocity due to its compaction and energy dissipation properties.

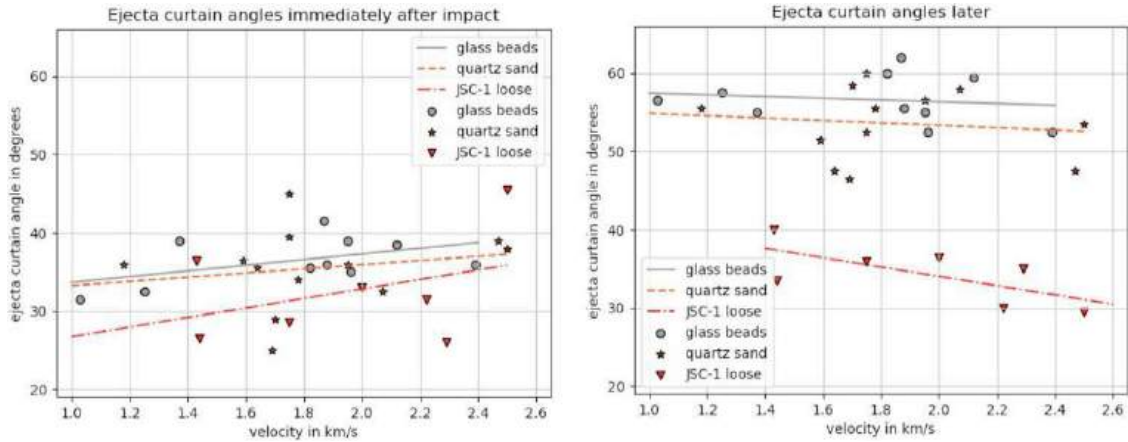


Figure 4: This figure shows the crater mass vs. impact energy for various materials. Glass beads exhibit greater crater mass and more efficient ejecta production than JSC-1A at equivalent impact energy, suggesting higher β (Cheng et al.).

Figure 4 shows that ejecta curtain angles for glass beads and quartz sand increase steadily with velocity, supporting more efficient momentum transfer. JSC-1A's curtain angles, in contrast, plateau or even decrease at later times, reflecting its inability to loft ejecta effectively due to energy losses in compaction and inter-particle friction.

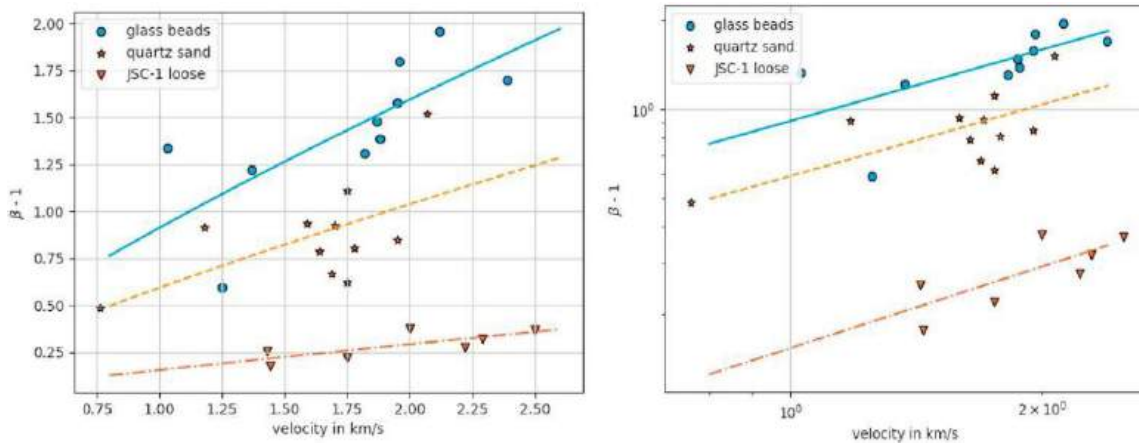


Figure 5: This figure shows the scaling law behavior of crater growth. Glass beads and quartz sand show stronger scaling trends with impact energy compared to JSC-1A, which levels off earlier due to its internal cohesion and compaction resistance (Cheng et al.).

Figure 5 further quantifies this by plotting $\beta - 1$ vs. velocity. The steeper slope and higher intercept for glass beads indicate strong scaling and better response to velocity increases. JSC-1A shows a shallow slope and lower peak, indicating that adding velocity yields diminishing returns on momentum enhancement for more cohesive surfaces.

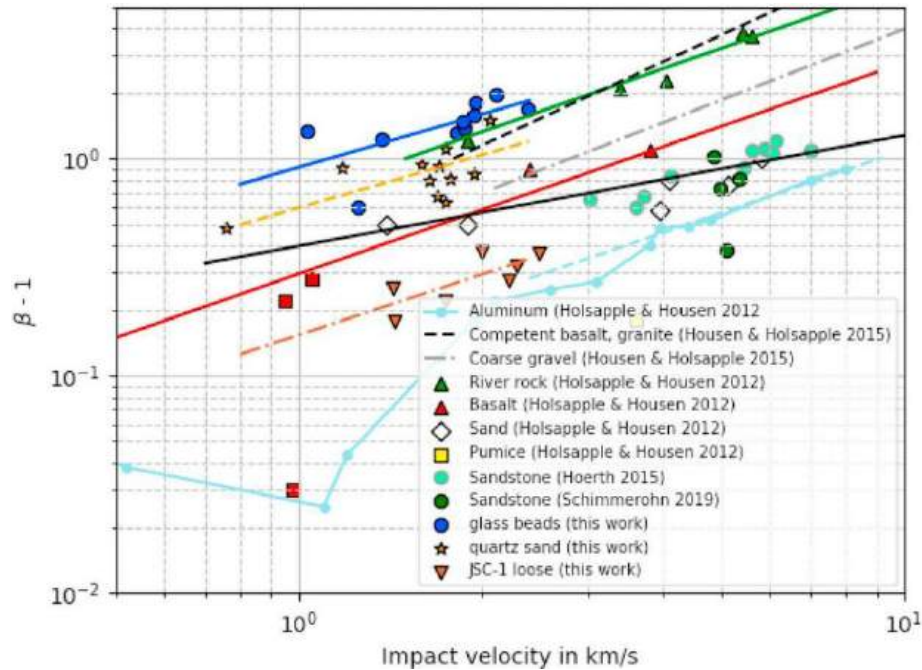


Figure 6: This figure shows the momentum enhancement factor $\beta - 1$ vs. impact velocity. Experimental results are compared with larger-scale impact tests. Bennu-like regolith analogs (e.g., JSC-1A) fall below glass beads and quartz sand, suggesting lower momentum transfer under identical impact conditions (Cheng et al.).

In Figure 6, experimental data are compared across material types, including larger-scale impact tests. JSC-1A clusters at the lower end of the momentum enhancement spectrum and falls well below materials like quartz sand and glass beads. Given that JSC-1A is a reasonable analog for certain cohesive zones on Bennu, this suggests that kinetic impactors may be less effective in those regions unless the impact velocity or mass is increased.

These results suggest that even small increases in impact velocity can significantly improve β under favorable surface conditions. For Bennu, whose regolith includes fine, loosely bound grains mixed with embedded boulders, this means that the momentum enhancement factor will vary across the surface. Regions resembling the cohesive structure of JSC-1A may yield lower β values (< 1.5), while impact sites composed of finer, unconsolidated grains may produce $\beta > 2$, enhancing the efficiency of a kinetic impactor. However, these are both considered exceptional outcomes for deflection (Cheng et al.).

Bern SPH Shock Physics Code

A research paper used the Bern SPH Shock Physics code to simulate impacts on rubble-pile asteroids, observing the reshaping and ejection processes that occur after impact. They used the code to model DART-like impacts, with 600 kg spherical aluminum projectiles impacting 160 m diameter rubble-pile-like spherical targets at 6 km/s (Raducan et al.). Figure 7 shows a visualization of the post-impact morphology of the asteroids in the simulations. The figure shows slices of the asteroids and shows how different boulder packing configurations affect the asteroid's response to the kinetic impactor (Raducan et al.).

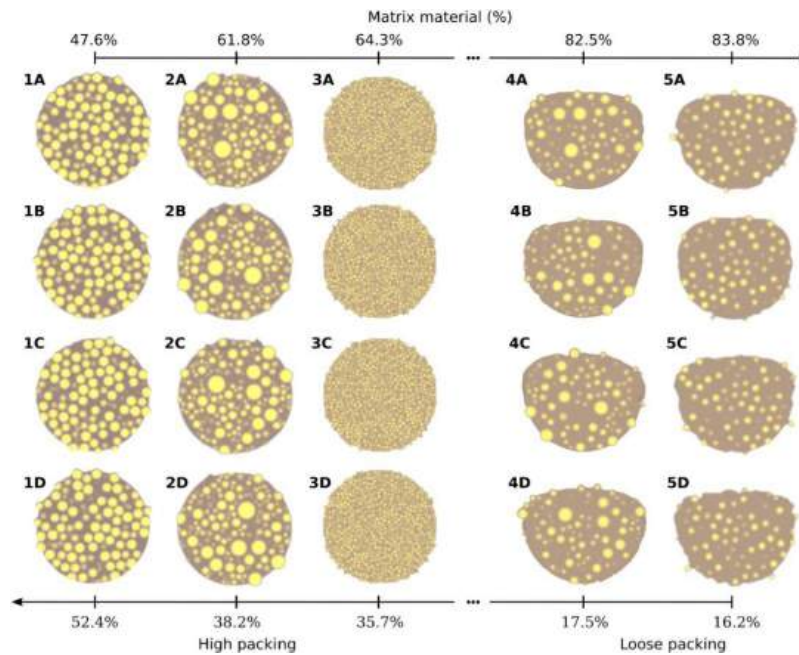


Figure 7: Post-impact morphology of rubble-pile asteroids with varying boulder size-frequency distributions. Panels 1–3 show densely packed boulders, where impacts produce small, localized craters. In contrast, Panels 4–5 depict loosely packed structures, leading to large-scale deformation and greater momentum transfer, improving the likelihood of successful deflection (Raducan et al.).

Panels 1–3 show targets with high boulder packing (more than 35% by mass), where the impact creates only small, localized craters. In contrast, panels 4–5 illustrate loosely packed targets (less than 20% boulder mass), which deform globally after impact. This structural flexibility enhances deflection by allowing more energy to be transferred to the asteroid’s orbital momentum. The results suggest that Bennu, whose surface is known to include loosely held rubble and low-strength materials, may respond similarly to the loosely packed cases, improving the chances of a successful kinetic deflection (Raducan et al.).

These simulations indicate that Bennu’s loose, unconsolidated surface, confirmed by OSIRIS-REx observations, likely supports favorable momentum transfer conditions for a kinetic impactor. If the projectile avoids large embedded boulders, β values around 3–4 are possible, representing highly efficient deflection performance for a kinetic impactor striking Bennu (Raducan et al.). However, regions with high boulder concentration or interlocking structures could absorb more impact energy, reducing the net momentum transfer and deflection angle alignment (Raducan et al.). However, these findings, along with the results from the electrothermal acceleration experiments, emphasize the importance of site selection and surface reconnaissance before executing a deflection mission.

Kinetic Impactor: Will it work on Bennu

Bennu is highly porous because it is a pile of rubble. Due to this, it releases more ejecta with impact; therefore, it will theoretically have a high momentum transfer efficiency. There is a complexity that Bennu will break up when impacted because it consists of many boulders held

together instead of its trajectory being changed. However, Dimorphos is also a rubble pile and was successfully deflected in the DART mission, so the success of the mission to change Bennu's trajectory may depend on other factors. Other than this, most of the factors are controllable such as the impact angle and velocity of the spacecraft so it may be possible to use this strategy on Bennu.

Gravity Tractor

The Gravity Tractor (GT) method is a relatively untested method for asteroid deflection that uses mutual gravity between the spacecraft and asteroid to slowly change the trajectory of the asteroid. The spacecraft hovers close to the asteroid and uses its own gravity to gently tug on it. Over time, this slow but steady pull shifts the asteroid's path. It's one of the safest ways to deflect rubble-pile asteroids because it avoids breaking them apart or relying on uncertain surface properties.

Overview of the Gravity Tractor Method

In the standard gravity tractor (GT) approach, the spacecraft hovers around 1.5 asteroid radii from the center of mass with electric (ion) engines canted 60 degrees outward to avoid plume impingement on the surface. This results in only about 50% of the thrust being inflicted on the asteroid for gravitational towing (Schweickart et al.). As shown in Figure 8, this configuration maintains the spacecraft's gravitational influence while ensuring that thruster exhaust does not disrupt the asteroid's surface (Mazanek et al.).

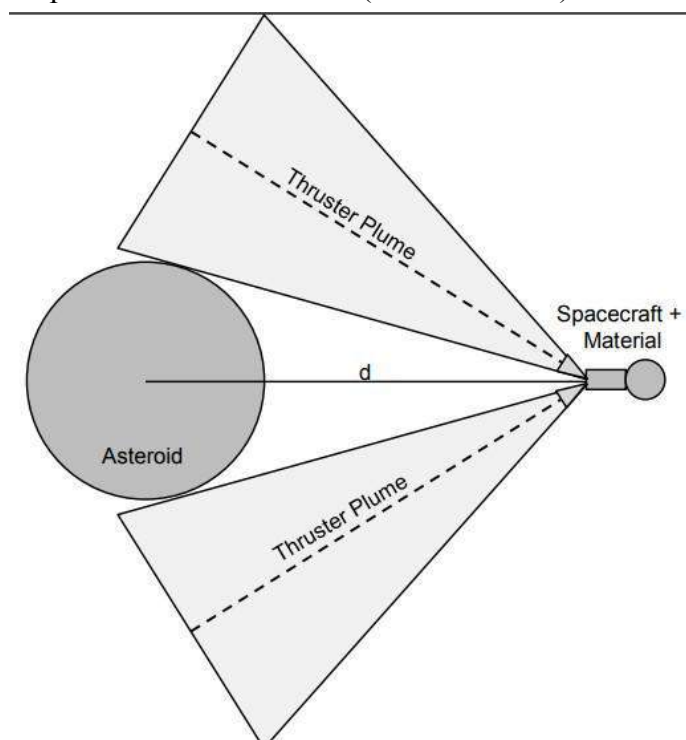


Figure 8: This figure shows the baseline gravity tractor configuration. A spacecraft hovers at 1.5 asteroid radii while maintaining outward-canted ion thrusters to avoid plume impingement. Only the horizontal component of thrust contributes to the net gravitational pull (Mazanek et al.).

The Enhanced Gravity Tractor (EGT) method improves on this by both increasing the effective mass of the spacecraft and optimizing its propulsion geometry (Mazanek et al.; Olympio et al.). After collecting surface material, typically a multi-ton boulder from the surface of the target asteroid or an asteroid on the spacecraft's flightpath, the spacecraft enters a spiral tractor orbit, as illustrated in Figure 9. This orbit eliminates the need for canting the engines, allowing 100% of the ion thrust to be directed along the desired deflection vector (Olympio et al.).

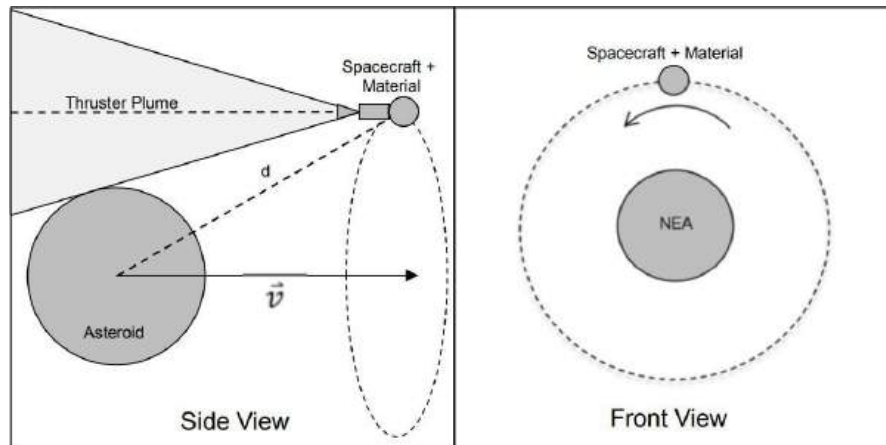


Figure 9: This figure shows the spiral orbit tractoring approach. In the EGT configuration, the spacecraft orbits along a spiral path aligned with the asteroid's velocity vector. This approach removes the need for thrust canting, enabling full thrust efficiency and closer proximity, both of which increase gravitational influence (Mazanek et al.).

Figure 10 compares the performance of standard GT and EGT methods. Asteroid Bennu has a diameter of approximately 492 meters. While an Enhanced Gravity Tractor (EGT) would still provide a significant performance boost, reducing the required deflection time by 5x, the absolute timescale would remain long, demanding early intervention and sustained operation. Sustained operation would be expensive, require large quantities of fuel, and serve the risk of being damaged (Mazanek et al.; Olympio et al.).

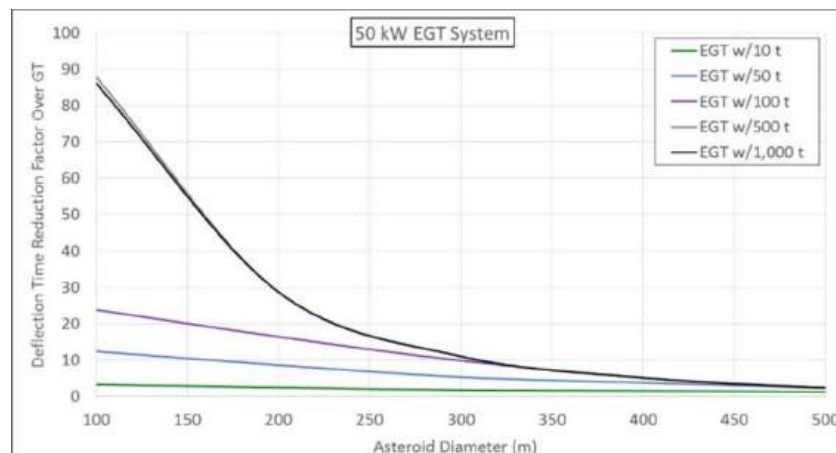


Figure 10: This figure shows the deflection time vs. propulsion power for standard and enhanced gravity tractors. For a 200-meter asteroid, EGT missions reduce deflection time by up to 97% compared to baseline GT configurations, especially with large mass augmentation (Mazanek et al.).

These results demonstrate that the Enhanced Gravity Tractor method offers a highly

efficient, non-destructive deflection strategy. For rubble-pile asteroids like Bennu, which raises concern due to surface heterogeneity and fragmentation risk, EGT provides a stable and controllable alternative. Its performance is largely independent of surface cohesion and does not require precise impact conditions, making it a possible candidate for deflecting Bennu.

Gravity Tractor: Factors to Consider

The asteroid's traits such as mass, spin, and structure are extremely important factors when considering this factor. A smaller mass would result in less effort needed to be exerted and less fuel being needed on the spacecraft. Since this method takes a long time to change the trajectory of an asteroid by a significant amount, a smaller mass would affect the mission duration as well. The structure of the asteroid is also key in exploring the feasibility of the gravity trap method. An asteroid with loose rocks may be more suited for the Enhanced Gravity Tractor approach, but it may cause instability. Spin might also be a factor. As mentioned above, the timing of this mission is a critical element of the GT method. The mission must be launched at least a decade before the estimated impact of the asteroid (Olympio et al.). This approach is extremely slow, which is a large opportunity cost compared to other methods such as the Kinetic Impactor. Spacecraft design is another major component of this. The propulsion system must be ideal to maximize thrust while maintaining the spacecraft above the asteroid. In relation to this, there must be an ideal amount of fuel stored on the spacecraft. There could also be additional mechanisms for collecting rocks from the asteroid.

Gravity Tractor: Will it work for Bennu

The Gravity Tractor may perform more efficiently than the Kinetic Impactor method in deflecting the Asteroid Bennu. During the OSIRIS-Rex mission, a spacecraft landed on the surface of Bennu to collect a sample. However, it ended up sinking half a meter into the asteroid and creating a crater that was bigger than expected. This is because Bennu is extremely loosely packed. A kinetic impactor may go straight through it or fracture it into pieces, which wouldn't be ideal for future deflection missions. Furthermore, due to Bennu's non-uniform mass distribution, it is difficult for a kinetic impactor to find an ideal impactor point. Since the GT approach doesn't require any contact, it may be effective against Bennu. Bennu is also a relatively light asteroid, which would allow the GT mechanisms to be lighter and require less fuel.

Nuclear Standoff Detonation

The Nuclear Standoff method involves detonating a nuclear bomb near an asteroid in the hopes of vaporizing it or adjusting its trajectory. This method is suitable for more time-sensitive threats due to its higher momentum transfer compared to kinetic impactors and gravity tractors.

Nuclear Standoff Detonation: Overview of Techniques

Nuclear standoff detonation is unique among deflection strategies due to its impulsive nature, delivering a large momentum change over a very short duration. This makes it

especially effective in scenarios with minimal warning time (Dearborn et al.). While direct testing on asteroids has not occurred, extensive simulations and historical nuclear data inform its feasibility. These models incorporate asteroid properties such as density, porosity, and composition to estimate energy coupling and momentum transfer from x-ray and neutron irradiation (Ahrens et al.; Frazier et al.).

Figure 11 presents results from a broad range of orbital simulations evaluating different deflection strategies. It shows that for short warning times, nuclear detonation is the only viable method capable of significantly altering an asteroid's trajectory. Techniques such as kinetic impactors and gravity tractors require longer lead times to accumulate sufficient deflection (Frazier et al.).

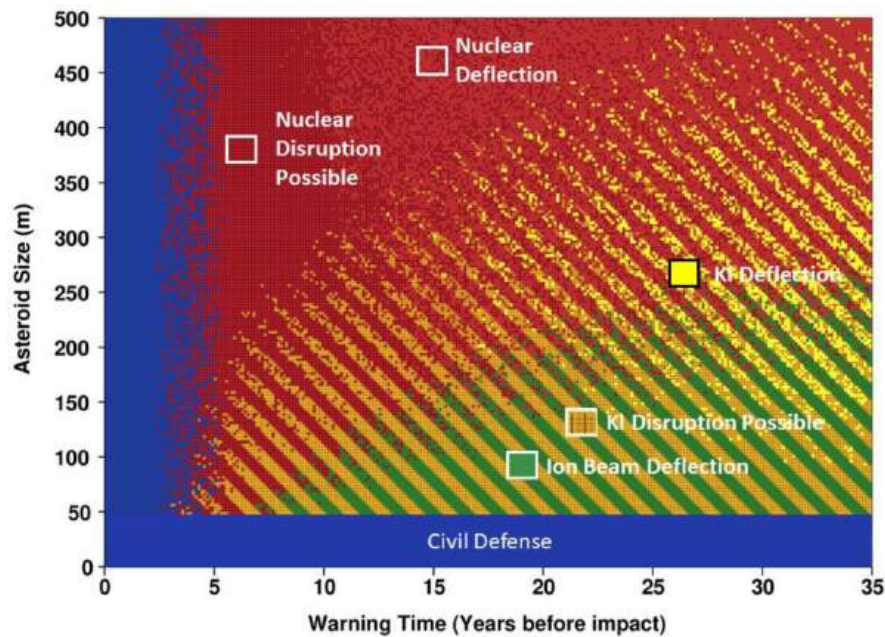


Figure 11: Deflection capability of various planetary defense methods over different warning times. Nuclear standoff detonation (top red zone) remains the most effective option for short-notice missions, particularly for large asteroids like Bennu. Kinetic impact and ion beam deflection (yellow and green) are only viable with longer advance warning (Frazier et al.).

Although effective, nuclear standoff poses risks of target fragmentation if energy exceeds a critical threshold. For Bennu, whose diameter is approximately 492 m, the simulations suggest that a properly scaled nuclear detonation could shift its orbit even with limited preparation time, providing a crucial last-resort option.

Nuclear Standoff Detonation: Factors to Consider

The Nuclear Standoff Detonation (NSD) method is reliant on more factors than the other methods discussed in this paper. There is an extremely high risk of asteroid fragmentation; inadvertent disruption can scatter debris, creating multiple smaller threats. It is important to manage the amount of energy released by the bomb because too much energy risks

fragmentation, while too little fails to adequately deflect the asteroid. The distance from the asteroid when it detonated is also significant.

The composition of the material is also important when considering NSD and determines how the asteroid reacts to radiation. Furthermore, porosity influences how the energy from a nuclear burst is absorbed and translated into deflection. Highly porous asteroids like Bennu may dissipate energy, reducing the efficiency of the deflection effort. Time is of the essence in all of these methods. If we were warned earlier, it enables the use of slower, controlled methods such as Ion Beam Deflection. Nuclear standoff becomes the fallback for short-notice scenarios, especially because the Outer Space Treaty prohibits nuclear explosions in space.

Nuclear Standoff Detonation: Will it work for Bennu

Bennu's size and low density makes the Nuclear Standoff Detonation (NSD) method a valid method for possible redirection. However, the porous surface of Bennu could absorb some of the blast energy, reducing the efficiency of momentum transfer. Additionally, carbonaceous asteroids, such as Bennu, require precise modeling because their composition and properties influence the effectiveness of any deflection technique. Bennu consists of numerous large boulders held together by gravity, and a nuclear blast might separate them, causing immense fragmentation. Due to this, multiple smaller nuclear blasts may be necessary. This may raise the opportunity cost of using the NSD method. There are many risks associated with using this method on Bennu; however, if the time constraint is small, it may be a necessary step in the protection of Earth.

Enhanced Yarkovsky Effect

The Yarkovsky Effect is a phenomenon that affects the motion of asteroids, and can potentially be harnessed in order to change the trajectory of an asteroid heading towards Earth. When an object absorbs sunlight, its surface warms up. As it rotates, it emits the absorbed heat as infrared radiation. This emission creates a tiny thrust because the photons carry momentum. Altering an asteroid's albedo can amplify the Yarkovsky effect, which is known as the Enhanced Yarkovsky effect.

Enhanced Yarkovsky Effect: Overview of Techniques

The leading method for how this principle could be applied is by coating the surface of an asteroid with a material, essentially changing the way photons interact with the surface of the asteroid and therefore the magnitude of the Yarkovsky effect (Fargion et al.; Katz et al.). The challenge is getting this material into space and onto the asteroid. One paper - Painting Asteroids for Planetary Defense - proposed applying a thin (0.1 micro-meter) reflective coating of lithium or sodium metal to the surface of the asteroid, dispersed as a vapor by an orbiting spacecraft. This metal sticks to the asteroid, as seen in Figure 2, forming a reflective layer that changes the force of solar pressure on it. The paper assumes that the vaporized material would effectively adhere to the surface of the asteroid and does not go into detail about how the spacecraft would generate or control the vapor (Katz et al.).

Separate researchers proposed using electrostatic forces to bind an ionized powder that changes an asteroid's albedo to the surface. The powder, either high-albedo or low-albedo, is ionized as it is dispensed, creating electrostatic attraction between the particles and the asteroid, which is naturally ionized. This ensures even distribution of the material despite there being no gravity in space. This method allows precise control of the asteroid's trajectory (Fargion et al.).

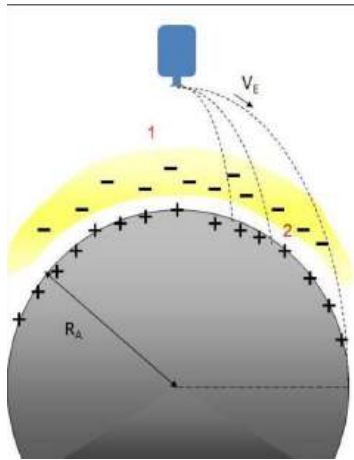


Figure 12: Demonstrates the electrostatic forces used to bind the ionized powder to the asteroid surface. They must be released at a high enough velocity to penetrate through the negatively charged cloud around the asteroid and reach the surface.

Enhanced Yarkovsky Effect: Factors to Consider

Models have revealed how the Yarkovsky effect alters the orbit of an asteroid due to its physical and thermal properties. The key factors influencing the effectiveness of the phenomenon are its spin state, surface material properties, thermal conductivity, and emissivity. However, engineered techniques could modify these properties to enhance the effect (Fenucci et al.).

It is necessary to consider whether to use a high-albedo material or a low-albedo material to coat the asteroid's surface in the Enhanced Yarkovsky Effect method. This depends on the spin state of the asteroid: Prograde or retrograde. Prograde rotation is when the asteroid rotates in the same direction as its orbit and thermal radiation creates a net force in the direction of motion, which increases the semi-major axis (pushing the asteroid outward, away from the Sun). Retrograde rotation is when the asteroid rotates opposite to its orbital motion and thermal radiation is emitted against the motion, resulting in a net force that decreases the semimajor axis (pulling the asteroid inward, toward the Sun). Different spin states require different modifications (high- or low-albedo materials) to enhance or counteract the natural Yarkovsky effect. To slow outward drift, apply a high-albedo (reflective) material to reduce heat absorption or use a low-albedo (dark) material to accelerate outward drift (Fenucci et al.; Katz et al.).

The physical properties of the asteroid are arguably the most important aspect of this technique. The properties of asteroid material, such as thermal conductivity and density, affect

how heat is absorbed and reradiated. The surface material and texture also play a role in allowing the coating of reflective materials to adhere properly. Additionally, smaller asteroids are more sensitive to the Yarkovsky effect because their mass-to-surface-area ratio is lower (Fargion et al.; Katz et al.).

Finally, this method takes an extremely long time – decades to centuries – to perform its intended goals. If there is a rapidly approaching threat, the Enhanced Yarkovsky Effect would not work.

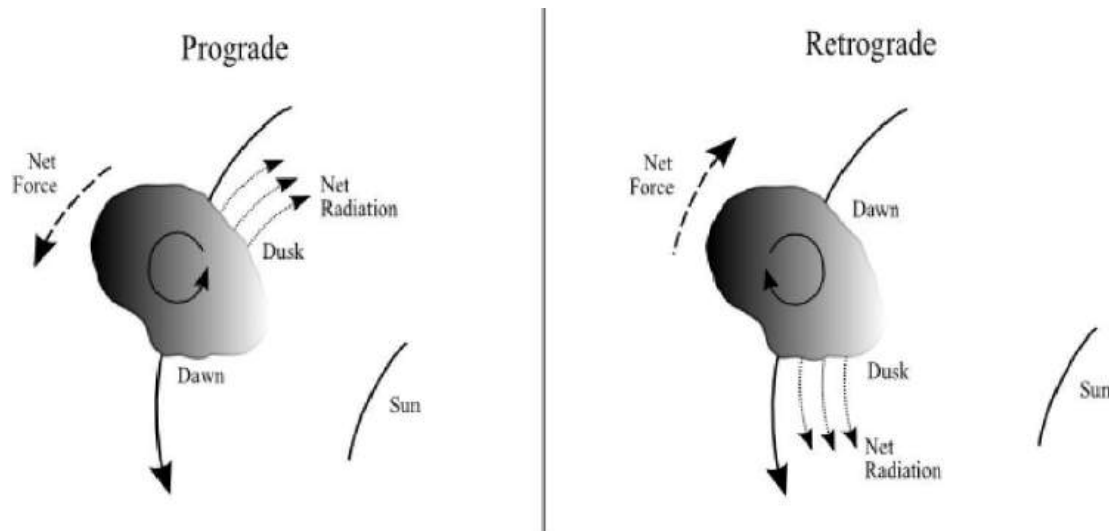


Figure 13: Provides a visualization for Prograde and Retrograde rotation. Left: A prograde-rotating asteroid emits more thermal radiation from its "dusk" side, creating a net force that pushes the asteroid outward, increasing its semi-major axis. Right: A retrograde-rotating asteroid emits more thermal radiation opposite to its motion, generating a net force that pulls the asteroid inward, decreasing its semi-major axis.

Enhanced Yarkovsky Effect: Will it work on Bennu

The Yarkovsky Effect is already a major factor in Bennu's orbit due to its retrograde rotation, small size, and highly absorptive surface, and it is a viable solution for a long-term deflection. However, Bennu's unique rubble-pile surface poses a challenge to get the albedo changing material adhered on its surface. Unlike a solid rock, Bennu's surface is composed of loosely packed boulders and dust, making it difficult for reflective coatings to adhere uniformly. However, the theory of using Electrostatic Powder to stick to the asteroid should fix this problem. While the Yarkovsky effect alone may not be sufficient for near-term deflection, it remains a highly viable long-term mitigation strategy on Bennu if enhanced and possibly paired with other methods such as the Gravity Tractor technique.

Conclusions

Asteroid Bennu has a unique set of physical properties: it is a B-type rubble-pile asteroid composed mainly of boulders and regolith. With a low cohesive strength (< 1 Pa) and low bulk density (~ 1190 kg/m³), the kinetic impactor method of asteroid deflection may not be the most obvious choice in this scenario. However, compared to the other methods discussed, a kinetic impactor emerges as, theoretically, the most pragmatic and effective mitigation strategy for Bennu.

Kinetic impacters have already been proven feasible by NASA's DART mission, which successfully changed the trajectory of a similarly composed asteroid. Many simulations have also shown that, despite Bennu's rubble-pile structure and low internal cohesion, the momentum transfer efficiency (β) from a kinetic impactor remains high, allowing a substantial deflection. Additionally, Bennu's mean diameter of 492 ± 20 meters places it within the effective range for the kinetic impactor strategy.

A major concern for using this method on rubble-pile asteroids is that a spacecraft might pass through the loose structure without significant energy transfer and potentially cause the asteroid to fracture into multiple dangerous pieces. However, designing a kinetic impactor with a large surface area helps mitigate this risk.

The risk of fragmentation is an even greater issue when considering the nuclear stand-off detonation method. While a well-placed nuclear explosion could deliver significant energy in a short amount of time, Bennu's frequent rotation could influence the trajectory of ejecta from the asteroid and may cause the energy to be absorbed unevenly. Additionally, this method is extremely imprecise.

The gravity tractor method also suffers from several major limitations when applied to Bennu. Despite being non-destructive, it is not optimal for an asteroid the size of Bennu. Furthermore, Bennu's irregular shape and the interference of other non-contact forces such as solar radiation pressure significantly reduce the method's efficiency.

Finally, the Yarkovsky Effect, while naturally occurring and enhanced by Bennu's low albedo, would require decades to centuries to produce a significant change in the asteroid's trajectory. Moreover, it is far too uncontrollable to serve as a practical deflection strategy.

Although no asteroid deflection method is perfect, the kinetic impactor strategy stands out as the most mission-ready and efficient solution for deflecting a rubble-pile asteroid. A well-designed kinetic impactor offers the best balance of precision and timely intervention, making it the optimal choice for planetary defense against Bennu.

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Engineering Inequality: How Designer Babies Reshape Society

By Ayush Dave

Introduction: The Pursuit of Perfection

In every corner of human experience, the quest for perfection manifests with relentless clarity. Before engaging in any given situation, humans have an “ideal” or perfect scenario that they anticipate or at least hope for. The same is true for parents, who dream about a preconceived notion of how their child will look, behave, and act. Imagine what the world would look like if parents could act on these preconceived hopes of the “ideal” offspring.

The parental ability to select or modify traits in human embryos through gene editing, often referred to as “designer babies”, will spark an upheaval of societal consequences including an increased wealth gap between the rich and working class that perpetuates systemic inequalities across generations, and the emergence of a genetically privileged class that will spark new societal norms around 'perfection', leading to an eventual reduction in genetic diversity.

The Rise of Designer Babies

In an era where science blurs the lines between natural and engineered, designer babies are no longer a possibility; they have become a reality. These “designer babies” refer to children specifically, engineered in vitro for specific traits such as enhanced intelligence or disease resistance, using CRISPR technology. Scientists all over either fear or look forward to these babies, but the one thing everyone can agree on is that their rise is quite plausible. It is often assumed that “designer babies” will offer a glimpse into a future where children are tailored to parental preferences, promising unparalleled human enhancements. This future first became visible back in 2018, when Chinese scientist He Jiankui claimed to have made the world’s first genetically engineered babies; he was later imprisoned for his research.

However, rising technological capabilities coupled with increasing public interest are bringing this future to the forefront of our society. Development of CRISPR-Cas9 and In Vitro Fertilization (IVF) technologies have significantly advanced our ability to make precise changes to DNA, even before birth. One of the primary motivations that drives this advancement in embryo editing is the potential to eliminate genetic diseases. This medical application is generally less controversial and could pave the way for more widespread acceptance of genetic editing.

The issue, however, is that one application will lead to another; in fact, it already has. Rather than assisting people to live better lives, the technology may eventually exclude them, a theory supported by the slippery slope. “The slippery slope is the idea that allowing certain forms of genetic engineering will open the door for them all since there is no clear cut distinction between therapy and enhancement” (Pugh 4). As awareness of genetic technologies grows, so does interest from potential parents who wish to give their children the best possible start in life, whether that means ensuring they are free of genetic diseases or selecting traits like intelligence or athleticism. To say that we have not generated successful enhancements since that of Jiankui would be a lie. These motivators have made sure of that. Few successful applications in disease mitigation and trait enhancement among designer babies have already

occurred, and may very likely become a societal norm in the future, at least for those with access to the technology.

Affordability and Inequality

The lack of access and affordability to gene editing technologies makes it so that only wealthy families can afford to enhance their offspring, in turn, widening socio-economic disparities. Gene editing is not a cheap practice and can be extremely expensive for people who elect to use it. The more impactful the “edit”, the steeper the price. George Fitzgerald, a Colby College author, illustrates this with the example of eye color selection costing parents upwards of \$2,000, highlighting a case from 2015, when a 36-year-old woman spent \$100,000 to ensure that she and her husband would have a baby girl. The issue, however, is that while she did indeed have the baby girl, not everyone can lay down tens of thousands of dollars on such modifications. Gene editing in embryos requires in vitro fertilization which is already an expensive process. The investment in research and development coupled with the cutting-edge nature of these technologies ensures that there are a limited number of facilities and experts capable of performing these procedures. This scarcity can drive up costs due to the principles of supply and demand. The price of gene editing isn’t going down anytime soon.

This financial barrier ensures that gene editing remains only accessible to wealthy, predominantly white demographics, essentially allowing them to buy better genes for their children while isolating historically marginalized communities. In a world where gene editing is becoming a norm, genetic modification in embryos will likely only be utilized by those with the means to improve physical capabilities, facial characteristics, and intellect. The field is a prime example of healthcare inequity, and its applications on designer babies exhibit a central part of the American dream: the drive for consumerism, or “the notion that you can spend your way to happiness” (Fitzgerald). The situation is often compared to that of plastic surgery, an expensive elective procedure to enhance one’s appearance, one that is typically not covered under insurance. The key difference, however, is that gene editing will entrench the inequalities that already exist in society.

A study conducted by the Pew Research Center found that of the surveyed group, 87% of U.S. adults agree that if gene editing to change a baby’s genetic characteristics becomes widely available, inequality will increase as the technology will only be available to the wealthy. In a society already grappling with accessibility issues for the underprivileged, CRISPR technology presents a pivotal dilemma, as it is exclusively accessible to the affluent. In a scenario where gene editing is a luxury only the rich can afford, we risk advancing toward a future characterized by genetically enhanced offspring who possess advantages such as higher intelligence, enhanced attractiveness, or innate talent. These traits could lead to superior job opportunities, fame, and further wealth accumulation, exacerbating the already widening gap in income inequality and the prevailing health disparities between the affluent and the less fortunate.

According to economics and technology journalist, Erik Sherman from Forbes, physical characteristics (including those attributed via genetic modification) do affect success. For example, “taller people tend to be more financially successful in life.” One study showed that over a 30-year career, a six-foot-tall person would make \$166,000 more than someone five-foot

five-inches (Sherman). It's no coincidence that "almost all Fortune 500 CEOs are at least six-foot two-inches tall", even though that is true of only 3.9% of the general population (Sherman). These studies demonstrate that physical beauty translates into higher earnings, as it is wrongly assumed that physical attractiveness has a strong correlation with competence and ability. This wrongful assumption coupled with the affluent's ability to edit the eye color, gender, or even height of their future offspring creates a world where income inequality may reach an unparalleled level. Sherman continues that intelligence could also become an engineered trait in time. While it transcends beyond genetics, "what you inherit is an enormous part of what you can eventually develop." In theory, the wealthy could "make it easier for kids to whip through school, standardized tests, and the other hurdles that surround academic achievement." Like intelligence and height, CRISPR technology could create a whole new array of Darwinian survival traits that would be exclusively accessible to the wealthy. The key issue with designer babies is that their edits may even be multi-generational, so these survival traits and income inequality could quite literally be passed down from one generation to the next. Changes made to the genome of an embryo affect every cell, which means its impacts can be passed to future generations and may be present in his or her descendants (Bergman). This effect quite literally perpetuates the cycle of poverty, as it provides the means "for those who already benefit from resource inequality to increase their access and share of competitive goods" (Nicodemo), clashing with certain theories of distributive justice. In the most simple terms, designer babies "will further advantage the already advantaged" (Cornetta et al. 2715). With only wealthy families being able to afford to enhance their offspring, socio-economic disparities would widen, creating a new dimension of inequality based on genetic traits, and possibly even leading to the emergence of a genetically privileged class.

The Threat to Genetic Diversity

Societal compulsion towards an "ideal" genetic standard may inevitably lead to a reduction in genetic diversity, increasing universal discrimination or stigmatization based on genetic modifications or lack thereof. "As people strive for perfection they can become blind to the consequences that may arise in spite of designer babies" (Fitzgerald). Gene editing allows parents to act on a preconceived idea of how their dream child may appear or even behave. This is because, in the creation of designer babies, CRISPR exhibits a "tantalizing offer to achieve the supposedly "best" kind of people at the genetic level" (Sufian & Garland-Thomson). As the technology advances and becomes more available, certain traits will begin to be viewed as biologically inferior, and human diversity may cease to exist. Often referred to as "genetic scissors", gene editing technology is steering in a direction to "eliminate rather than to treat genetic difference, we as a society would essentially instrumentalize this moralistic and reductionist assumption" (Sufian & Garland-Thomson).

Everyone with access to the technology would likely elect to have their child be over 6 feet tall, have bright blue eyes, and have the intellectual capabilities of Einstein. Dr. Christopher Gynnell, a research fellow in Biomedical Ethics, explains that "If we use germline gene editing overzealously, it may harm future generations, by removing valuable forms of human diversity." There is no doubt that genome editing is a powerful technology with the potential to reshape medical treatments and save many lives, but its applications on "designer

babies” will edit out all kinds of people that society has deemed either genetically contaminated or inferior. The reduction in genetic diversity costs everyone. “All members of a community contribute to its welfare by existing in their individual distinctiveness” (Sufian & Garland-Thomson).

This is because diversity, in all its forms, including disability, strengthens the global community by opening the public to a variety of perspectives, ideas, and experiences that contribute to overall growth and mutual flourishing. Dr. Gyngell’s research, published by the Journal of the Royal Society of Medicine, explains that humans both rely on and benefit from valuable forms of diversity. This can include immuno-diversity (diversity in the genes that influence innate immunity) and cognitive diversity (diversity in the genes that affect our cognitive traits). With 80% of U.S. adult respondents who partook in the Pew Research Center’s study agreeing that making a baby more intelligent is an example of taking the technology too far, it becomes clear that cognitive diversity, much like other forms of diversity, is essential for social order. In fact, among those with high science knowledge, only 24% found this application appropriate, and even they are not factoring in the long-term effects of a homogenous human population (Funk & Hefferon, 9). Wiping our species clean of “undesirable” traits could lead us to become a very placid species, one without diversity or edge.

A reduction in genetic diversity would also re-ignite previous forms of discrimination, further dividing our population based on this criterion of “genetic standing”. The pursuit of perfection via genome editing may lead to consequences, “potentially even resulting in two subspecies of human kind: the enhanced and the unenhanced” (Pugh 4). As the technology is used to create designer babies with enhanced qualities such as intelligence, musical talent, or athleticism we may experience diminished diversity of talent, personalities, or qualities in people. Overall tolerance for difference may be reduced. “The implications that arise in selecting your child’s genes causes people to look at someone as though they are ideal, or not ideal. Being born naturally would no longer be the norm and some may be alienated by people who boast the title of designer baby.” (Fitzgerald). The creation of this divide or the discrimination against non-designer babies is a frightening, yet perfectly possible future. Designer babies create a world where people are either perfect or flawed, and not only is this dominated by economic class, but it will further segregate marginalized groups. Segregation between society’s two groups, the enhanced and the unenhanced would reach an unprecedented level, as these groups, in theory, translate to the wealthy and the poor. Future generations may be subject to judgment not only for not being a designer baby but for the fact that they “don’t come from a family that is financially able to genetically modify their embryo” (Fitzgerald). With people already being discriminated against for their attributes today, dividing the world into classes of genetically perfect or flawed will perpetuate this stigmatization to an unprecedented level, where people will continuously be judged for their financial standing or lack of “ideal” traits. Designer babies encompass the idea that an “ideal” genetic standard exists, and its increasing prevalence would not only result in a reduction of global diversity but also a rapid increase in segregation and discrimination between two, ever more unequal, social classes.

Conclusion: A Divided Future

With gene editing capabilities at the forefront of innovation, designer babies have become a reality. Parents can picture their children in their dreams, and then simply paint them into existence. Yet, this magnificent capability has a dark side, a consequence that could disrupt the social order of human existence. The high price tag associated with designer babies ensures that they will only ever be available to the wealthy, widening socio-economic disparities and exacerbating income inequality over a multi-generational period. These babies can exhibit superior traits such as increased height, intellect, athleticism, etc. The possibilities are endless, but no matter what specifications each parent prioritizes in their custom order, the result will always be the same: another addition to the growing genetically privileged class.

As this practice becomes a norm, an ideal genetic standard will slowly be agreed upon by the elite. This pursuit of perfection would essentially eliminate genetic differences, as traits society has deemed genetically undesirable or inferior would be edited out. Inevitably, this would result in the loss of valuable forms of human diversity. With people being viewed as ideal or not ideal, superior or inferior, perfect or flawed, discrimination against those unable to access the benefits of gene editing would skyrocket. The world would segregate into two very unequal genetic classes: the enhanced and the unenhanced, scientific terms that unofficially translate to, the wealthy and the poor.

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Analysis of the Economic Impact of Consumer Coupon Policy to Recover Public Welfare in South Korea By Minchan Koo

Abstract

The South Korea government under new President Lee's administration has completed distributing the first round of consumption coupons, prepared through the second supplementary budget, to help restore and stabilize people's livelihoods by promoting local consumption. After the distribution, an online survey of small business owners conducted by the Federation of Small Businesses and the Federation of Korean Merchants showed that more than 75 percent of the small business owners thought that the consumption coupons were effective in inducing the use of traditional markets and alley business districts and believed that the use of consumption coupons would help boost consumption. This paper attempts to look into the political and administrative background of the government's consumer coupon policy and analyze and estimate its impact on the overall national economy along with the inflation effect in a quantitative and qualitative way.

1. Introduction

1.1. Theoretical background

Most countries became accustomed to spending more than they collected in taxes after the Great Depression of the 1930s. As evidenced by the term "sound fiscal policy" or "balanced budget," spending more than the taxes collected was considered a sound fiscal policy, making it difficult for governments to accept debt. The Great Depression, however, highlighted the need for fiscal spending that went beyond sound fiscal policy, and the man who provided the theoretical foundation for this was J. M. Keynes. Baker et al. (2020) noted that increased liquidity sustains personal consumption expenditure (PCE) and disposable personal income (DPI) because of the multipliers it produces. Keynes's proposed multiplier theory was quite groundbreaking for its time. However, for this multiplier effect to truly manifest, it necessitated that the released money continue to circulate, rather than being saved and stored away in the closet (Keynes, 1937). This is why the argument that when the government wants to distribute cash to its citizens, it should exclude high-income earners, who are more likely to save, has gained attraction. Monetarists believe that expansionary monetary policy could produce the desired outcome of stimulating economic activities in the long run. Milton Friedman (1968) argued that monetary policy could offset severe economic disturbances from other sources in the long run. Continuing this logic, it's not uncommon to see arguments that, rather than simply handing out money to the public, the government should directly purchase goods from the market, thereby boosting production and job creation. The argument is that if money were simply handed out to the public, some would undoubtedly squander it and leave it in their closets.

The South Korea government's distribution of consumption coupons reveals a profound consideration of the multiplier effect proposed by Keynes. A typical example is to give high-income people in the form of consumption coupons rather than cash so that they cannot save them instead of being completely excluded from the payment of consumption coupons. Additionally, the policy can prevent indefinite postponement of consumption by setting a

deadline and allowing them to be used by consumers closely related to daily life. Furthermore, the decision to pay more consumption coupons to low-income people is, of course, a social security consideration for low-income people, but the conviction that the multiplier effect will be accelerated because those who have relatively little room to save will run out of coupons faster must have worked.

Another condition to expedite the use of coupons is that the consumption coupons can only be used in the district area of the holder's address. This is to limit the multiplier effect to the space by allowing the purchasing power provided by the government to be consumed within a certain regional radius. This is because if money does not leave the region and circulates only within it, it will also directly contribute to the recovery of the local economy at risk of falling.

1.2. Opportunity cost of the coupon

The funding for about 10.7 billion dollars to issue the coupons is financed through the issuance of new government bonds, and a large part of it is financed through the supplementary budget. As a result, South Korea's national debt is expected to exceed 1 trillion dollars, and the ratio of national debt to gross domestic product (GDP) is expected to reach 49%. Eventually, this subsidy may help with immediate consumption, but the burden will remain intact as a debt that future generations will have to bear.

The concept to pay attention to here is 'opportunity cost'. When a budget of 10.7 billion dollars was invested in subsidies for people's livelihoods, it means that the same amount could not be invested in other areas. This cost is not just a number; it is a possibility of the future that we have not chosen. Take, for example, LG Electronics' current market capitalization is 9.7 billion dollars, employing about 74,000 people worldwide. The grants are large enough to buy an entire LG Electronics company. If the finances had been invested in high-tech industries or strategic companies, they might have created tens of thousands of jobs and continued to generate stable income for decades. Consumption disappears in an instant, but investment leaves a sustainable outcome (Dong A Daily 2025).

Some overseas cases also have great implications. During the COVID-19 crisis, Singapore focused on employment maintenance subsidies, investment in strategic industries, and vocational retraining rather than cash payments. As a result, the unemployment rate was managed at around 3%, and it succeeded in recovering quickly. There are many evaluations that the US's 'CARES Act (Coronavirus Aid, Relief, and Economic Security Act)' was more effective in terms of employment maintenance than simple cash payments (Yeo et al, 2021).

1.3. Current development of the policy

A month after the first distribution of the consumption coupons, President Lee in South Korea mentioned that the effect of consumption coupons for people's livelihood recovery has shown little by little and that it would be necessary to revitalize the second domestic demand, raising the prospect of another money-releasing measure to boost consumption.

However, some experts are concerned that another fiscal injection will not have a significant impact on boosting domestic consumption at a time when 10.7 billion dollars is invested in the payment of the consumption coupons. Seok Byung Hoon, an economics

professor at Ewha Woman's University, said, "It is more effective to directly purchase goods and services or invest in social overhead capital (SOC) than the government to inject money." In fact, according to the Bank of Korea's estimate, if the government spends 769 million dollars on transfer expenditure (income paid regardless of production activities), which sprays money at no cost, gross domestic product (GDP) will increase by 253 million dollars annually over three years. On the other hand, the Bank of Korea analyzed that if the government directly consumes goods, the GDP will increase to 700 million dollars and government investment such as SOC expenditure will reach 661 million dollars. Ahn Dong Hyun, an economics professor at Seoul National University, said, "Since we have limited financial capacity, we should stop saving consumption and start preparing a large-scale industrial policy."

Meanwhile, the financial burden of consumption coupons is concentrated on the high-income bracket. According to the data submitted by the National Assembly Budget Office and the Ministry of Public Administration and Security to Rep. Park Soo Young, the top 10 percent of income earners will pay 1.5 thousand dollars per person, 13 times more than the amount they received 115 dollars. This is because the top 10 percent of earners pay 77 percent of income tax. The top 10 to 20 percent of income earners will also have to pay 223 dollars considering the 11.6 percent income tax burden, which is 31 dollars more than the coupon amount (192 dollars). "The government is trying to easily win votes by distributing precious taxes to the entire population instead of spending them on productive sectors such as jobs or SOC," Rep. Park said.

2. Overview of the policy

2.1. Background and purpose

It is a very important task at this point to analyze in-depth the various effects of the government's consumer coupon policy for the recovery of people's livelihoods on the national economy and to estimate its economic effects and inflation-inducing potential quantitatively and qualitatively. The policy was designed as a financial countermeasure against the complex crisis situation, such as a prolonged slump in domestic demand, a decrease in real income of households due to high prices and high interest rates, and a deepening of business difficulties for small business owners and self-employed people.

The explicit goals of the policy can be summarized into two main categories. First, it serves as a priming point for short-term economic stimulus by directly stimulating shrinking consumer sentiment. Second, by concentrating the flow of funds on local small business owners rather than large companies or online platforms, it is to strengthen the foundation of the grassroots economy and maximize the effect of income transfer.

2.2 Funding structure

To achieve this goal, the policy has a very specific and elaborate design structure. The total fiscal input was set at about 10.7 billion dollars, similar to the total amount of the first emergency disaster support fund paid at the beginning of the COVID-19 pandemic in 2020. Most of the funds will be raised by issuing government bonds through the preparation of an additional budget, which inevitably entails debate over an increase in national debt and deterioration of fiscal soundness.

2.3 Payment structure and methods

The payment method takes a complex form in which the amount of support is differentiated according to the income level while maintaining a framework of universal support for all citizens. Specifically, in the first stage, 115 dollars per person is first paid to all citizens, and then in the second stage, an additional 77 dollars per person is paid to the rest of the citizens excluding the top 10% of income. In particular, a total of 385 dollars will be paid to basic living recipients and 308 dollars to the secondary poor and single-parent families, thereby providing thick support to the socially vulnerable. This is a policy direction that is in part consistent with the recommendations of the Organization for Economic Cooperation and Development (OECD) that the effect of boosting consumption is maximized when support is focused on low-income groups with high marginal propensity to consume (MPC) rather than saving when additional income is generated. Furthermore, the policy goal of balanced regional development was also explicitly included, including a provision to pay 23 dollars to non-metropolitan residents (excluding Seoul, Gyeonggi, and Incheon) and 38.5 dollars to residents of rural population declining areas (84 cities and counties). The receiving method was diversified to allow people to choose from credit and check card points, local love gift certificates in the form of mobile or tributary, and prepaid cards to ensure the convenience and choice of the people.

2.4 Redemption structure and restrictions

The most important variable that determines the macroeconomic effect of this policy is the strict restrictions imposed on the place of use and the period of use. This should be interpreted as an intentional policy design to artificially maximize the multiplier effect of fiscal input beyond simple administrative regulations. First, the use of coupons is strictly limited to small business owners and self-employed stores with annual sales of less than 2.3 million dollars. In principle, the use of large discount stores such as E-Mart and Lotte Mart, department stores, duty-free stores, large online shopping malls, and direct franchise stores such as Starbucks is excluded. This is a measure to minimize the 'leakage effect' in which financial subsidies are absorbed into large companies or lead to consumption of imported goods.

Second, the available areas are also limited to the metropolitan area or basic local government to which the address belongs according to the recipient's resident registration. This geographic restriction aims to create a chain-like income increase effect among small business owners in the region by inducing the invested funds to circulate as much as possible within the local economy. Third, the deadline for use is set relatively short until November 30, and the unused balance is extinguished and returned to the national treasury. However, in the case of tributary local love gift certificates, an expiration date of 5 years may be exceptionally applied. This short expiration date serves to strongly induce households to spend on immediate consumption rather than saving subsidies or using them to repay debts.

These three restrictions, namely business restrictions, regional restrictions, and time limits, interact to artificially increase short-term marginal propensity to consume, and are designed to speed up the circulation of money within the local small business economy. Therefore, this policy can be evaluated as an economic engineering attempt that is finely tuned

to maximize the short-term multiplier effect within a specific economic sector, not just cash assistance.

3. Expected policy effects and risks

3.1. Analysis of past similar policy case

In order to estimate the economic effect of these policies, it is useful to analyze the empirical results of similar policies in the past. The in-depth analysis of the first emergency disaster support fund implemented in the face of the pandemic in 2020 provides an important reference point. The Korea Development Institute (KDI) analyzed that the 11 billion dollar's worth of subsidies at that time caused a net increase in sales, ranging from about 26.2% to 36.1% of the input budget (Jeong, 2020). This figure means that a large part of the subsidy remained in the effect of substituting the consumption originally intended by households, but at the same time, it empirically shows that it has had a positive effect on the domestic economy by creating an additional consumption effect. Based on this past analysis, experts predict that the consumption coupon for people's livelihood recovery will have a similar level of boosting consumption. Some predict that the marginal propensity to consume could range from about 40% to a maximum of 50%. Meanwhile, the National Assembly Budget Office analyzed that the production inducement coefficient of the first disaster support fund reached a maximum of 1.81 times (the 22nd National Assembly's policy briefing). This means that the input of one unit of finance caused 1.81 units of production in the economy as a whole, and a high ripple effect was observed in industries with high concentration of small business owners, especially restaurants, lodging businesses, wholesale and retail businesses, where benefits were concentrated due to restrictions on usage.

Past data consistently show that the short-term effect was very clear, with credit card sales soaring immediately after the disaster support was paid and the consumer sentiment index improved. However, these positive effects clearly revealed the limitations of the so-called "sparkling effect" that rapidly disappeared after the expiration date was imminent or ended and left fundamental questions about the continuity of the policy (Baker et al, 2023).

However, when analyzing the effect of this consumption coupon, a macroeconomic context different from that of 2020 must be considered. Since the 2020 disaster support fund was implemented under strong restrictions such as social distancing, consumption tended to be concentrated on the consumption of semi-durable goods such as clothing and furniture and commodities such as essential goods rather than the service industry, where face-to-face contact is essential. The KDI study also pointed out that the subsidies at that time had a limited effect on recovering sales in the face-to-face service industry such as food, travel, and sauna (Kim and Oh, 2021). On the other hand, restrictions on face-to-face activities have completely disappeared. Rather, the potential demand for services such as eating out, beauty, academies, and leisure activities in the region, which has been suppressed for a long time, may be high.

In addition, since this consumption coupon is designed to fundamentally exclude online shopping and induce face-to-face payments in the region, a much larger proportion of the subsidies are likely to flow into the service industry run by small business owners than in the past. Therefore, even though the overall multiplier effect size is similar to the past, it is estimated that the distribution of benefits by sector will move from product to service industry,

which will have a more direct and visible effect on revitalizing the 'alley commercial district' originally intended by the policy.

3.2. Short-term economic revitalization and livelihood recovery

The consumption coupon policy aims to promote short-term consumption and recover economic power centered on small business owners through a short period of use and strict restrictions. In anticipation of a 26-36% increase in net sales compared to the input budget due to the short period of use until November 30, it is forecasted that there will be an increase in sales of small business owners with annual sales of less than 2.3 million dollars, excluding large franchise retailers and online shopping malls, resulting in alleviating income inequality and promoting balanced regional development and economic circulation through additional support for vulnerable groups.

Small business owners and self-employed people, who are the direct beneficiaries of these policies, are generally expressing expectations for increased sales. In particular, the restaurant industry, such as convenience stores, local marts, and chicken restaurants, experienced a clear increase in sales during the payment of disaster support in the past, so they are expecting a similar special this time. In the self-employed community, there are both expectations that the effect will be temporary and concerns that it will eventually return to the burden of inflation. On the other hand, large retailers such as hypermarkets and department stores, which are excluded from use, are moving to defend against customer churn through large-scale discount events, fearing a decrease in sales caused by consumers moving their purchases to use consumer coupons. This is a phenomenon that proves that the effect of income transfer between sectors intended by the policy is actually working.

3.3. Estimating consumption stimulation and contribution to GDP

Based on this, it is possible to estimate the expected economic effect and contribution of the consumption coupon to GDP. The government and some research institutes expect that the fiscal expenditure through the supplementary budget will increase the GDP growth rate by about 0.2% this year. In addition, the Democratic Research Institute under the Democratic Party of Korea argued that the 10.7 billion dollars subsidy could raise GDP from 0.2% to 0.4%, and Hanyang University professor Lee Jung-Hwan predicted the effect of raising the growth rate by up to 0.32%. This estimate is based on the concept of a fiscal multiplier. However, according to a past study by the Bank of Korea, the fiscal multiplier of transfer expenditures such as disaster subsidies is 0.33, which is relatively lower than government consumption (0.91) in which the government directly purchases goods or government investment (0.86) in social overhead capital. This is the basis for criticism that even if the same fiscal expenditure is invested, the economic stimulus effect of the transfer expenditure method may be inefficient compared to other fiscal policy measures.

3.4. Inflation risk

Although there are legitimate expectations for the positive effects of the policy, inflation risks must be carefully evaluated, which may arise when enormous liquidity of 8.5 billion dollars is intensively supplied to a particular sector of the economy in a short period of time.

Concerns have been steadily raised in academia and markets about the so-called "coupon-flation," in which demand for goods using coupons exceeds supply of food and other necessities and causes inflation to rise. These concerns are based on past experiences, not just imaginary worries. In fact, after the first disaster support fund was distributed in 2020, as the purchasing power of households temporarily increased than usual, the demand for some high-end food materials such as Korean beef and pork belly surged, and the price of the item soared in the short term. This is a clear example of how if subsidies are concentrated on specific items, it can cause local price instability in areas where supply is inelastic.

Abramain (2023) found in his research that while Federal stimulus and monetary policy initiatives were crucial in mitigating the immediate economic downturn caused by the pandemic, they have also contributed to the current inflationary environment. Furthermore, from a macro perspective, the fact that most of the policy's resources depend on government bond issuance is also pointed out as a factor in long-term price instability. The issuance of government bonds means an increase in national debt, and deterioration of fiscal soundness can stimulate "expected inflation" by forming expectations for increased tax burdens or monetary evaporation in the future. According to a fiscal study by the Korean Association of Public Finance, a 1% increase in government debt when other conditions are constant can increase consumer prices by up to 0.15% (Lee et al, 2025).

However, the counterargument that the impact will be limited on these inflation-inducing concerns is also quite persuasive. The Bank of Korea officially assessed that the impact of the supplementary budget on prices will be limited, but rather, it contributes to growth to boost the sluggish economy. Specifically, it was also predicted that if an extra budget of 10.7 billion dollars is spent, it will only increase the consumer price index by about 0.1% next year. There are several important grounds for this judgment. First, the Korean economy is currently experiencing a lack of effective demand due to high interest rates and a decrease in real income, that is, a lack of effective demand due to high interest rates and sluggish domestic demand. Therefore, since there is considerable idle production capacity throughout the economy, there is more room for the increase in demand due to consumption coupons to be absorbed by the increase in production using idle facilities and manpower rather than leading to an immediate price increase. Second, the payment of consumption coupons is fundamentally different from quantitative easing in which the central bank directly issues money and releases it on the market. Since the government absorbs the funds of commercial financial institutions or individual investors through the issuance of government bonds and transfers them to other economic players, it does not change the total monetary volume (M2) of the entire economy itself. Third, it is important that the place of use is strictly limited to small business owners with annual sales of less than 2.3 million dollars, excluding hypermarkets and online shopping malls. This suggests that inflationary pressure is more likely to be only temporary price fluctuation limited to some popular items or services, rather than spreading throughout the economy. This policy design is distinct from the case of the United States or Europe, which suffered severe inflation due to large-scale cash aid, and rather, it is possible to find similarities with the case of Hong Kong, which achieved the effect of boosting consumption without stimulating prices by paying consumption vouchers with limited use.

4. Arguments for and against the policy

4.1. Evaluation of the policy

Among these conflicting views, the prudent approach proposed by the Korea Development Institute (KDI), a national research institute, raises the issue of policy timeliness and provides an important analytical perspective. KDI's position has dual perspectives that appear to be contradictory to each other superficially. Therefore, understanding those views thoroughly would be the major factor to the policy evaluation. KDI empirically analyzed that disaster subsidies in 2020 affected the increase in consumption (26.2% to 36.1%) to a certain extent through past studies and recognized the mechanical effectiveness of the policy. On the other hand, in recent years, fiscal expenditure policies for the entire population, such as the Public Welfare Recovery Support Fund, have been strongly criticized for the strategic inadequacy of the policy, arguing that they are not currently necessary or they may disrupt the trend of stabilizing inflation. This is the result of KDI's shift of focus on analysis from the mechanical effect of the policy to suitability with the macroeconomic context. In other words, the logic of KDI can be reconstructed as follows (KDI Monthly Economic Trends 2025).

Since 2020 was a situation of extreme demand shock caused by the pandemic, the top priority was to increase consumption by investing finance even at the expense of some inefficiency. However, currently, price stability is still an important policy goal, and the economy is showing signs of a gradual recovery, mainly in exports. In this situation, short-term stimulus measures through large-scale fiscal expenditures are at greater risk of damaging the price stability stance and delaying the timing of the base rate cut than their effects. After all, KDI points out that just because a policy tool is effective to achieve a particular goal, it does not mean that it is an appropriate prescription for all economic situations (Kim and Lee, 2021).

4.2. Issues with universal and selective subsidy

Beyond the analysis of these economic effects and risks, the consumer coupon policy for the recovery of people's livelihoods brings fundamental questions about the long-disputed issues including universal and selective subsidy, the role of finances, and the economic growth model back to the surface. This policy has chosen universal and selective subsidy, paying all citizens but in different amounts based on their disposable income. The payment strategy intends to compromise the advantages and disadvantages of universal and selective subsidy.

Selective subsidy has the obvious advantage of maximizing financial efficiency by concentrating limited financial resources on the most urgently needed vulnerable groups. However, the enormous administrative costs that arise in the process of selecting targets for support, the technical difficulties of accurately identifying income and assets, and the constant social conflict over the fairness of standards are serious problems. For example, there were more than 460,000 objections to the policy because the upper income class was excluded based on health insurance premiums when the COVID-19 disaster support fund was distributed in 2021, which demonstrates the seriousness of this problem (Kim and Ho, 2020).

In addition, a reversal of income can occur for those who are in the borderline class that is narrowly eliminated from the eligible subsidy group. Receiving the subsidy can be misperceived as the effect of social stigma, which is a sign of poverty in itself, which is another

fundamental limitation of the selective subsidy. Meanwhile, universal subsidy has an advantage of reducing the administrative and social costs and cultivating a sense of community that all citizens are equal members. However, the policy cannot be free from the criticism of fiscal waste of unnecessary support even to the high-income class and the problem of increasing the national financial burden.

4.3. Theoretical controversy on the financial role of the government

In the end, this debate results in differences in theoretical perspective on the role of national finance and sustainability. Relying on the issuance of government bonds worth about 11 billion dollars directly increases the national debt, which is the strongest argument raised by those who value fiscal soundness. They strongly criticize that it is an irresponsible populist policy to pass on debt to future generations for short-term and temporary effects. This view is clearly supported by the point that there would be no poor country in the world if money can be sprayed to save the economy. In response to this criticism, proponents refute that, if the current severe public welfare crisis and economic downturn are left unattended, enormous amounts of social and economic costs, such as unemployment, business closures, and intensifying inequality, may occur and become a greater burden to the government in the future. Therefore, it is argued that overcoming the current crisis through the active economic control function of finance is rather strategic investment for the future.

At this point, the debate on consumption coupons for people's livelihood recovery leads to fundamental reflections on the growth model of the Korean economy, beyond simply evaluating the effectiveness of fiscal policy. Opponents criticize that such cash subsidy is only a temporary and short-sighted measure that does not solve the structural problems in the Korean economy, such as excessive competition for small-medium businesses or failure to adapt to digital transformation. From their point of view, consumption coupons are like a harmful anesthetic that avoids and delays painful but essential structural reforms.

On the other hand, proponents argue that we should face the reality that the trickle-down effect of the export-led growth model no longer exists as it did in the past. Proponents also think that consumption coupons for people's livelihood recovery can be considered a strategic investment that seeks to shift to a new economic model which balances exports and domestic demand, beyond simply beneficial measures to help households in need. In other words, it is an attempt to improve the constitution of the economy and increase resilience to external shocks by strengthening the weakened domestic base. As such, the consumption coupon policy has become one of the most controversial issues in public administration in which two different diagnoses and prescriptions collide with each other when it comes to the direction of the Korean economy.

5. Limitations and Implications of the Policy

Consumer coupon policy for the recovery of people's livelihoods can be a significant potential policy to exert the effect of boosting consumption in the short term and locally and increasing sales of small business owners through sophisticated design which limits where they are used, regions, and periods. The results of empirical analysis on similar policies in the past support that this effect is not just a possibility but can actually occur. One of research found that

over 30% of households across all income groups increased their food and overall household spending (Kim and Lee, 2020)

However, the effect of the policy might be temporary in nature and has a clear limitation that it can cause a 'consumption cliff' phenomenon, in which consumption shrinks again after the implementation policy is completed. It can also bring the risk of local inflation and the undeniable cost of increasing national debt. Therefore, the success of the policy will depend on whether the shrinking sentiment of economic players can be restored and the self-sustaining consumption and investment cycle of the private sector can be restored before the short-term stimulus effect expires. In other words, whether consumption coupons can successfully play a 'bridge' role for economic recovery beyond simple 'life-saving treatment' will be a key criterion for policy evaluation.

6. Conclusion

In conclusion, relying on this repetition of short-term transfer spending policies is not a sustainable solution. Long-term and consistent policy efforts must be made to solve fundamental structural problems facing the Korean economy, such as structural excesses of self-employment, deepening income inequality, and the absence of new growth engines. In addition, the development of a balanced domestic economic demand market structure that does not rely on export-led growth should be sought. The organic linkage between short-term financial support and long-term structural reform policies should be tightened and strengthened.

Consumer coupons for public welfare recovery are recognized for short-term economic stimulus effects but can only serve as catalysts for true economic recovery if they are combined with long-term and consistent policy efforts to solve fundamental structural problems. The final evaluation of this policy will be based on whether it ends up being a productive investment that buys valuable time for this long-term structural transformation or a nonconstructive debate that does nothing but delays the transition to the long-term structural transformation.

Policy can be considered the art of choice among many political options. This time, the South Korean government decided to choose a cash sharing option with the entire nation and believes that the result will be effective and beneficial to both the citizens and the economy. However, the government must clearly recognize that the option can become a financial burden to future generations at the same time. It must also remind that there are opportunity costs which can be used in other alternatives for the similar purpose. After all, the government decides where and how the budget should be spent. I hope that the release of money for consumption coupons, which has been launched despite the deficit, will respond with a great multiplier effect that ignites the leap of the economy of South Korea.

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Using Models of Market Structures to Understand the Dairy Industry Restructuring Act's Impact on Fonterra's Domestic and International Activity

By Hankai Alex Shao

Abstract

The dairy industry is a cornerstone of New Zealand's economy. Within this sector, Fonterra processes over three-quarters of all the milk production and also serves as the nation's leading exporter. However, this dominance does not go without regulation. The Dairy Industry Restructuring Act 2001 (DIRA) was implemented to pursue two conflicting objectives: enabling Fonterra to be competitive on the international market while protecting domestic consumers from excessive prices. This research paper analyses and evaluates the effectiveness of DIRA in achieving these objectives through the application of three microeconomic market structures: monopoly, Cournot duopoly, and threat of entry. The findings support that a monopoly would provide Fonterra with sufficient profit to fund international expansion but would be at the expense of domestic consumers. On the contrary, a Cournot duopoly would hinder Fonterra's global competitiveness but generate better prices for domestic consumers. Finally, the threat of entry model emerges as the most balanced outcome, as it preserves Fonterra's capacity to compete internationally while incentivising lower prices to deter new entrants. In combination, these findings illustrate how DIRA has shaped a regulatory equilibrium within the dairy industry in New Zealand and why DIRA has opted to create the market structure with the threat of entry.

Introduction

New Zealand's dairy industry plays a significant role within the nation's economy. For example, in 2021, New Zealand's dairy exports were valued at \$18.6 billion NZD. Alone, this portion of international trade contributed to 5.3% of nominal GDP (Anderson, 2022). At the heart of New Zealand's most significant industry is Fonterra, which is a cooperative owned by local farmers. In the 2024/25 season, Fonterra processed the majority of the nation's total milk production, amounting to 77.7% (Dairy News, 2025).

In order to facilitate the creation of the cooperative Fonterra, the Dairy Industry Restructuring Act 2001 (DIRA) was enacted by the New Zealand government. This act intends to create international competitiveness for dairy through economies of scale, while simultaneously ensuring domestic consumers are protected and unharmed (Ministry of Primary Industries, 2018). The balance between these partially conflicting objectives is crucial to the success of the dairy industry as a whole. Selling to the international market is proven to be beneficial for Fonterra. With higher prices and a larger market, Fonterra can significantly benefit from economies of scale. They will be able to draw in more revenue and profit. However, for this study, there will be an assumed cost of entry into the international dairy market that Fonterra must pay.

Currently, DIRA employs one main method of regulation on Fonterra. This is the compulsory provision of raw milk to local competitors for a regulated price. It is stated that up to 5% of the raw milk Fonterra collects from dairy farmers across the nation must be sold to competitors for a regulated or agreed price (Cossar, 2012). Fonterra is still dominant with

77.7% of all milk production in the 2024/25 season (edairy News, 2025). Is the present market structure the best possible outcome for DIRA's regulation?

This paper addresses the research question: Is DIRA successful in empowering Fonterra's international competitiveness while protecting domestic consumers? To answer this question, three market structures will be analysed. They include monopoly, Cournot duopoly, and threat of entry. Monopoly and Cournot duopoly are alternative market structures that can be achieved naturally and through intervention. The threat of the entry model is the current market situation. The three market structures will be analysed through microeconomics and compared to form a conclusion.

Theory

In this analysis with various models, there will be a regulator who must decide whether the dairy market will be a monopoly, a Cournot duopoly, or a large firm with the threat of entry. This regulator is the New Zealand Government. The regulator aims to balance two objectives. The first goal is to allow a firm, Fonterra, to be large enough to pay the fixed cost of entering the international market and earn some fixed profit from that market. The second conflicting objective is to keep prices reasonably low for the domestic market. The profit from the large firm will be analysed in the three different market structures for an assessment of the first objective. On the contrary, the domestic prices will be analysed to determine the achievement levels of the second objective for each market structure. Finally, the two results can be synthesised to determine what market structure best balances both objectives of the regulator.

Monopoly

The implications of allowing Fonterra to become a monopoly in the domestic market will be analysed. The two areas of analysis are the profits as it relates to the ability to pay for Fonterra to pay the international market entry fee and the domestic prices as it directly affects local consumers.

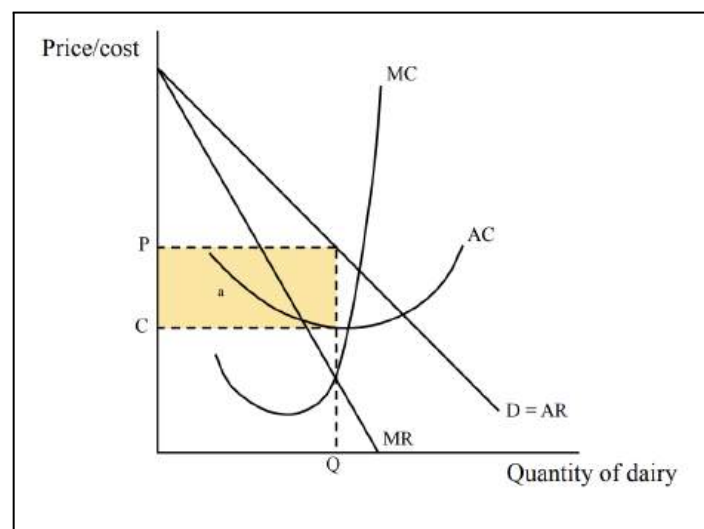


Fig 1: monopoly

As a monopoly, Fonterra is able to make supernormal profits. In this monopoly model, average cost (AC) increases when marginal cost (MC) becomes greater than AC. Normally, monopolies maximize profit by producing the output quantity at the point where marginal revenue (MR) equals MC. Being the most dominant firm in the industry, Fonterra would be price makers. This would cause the price of dairy products to be set above the MC. This causes the cost (C) to be less than the price (P), resulting in supernormal profits from Fonterra. These profits are represented by the area a, which shows the difference between total revenue ($P \times Q$) and total cost ($C \times Q$). With high profits, Fonterra can easily pay for the international market entry fees and compete outside of the domestic market.

The market structure as a monopoly leads to high prices for consumers in the domestic market. Being the most dominant firm with a lack of competition, Fonterra are free to act as price makers. Due to self interest, the prices will be high to maximise profit for Fonterra. Given that dairy products have a high necessity within the lives of domestic consumers, this high price is extremely harmful.

Cournot Duopoly

Next is the Cournot duopoly model which demonstrates a market structure. In this scenario, two firms choose quantities of output simultaneously. For this study, the two competing entities will be Fonterra and other competitors such as Synlait or Open Country Dairy.

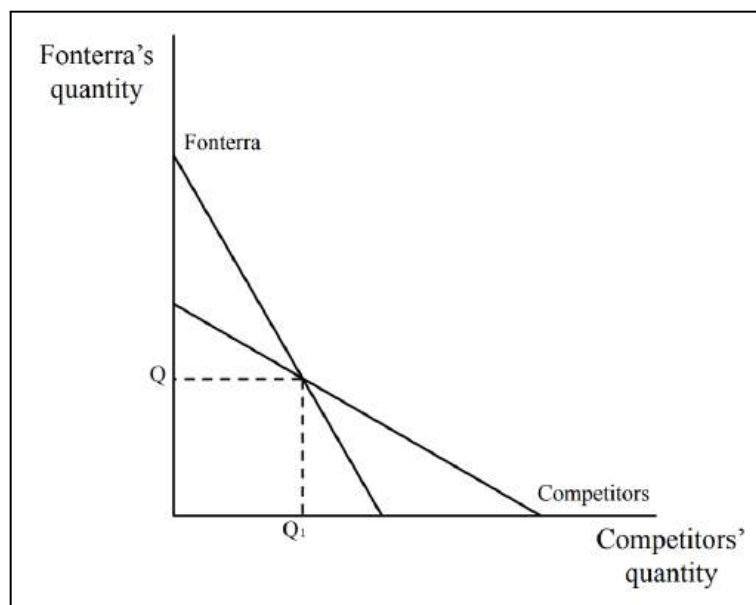


Fig 2: Cournot duopoly

In the market structure of Cournot duopoly, Fonterra will make a relatively low amount of profit. This model assumes that firms compete on output, independently make decisions simultaneously, and total market output determines total price. The horizontal axis represents the competitors' output, while the vertical axis represents Fonterra's output. The downward-sloping reaction functions show how each firm adjusts its quantity based on the

assumed output of the other. The point where the two reaction curves intersect is (Q_1, Q) , which represents the Cournot Nash equilibrium. Here, neither firm can increase profits by changing output, resulting in negligible incentives. As Fonterra is unable to freely set prices, their profit is reduced significantly. This hinders Fonterra's ability to pay the international market entry fees.

Under a Cournot duopoly, domestic prices will be lowered significantly. The competition within the market applies downward pressure on prices as firms compete with the quantity produced. Thus, consumers will have more choice and be required to pay lower prices.

Threat of Entry

Another possible regulatory outcome is the threat of entry situation. In this model, there are market entry opportunities for competitors. The barriers of market entry are limited but not negligible. Thus, Fonterra are forced to act strategically, setting prices low enough to disincentivise competitor entry. Under the threat of entry, full market dominance is contestable, even if actual large-scale entry remains unlikely.

For Fonterra's profit, it will be moderately limited. As other firms can enter the market with relative ease, high prices will attract more competition, negatively affecting Fonterra's dominance. With the threat of entry of other firms, Fonterra will lower prices to remain competitive and attract consumers. The decrease in prices will then cause Fonterra's profits to fall, weakening its ability to pay the international market entry fees.

Under the threat of entry, domestic prices will also be lowered. Fonterra will be unable to set high prices to earn supernormal profits, as doing so would risk attracting new competitors into the market. Instead, the firm must adopt a more cautious pricing strategy to deter entry. This practice, known as limit pricing, helps maintain Fonterra's dominant position by making market entry less appealing to potential rivals. For domestic consumers, this leads to lower prices and improved affordability of dairy products.

Comparison

A comparison of the three different market structures caused by possible regulation will be compared. The comparison between Fonterra's profits and domestic prices can be made to reveal the different regulatory outcomes.

The profits are evidently the highest for Fonterra under a monopoly market structure. The profits are the lowest in a Cournot duopoly model. Finally, the profits are in between that of a monopoly and Cournot duopoly with the threat of entry.

The domestic prices of dairy products are the highest if Fonterra acts as a monopoly. These drop significantly in a Cournot duopoly. Again, the prices in the threat of entry model lie between monopoly and Cournot duopoly.

The results from the comparison suggest that the threat of entry market structure is the most optimal result of regulation. The New Zealand government would be able to balance the dual objectives of enabling Fonterra's international competitiveness while keeping domestic prices low. In this model, Fonterra can earn moderate amounts of profit, enabling it to enter the international market. However, with low barriers to entry, Fonterra lowers prices to disincentivise competitors from entering the market, maintaining its dominant position.

Conclusion

The current regulation of Fonterra by Dira positions Fonterra in a dominant position. This is represented by the large milk processing Fonterra undergoes, including 77.7% of all milk production in the 2024/25 season (Dairy News, 2025). However, Fonterra does not operate as a monopoly and is unable to set prices freely. DIRA lowers the barriers of market entry for competitors by forcing Fonterra to sell up to 5% of its raw milk supply to competitors for a regulated price (Cossar, 2012).

Out of the three market structures analysed, this current situation aligns most with the threat of the entry model. This is because DIRA is lowering the barriers to market entry and pushing Fonterra to lower prices to discourage competitors from entering the dairy market. As a result, DIRA achieves a balance between the two objectives of allowing Fonterra to gain enough profit to pay the international market entry fee while maintaining reasonably low domestic prices.

DIRA plays a pivotal role in shaping the structure and outcomes of New Zealand's dairy industry. In particular, it determines the role Fonterra plays. Through examining three market structures, monopoly, Cournot duopoly, and threat of entry it becomes clear that each offers distinct trade-offs between supporting Fonterra's international competitiveness and protecting domestic consumers. Under a monopoly, Fonterra generates the highest domestic profits, enabling significant investment in international markets. However, this comes at the cost of high prices and reduced surplus for domestic consumers. In contrast, a Cournot duopoly fosters domestic competition and consumer surplus through lower prices and product diversity, but leaves Fonterra with diminished profit that may hinder its ability to fund costly international market entry. The intermediate scenario, where Fonterra operates under the threat of entry, emerges as the most balanced model. It allows Fonterra to maintain sufficient profitability to invest abroad, while DIRA's regulatory provisions ensure that domestic prices remain fair and market power is kept in check. This analysis shows that DIRA has successfully crafted a regulatory framework that positions Fonterra between monopoly and Cournot duopoly, preserving New Zealand's dual objectives. By mandating the supply of raw milk to independent processors and keeping barriers to entry contestable, DIRA creates a disciplined environment for Fonterra without stripping it of the market power required to compete globally. The threat of the entry model achieves a pragmatic compromise, encouraging innovation, deterring anti-competitive behavior, and sustaining global competitiveness. In a globally competitive industry with significant fixed entry costs, this regulatory equilibrium is essential not only for Fonterra's success but for the broader health of the national economy. The threat of the entry model explains why the regulation of DIRA was chosen and implemented. With DIR, the New Zealand government can effectively balance and meet its dual objectives within the dairy industry.

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Biases In Medical Decision Making By Ece Marangoz

Abstract

The healthcare sector presents high-pressure, time-sensitive decision-making environments, where clinicians are often required to make swift judgments. Among the most prevalent are confirmation bias, the tendency to seek or prioritize information that supports pre-existing beliefs, and anchoring bias, the overreliance on initial information when forming diagnoses. Both can significantly distort judgment and compromise patient care. This literature review explores how these biases contribute to distortions in clinical judgment. Drawing on behavioral research and case-based examples, the literature review argues that longstanding issues in medical error and misdiagnosis may be better addressed by incorporating bias-awareness into health policy and clinical practice. Emerging bias-aware technologies that account for human cognitive limitations offer promising avenues for improving diagnostic accuracy and reducing errors in clinical settings.

Key Words Confirmation Bias, Anchoring Bias, Diagnosis, Emergency, Systematic.

1. Introduction and Background

Traditional economic theory assumes decision-makers act rationally and with complete information. Behavioral economics, however, challenges this by recognizing the systematic cognitive biases and irrational tendencies that often influence real-world choices. The health sector offers a rich area for behavioral economic analysis, considering the complex choices involved, the urgency of decisions, and the significant reliance on expert guidance. Healthcare decisions often take place under stress, uncertainty, and a lack of balanced information between patients and providers. Moreover, healthcare often involves 'credence goods'—services whose quality is difficult to assess even after they've been used. This makes patients particularly reliant on a physician's judgment. Behavioral economics helps us understand these dynamics by showing how heuristics, framing effects, default options, and biases like confirmation and anchoring can distort medical decision-making. The consequences of such distortions are far from theoretical. A 2023 study published in *BMJ Quality & Safety* estimates that approximately 371,000 people die and another 424,000 are permanently disabled each year in the United States due to diagnostic errors—totaling nearly 800,000 people experiencing serious harm annually (Merelli, 2023). As David Newman-Toker, the lead author and director of the Center for Diagnostic Excellence at Johns Hopkins, notes, misdiagnosis may be the most common cause of death or disability from medical malpractice, though many cases go undetected and the true number could be even higher (2023, Newman-Toker). As emphasized in *Nudge* by Thaler and Sunstein (2008), health has long been a central domain for applying behavioral interventions like default options and planning prompts to improve public health outcomes. For example, behavioral tools such as 'nudges' have successfully improved public health outcomes, from increasing vaccination rates through default appointments to enhancing medication adherence with automated reminders. These interventions utilize insights from concepts like loss aversion,

status quo bias, and time-inconsistent preferences to guide individuals toward healthier behaviors. Despite these successes, many aspects of clinical decision-making are still underexplored from a behavioral economics perspective. This literature review aims to investigate how specific cognitive biases—confirmation bias and anchoring bias—influence medical decision-making, particularly in high-stakes clinical environments. In doing so, it contributes to a growing body of work that challenges the assumption of rationality in professional judgment and highlights the need for bias-aware frameworks in medical practice. In the following sections, this article first examines confirmation bias in clinical contexts, outlining its psychological underpinnings, and illustrates its impact through research examples such as emergency medicine case studies and Alzheimer's biomarker studies. It then analyzes anchoring bias, detailing empirical evidence and real-world diagnostic delays, with an emphasis on high-risk settings such as emergency departments. For each bias, it examines proposed mitigation strategies at both the individual and system levels, including metacognitive training, diagnostic timeout, and bias-aware decision support tools. The discussion concludes by integrating these findings into a broader framework for designing healthcare environments that reduce diagnostic error while respecting the role of clinical intuition.

1.1 The Unique Environment in Healthcare

Healthcare is a unique intersection of economics, psychology, and high-stakes decision-making. While most people imagine hospitals, doctors, and patients when thinking of healthcare, the system extends far beyond its physical components. Becoming a physician is a long, demanding journey: students first take rigorous coursework and the MCAT, then enter four years of medical school, followed by 3 to 7 years of residency training under intense clinical supervision. Even after residency, physicians must continue lifelong education to stay updated in their fields. Despite this extensive preparation, physicians remain vulnerable to cognitive errors. Medical professionals operate under constant pressure, navigating life-or-death decisions often with incomplete information, time constraints, and emotional intensity. The intensive care unit presents a setting where clinicians must make rapid judgments under uncertainty, frequently without clear guidelines and with significant consequences (Evans, 2021). These conditions create an environment highly open to cognitive errors. Even before entering clinical practice, medical students begin developing decision-making habits rooted in intuitive (System 1) and analytical (System 2) thinking, yet they often receive little structured guidance in managing these processes (Sanders & McHugh, 2021). This complex environment, worsened by information asymmetry between patients and providers, renders healthcare particularly susceptible to biases in both clinical and policy decisions. Understanding how behavioral economics principles apply in this context is crucial to improving health outcomes.

1.2 The Role of Cognitive Biases in Clinical Judgment

Throughout the entire treatment process, practitioners continually gather information and make informed decisions. Every client-worker relationship involves a complex process that includes gathering personal information, having conversations, and storing all of it. This information is then used for making comparisons, identifying correlations, and forming

predictions. The process relies heavily on cognitive activities, which are highly open to potential biases. As a result, there is a significant risk of error in these cognitive tasks.

When examining cognitive biases in clinical judgment, it is important to distinguish between implicit and explicit biases, both of which contribute to health and healthcare disparities. Explicit biases are conscious attitudes and assumptions that individuals can recognize and directly report; they often underlie discriminatory acts such as racism, sexism, and homophobia. In contrast, implicit biases are unconscious attitudes and beliefs about characteristics such as race, ethnicity, age, ability, and gender. These implicit biases operate outside of conscious awareness and can only be measured indirectly, but they subtly influence judgment and behavior in clinical settings.

Diagnostic errors are mistakes that occur due to missed or delayed diagnoses. These errors have been increasing rapidly and have drawn significant attention in recent years. Studies estimate that diagnostic errors occur in up to 15% of medical cases. No physician is entirely immune to such errors, regardless of their experience or expertise. Approximately 7.4% of physicians in the United States are involved in medical malpractice claims annually, with diagnostic errors being one of the leading causes of litigation. These errors often result from system breakdowns, such as communication failures or workflow issues, as well as from faulty clinical reasoning caused by cognitive biases. In many cases, both factors are involved. A study by Graber and colleagues, which analyzed 100 diagnostic error cases, revealed that most errors had multiple contributing causes. Both system-related issues and cognitive biases were commonly present. These findings highlight the critical need to examine the role of cognitive biases in clinical judgment, as they significantly contribute to diagnostic errors and compromise the quality of care.

2. Confirmation bias

Psychologist Raymond Nickerson defines confirmation bias as “seeking or interpreting evidence in a way that is biased toward existing beliefs, expectations, or a given hypothesis.” (Nickerson, 1998, pp. 175). More simply, it is our tendency to seek, interpret, and recall information in ways that support what we already believe or expect. As Hahn and Harris (2014) explain, this bias can manifest in a variety of ways: selectively gathering evidence, resisting contradictory data, failing to consider alternatives, and overestimating the validity of our existing views. Confirmation bias can be motivated, meaning people are consciously or unconsciously driven to confirm a preferred outcome, or unmotivated, occurring even when people reinforce beliefs they do not want to be true (Nickerson, 1998; Steel, 2018). Although often associated with motivated reasoning (Kunda, 1990), confirmation bias often operates as an automatic and unconscious cognitive shortcut. As Klayman and Myers & DeWall note, people naturally favor information that supports their prior beliefs while ignoring or dismissing contradictory evidence.

This process is closely tied to System 1 thinking, the fast, intuitive, and low-effort way of thinking identified by Kahneman. In contrast, System 2 thinking is more deliberate and analytical, capable of overriding initial impulses but requiring more time and mental resources. In the fast-paced, high-pressure environment of clinical practice, physicians often rely on System 1 out of necessity, making them particularly susceptible to confirmation bias.

One of the most well-known demonstrations of confirmation bias comes from a classic lab experiment by Peter Wason, who studied how individuals test hypotheses. Participants are shown a sequence of three numbers—2, 4, 6—and are told that these numbers follow a rule. Their goal was to discover the actual rule by proposing additional sequences, after which they would be told whether their new sequences conformed to the rule. Most participants assumed the rule was “increasing by twos” and suggested sequences like “8, 10, 12” or “20, 22, 24” that were confirmed to be true. What they failed to do, however, was test disconfirming examples like “2, 3, 4” or “10, 11, 13” that could potentially refute their hypotheses. In reality, the original rule was simply “any sequence that increases.” Participants failed to discover the correct rule because they only sought evidence that confirmed their initial ideas and avoided generating sequences that could refute them. This experiment revealed a well-established cognitive bias: when forming beliefs or judgments, people are more likely to seek confirming evidence than to question their assumptions. Crucially, this process occurs even when individuals are explicitly told to scientifically test their hypotheses, highlighting that confirmation bias is not just a logical error but also an innate human flaw in information processing.

One area where the consequences of this bias become especially evident is in the diagnostic process. Diagnosis is typically made in two steps: first, doctors make a prediction based on the patient's initial symptoms; then they gather more information to confirm or refine that prediction. Ideally, this second step keeps doctors open to new information. However, confirmation bias often gets in the way. Instead of fairly considering all the evidence, doctors might unconsciously look for or put more weight on information that supports their first impression, while overlooking or downplaying anything that goes against it. This pattern, called premature closure, is a frequent result of confirmation bias. Once doctors settle on a diagnosis, they might stop exploring other possibilities too soon.

A particularly compelling example comes from Jesse Pines, who presents a case study of a 51-year-old patient, “Mr. W,” who suffered from severe back pain and was misdiagnosed due to a series of cognitive and systemic errors stemming from confirmation bias. In scenario 1, the emergency physician (EP) was influenced by a colleague's prior diagnosis and a nurse's framing of the patient as someone seeking medication. Under pressure and cognitive overload, the EP reconfirmed the initial impression of musculoskeletal pain without performing a full examination or laboratory work and discharged the patient based on selective interpretation of the data.

Critically, this decision overlooked clinical red flags such as fever (100.5°F) and tachycardia (HR: 105), which were early signs of a serious underlying infection. This scenario reflects broader trends: diagnostic errors are the leading cause of malpractice claims in emergency departments, and one-third of malpractice cases in emergency departments are attributed to missed or delayed diagnoses (Pines, 2006). Furthermore, a 1993 multicenter study found that approximately 2% of patients with acute myocardial infarction were incorrectly discharged from the emergency department, demonstrating that initial diagnostic impressions—if left unchecked—can have life-threatening consequences.

The importance of slowing down cognitive shortcuts becomes even clearer in Scenario 2, where the same patient is thoroughly evaluated again and diagnosed with a spinal epidural

abscess, a rare but potentially fatal condition. When properly examined, Mr. W had a higher fever (102.2°F), an elevated ESR (47 mm/hr), a WBC count of $11.8 \times 10^3/\text{mm}^3$, and a recent history of intravenous drug use—all diagnostic clues that had been missed in the earlier encounter due to cognitive fixation and confirmatory thinking. The risk of missing such a diagnosis is not insignificant: spinal epidural abscesses have a mortality rate of 5–15%, and up to 45% of patients experience permanent neurological deficits if treatment is delayed. While this clinical report is not a randomized trial, it reflects the real-world consequences of cognitive bias under common emergency room conditions: fatigue, high patient volume, and fragmented communication.

Pines also cites a study of trauma patients in which judgment errors were observed in 100% of resuscitations, highlighting the extent of cognitive pitfalls when clinicians are forced to make rapid decisions. These data generally emphasize that confirmation bias is not a subtle or occasional problem but a common and important feature of diagnostic reasoning in emergency medicine. To mitigate these risks, Pines advocates for explicit training in metacognition and Bayesian reasoning, as well as structural reforms such as cognitive challenge strategies and protocol-based decision support tools that can help healthcare providers pause, reassess, and consider alternative diagnoses under pressure.

Confirmation bias doesn't just affect doctors during treatment—it also shows up in how scientific research is done, especially in the study of Alzheimer's disease (AD). For many years, most research has focused on what's called the "amyloid cascade hypothesis," which suggests that a protein called amyloid-beta ($A\beta$) causes brain damage that leads to Alzheimer's. Because this idea became so dominant, scientists have tended to focus on evidence that supports it and ignore studies that suggest other causes—a clear example of confirmation bias. As new technologies like brain scans and spinal fluid tests became available, researchers began diagnosing Alzheimer's based on these protein markers (amyloid and tau) even when patients didn't show memory loss or other symptoms. This shift has increased the risk of overdiagnosing people who have these biological signs but may never develop the disease. In this case, confirmation bias may have slowed progress by keeping science narrowly focused on one theory for too long.

A review by Souchet et al. (2023) highlights that amyloid-related tests exhibit variable sensitivity (64–100%) but generally low specificity (around 66.5%), meaning that approximately one-third of individuals without AD test positive and nearly 20% of those who develop AD test negative, complicating diagnosis and treatment. Autopsy studies reveal that many cognitively healthy older individuals harbor significant amyloid and tau pathology, calling into question their role as definitive disease indicators. Such evidence challenges the view that these biomarkers definitively indicate Alzheimer's. Longitudinal studies, including the A4 Study, show that many amyloid-positive but cognitively normal individuals do not develop dementia, suggesting these markers signal risk rather than certainty. Despite this, the prevailing focus on amyloid has created a self-reinforcing cycle, where positive test results are interpreted as proof of disease and contrary evidence is rationalized away or overlooked. As Souchet notes, this persistence "It is hypothesized that such a persistent focus [on amyloid biomarkers] might be influenced by confirmation bias in the field." (Souchet, 2023, p.9).

Longitudinal studies, such as the A4 Study, have found that only a minority of amyloid-positive but cognitively normal participants show cognitive decline over the years, suggesting that these markers signal risk but are not definitive of progression. This ingrained belief in the centrality of amyloid creates a self-reinforcing cycle in which positive tests are viewed as evidence of AD and opposing evidence is rationalized, exemplifying confirmation bias.

This has serious clinical implications: expensive anti-amyloid drugs like lecanemab, which can cause harmful side effects, may be overprescribed to patients who do not actually have Alzheimer's disease, leading to unnecessary risks and increased healthcare costs. Recognizing and addressing this bias is crucial to improving the accuracy and ethics of Alzheimer's diagnosis and treatment.

The consequences of unchecked confirmation bias are very extensive. Because confirmation bias continues to subtly influence clinical thinking, it leads to both under- and overdiagnosis, delays in care, and costly medical errors. Understanding how this bias manifests in real-world healthcare is an important first step toward creating systems that minimize its effects.

To effectively reduce confirmation bias in medical decision-making, a multifaceted and system-wide approach is essential. Because confirmation bias influences how clinicians seek, interpret, and recall information, solutions must target both individual cognition and the broader structures that shape clinical and scientific practice. Rather than relying solely on intuition or experience, clinicians can benefit from tools and habits that prompt reflective, evidence-based reasoning.

One proven strategy involves implementing structured pauses in the diagnostic process. These deliberate moments of reflection, known as diagnostic “timeouts,” encourage clinicians to reassess initial impressions and actively seek disconfirming evidence. Graber et al. (2014) found that such cognitive challenge strategies increased diagnostic accuracy by 17–20% in emergency simulations.

Differential diagnosis checklists serve a similar function by expanding the diagnostic framework and preventing premature closure. Their use has been shown to reduce errors by 18% in complex cases (Sibbald et al., 2013), while electronic decision support tools integrated into health records have reduced diagnostic delays by 23% in high-risk scenarios (Schiff et al., 2015). These interventions create a cognitive buffer against bias by slowing automatic reasoning and injecting deliberate scrutiny into the decision-making process.

Equally important is the development of metacognitive awareness, the ability to monitor and review one's own thought processes. Rollwage and Fleming (2021) found in a large-scale decision simulation that individuals with high metacognitive efficiency were able to adaptively use confirmation bias, achieving higher accuracy when new evidence emerged after the initial judgment. This finding suggests that the bias itself is not always harmful, but rather becomes problematic when not supported by reflection.

Training clinicians to adjust their confidence, recognize when they might be wrong, and remain open to corrective information transforms confirmation bias from a burden into a tool that can be managed and, in some cases, evaluated.

Beyond individual cognition, team-based practices offer powerful safeguards. Collaborative case reviews, structured handoffs, and interdisciplinary rounds can disrupt biased diagnostic momentum. O'Hare et al. (2018) reported a 36% reduction in significant diagnostic discrepancies in critical care settings when such practices were implemented.

Feedback mechanisms play a similar role: regular audits and diagnostic reviews help identify recurring error patterns; studies such as Haskel (2007) show a 25% reduction in recurring diagnostic errors following structured feedback. These collaborative and iterative processes broaden the perspective of individual clinicians and create a culture that values uncertainty and second opinions, an important antidote to cognitive fixation.

Confirmation bias also operates at the research and policy levels, particularly in how diseases are defined and studied. For example, in Alzheimer's research, the long-standing dominance of the amyloid cascade hypothesis has shaped both diagnostic criteria and drug development, despite growing evidence that amyloid positivity does not reliably predict cognitive decline.

This reflects a deeper pattern: as a theoretical model gains momentum, supporting evidence is emphasized, while conflicting data are minimized or rationalized. To address this, researchers should adopt practices that reduce circular reasoning and selective interpretation. Longitudinal cohort studies can help confirm whether biomarkers truly predict meaningful outcomes over time, rather than assuming their presence equates to disease.

Souchet et al. (2023) advocate for redefining Alzheimer's disease using outcome-predictive biomarkers instead of pathology-based ones, aiming to reduce the risk of overdiagnosis and inappropriate treatment. Pre-registering hypotheses and prioritizing independent replication trials reduces the risk of confirmation bias in scientific reporting. Preregistration involves publicly documenting a study's research questions, hypotheses, methods, and planned analyses before data collection begins. This process prevents researchers from retroactively adjusting their hypotheses to fit the results (a practice known as HARKing), which can distort scientific conclusions and falsely inflate the impression of support for a theory. By committing to a specific research area in advance, researchers are held accountable for objectively testing their original ideas, rather than interpreting uncertain results to confirm their expectations. Similarly, independent replication experiments serve as a safeguard against selective reporting or unintentional biases that might arise in original studies. When other research teams (ideally with no vested interest in the outcome) replicate the study using the same methods, they test whether the original findings are robust or simply the result of chance, methodological flaws, or confirmation bias. If a result can be consistently replicated by different groups, it becomes more reliable and less likely to be influenced by the original researchers' assumptions. Preregistration and replication together create a more transparent and self-correcting scientific process, helping to distinguish truly valid findings from those influenced by cognitive biases or selective interpretation. Additionally cost-effectiveness analyses ensure that treatments, such as anti-amyloid drugs, are evaluated not only based on their biological targets but also on their actual patient benefits.

Together, these interventions represent a comprehensive strategy for managing

confirmation bias in medicine. They do not, and should not be the goal, to eliminate bias entirely. Instead, they recognize that cognitive shortcuts are part of human reasoning and that their risks can be mitigated through reflection, transparency, and carefully designed systems. When supported by metacognitive skills and institutional mechanisms, even a deep-seated bias like confirmation bias can be transformed from a source of error into an opportunity for improved accuracy, better outcomes, and more ethical care.

3 Anchoring Bias

Anchoring bias is a cognitive heuristic in which individuals disproportionately rely on initial information, the “anchor,” when making judgments, even when subsequent evidence suggests they should have adjusted their judgments (Tversky & Kahneman, 1974). In one of their classic experiments, Tversky and Kahneman asked participants to spin a wheel of fortune set to stop at either 10 or 65. Participants were then asked whether the percentage of African countries in the United Nations was higher or lower than the number on the wheel and then asked to provide their own estimates. Strikingly, those who saw the wheel stop at 10 gave an average 25% estimate, while those who saw it stop at 65 gave an average 45% estimate. Despite knowing the number was random and irrelevant, participants' judgments were biased toward it. This simple but powerful experiment demonstrates how even arbitrary anchors can unconsciously shape decision-making.

This bias takes on even greater significance in medicine. Clinicians often form premature diagnostic impressions based on limited information (such as triage notes or initial symptoms), which can disproportionately influence subsequent testing and treatment decisions. Emotional states can exacerbate this effect; Bodenhausen et al. (2000) found that sadness reduces cognitive flexibility and increases reliance on anchors. These pressures are particularly important in high-risk, fast-paced environments such as emergency departments, where time constraints and stress can narrow the diagnostic focus and delay recognition of alternative conditions.

Ly et al. (2023) provide clear evidence of anchoring bias affecting clinical decision-making in emergency medicine through a large-scale cross-sectional analysis of 108,019 Veterans Affairs emergency department visits. The study focused on patients with congestive heart failure (CHF) presenting with shortness of breath (SOB), a common symptom in both CHF exacerbation and pulmonary embolism (PE). A key consideration was the “reason for visit” section documented by triage nurses prior to physician assessment. When CHF was explicitly mentioned in this initial documentation, it served as an anchor for subsequent clinical decisions. Anchoring bias occurs when decision-makers overrely on initial information and fail to adequately adjust their judgments with new data. Here, physicians who received triage notes emphasizing CHF tended to narrowly focus on CHF as the cause of symptoms and frequently neglected alternative diagnoses such as PE. Consequently, when CHF was mentioned, physicians ordered significantly fewer PE diagnostic tests (8.8% vs. 13.4%; difference, −4.6 percentage points; 95% confidence interval [CI], −5.7 to −3.5) and delayed tests by an average of 15.5 minutes (90.4% vs. 74.9 minutes; 95% CI, 5.7 to 25.3). At the same time, testing for CHF exacerbation using B-type natriuretic peptide (BNP) increased by 6.9 percentage points (78.0% vs. 71.1%; 95% CI, 4.3 to 9.4). The mechanism is clear: the triage note served as an anchor that

shaped physicians' initial expectations and led them to cognitively focus on CHF. This finding led to disproportionate testing for CHF, even when clinical symptoms warranted, and underassessment of PE—a hallmark of anchoring bias, which is typical of underadjustment from the initial anchor.

Although PE diagnoses were lower when CHF was noted during the emergency department visit (0.08% vs. 0.23%; difference, -0.15 percentage points; 95% CI, -0.23 to -0.08), 30-day PE diagnosis rates did not differ significantly (1.2% vs. 1.1%; difference, 0.06 percentage points; 95% CI, -0.23 to 0.36). This suggests that anchoring bias leads to delayed rather than missed PE diagnoses, potentially impacting timely patient care.

Delays in the diagnosis of pulmonary embolism (PE) due to anchoring bias are clinically significant because PE is a potentially life-threatening condition that requires prompt diagnosis and treatment. Studies show that early diagnosis and anticoagulant therapy can significantly reduce mortality rates. According to the American Heart Association, the estimated mortality rate for untreated PE is up to 30%, but with timely diagnosis and intervention, this rate decreases significantly, often to less than 10%. Delays in diagnosis increase the risk of complications such as right ventricular failure, recurrent embolism, and chronic thromboembolic pulmonary hypertension, all of which contribute to higher morbidity and healthcare costs.

A similar clinical scenario illustrating the detrimental effects of anchoring bias involves a 29-year-old man initially suspected of having a polysubstance overdose. The clinical team focused on this diagnosis due to the patient's presentation and positive drug screens, which delayed further investigations. After the patient's condition worsened, imaging revealed a large brain tumor that caused life-threatening complications. This case highlights how focusing on the initial diagnosis can overshadow potentially more serious alternative conditions, leading to delayed diagnosis and adverse outcomes. Such examples highlight the critical importance of clinicians remaining vigilant against cognitive biases to ensure timely and accurate diagnosis in high-risk medical conditions such as pulmonary embolism.

The case involves a 29-year-old man known for chronic headaches. He was brought to the emergency department (ED) under a police escort for suspected multiple substance overdose. He reported experiencing a suspected seizure and ingesting an unknown quantity of medications, including clonazepam, sumatriptan, and ibuprofen. However, he could not provide specific information about when or in what quantity the medication was ingested. During his initial examination in the ED, he experienced confusion, bradycardia, and hypertension. A urine drug screen was positive for amphetamines, benzodiazepines, and cannabinoids. Based on these findings and the context, the medical team focused on a diagnosis of drug overdose as the primary explanation for the patient's altered mental state.

Over the next several hours, the patient's condition worsened; he became increasingly drowsy and intermittently agitated, requiring soft restraints for safety. On his first day in the hospital, he was lethargic, unresponsive, and hypoxic on room air. A code blue was called, and the patient was intubated and transferred to the Intensive Care Unit (ICU). A neurological reexamination revealed fixed and dilated pupils, and an urgent CT scan of the head was performed. The imaging revealed a large, 10-cm hyperdense mass in the right frontal lobe,

accompanied by severe swelling (vasogenic edema), uncal herniation, and hydrocephalus. These findings were highly suspicious for a meningioma or brain tumor.

A detailed history taken from the patient's mother revealed a distinct pattern of personality changes, bizarre behavior, memory loss, worsening headaches, and gait disturbances over the years. The mother initially assumed these symptoms were related to drug use, contributing to her diagnosis of overdose. She also confirmed that the number of pills remaining in the prescription bottles was consistent with the patient's statement and did not indicate an overdose. Consequently, the patient was referred to a tertiary hospital for neurosurgical intervention, but unfortunately, he died from complications related to the brain tumor and its associated herniation.

This tragic outcome highlights how fixating on an initial diagnosis of drug overdose can lead to a critical delay in recognizing the true underlying condition. By overlooking alternative explanations early on, the clinical team missed the opportunity for timely diagnosis and intervention, potentially altering the patient's prognosis. Thus, anchoring bias not only compromised the quality of care but also directly impacted patient survival, demonstrating the profound implications of cognitive biases in medical decision-making.

A similarly instructive scenario is described in Case 6 by Waldrop (2017), which exemplifies anchoring bias in pediatric emergency medicine. The case involved a 15-year-old female with known sickle cell disease (SCD) who presented with abdominal pain described as distinct from her typical vaso-occlusive episodes. Despite this clinically significant clue, the emergency department (ED) team made an early diagnosis of a routine pain crisis based on the patient's history of frequent ED visits and perceived drug-seeking behavior. Anchoring bias, reinforced by confirmation bias, led the team to discharge the patient after administering opioid analgesia without performing imaging or laboratory tests beyond the initial workup.

Within 24 hours, her condition worsened, and further evaluation revealed portal vein thrombosis, a life-threatening vascular complication. While Waldrop's report did not provide patient-specific mortality data, portal vein thrombosis has a reported mortality rate of 10–20% in untreated acute cases, and delayed diagnosis significantly increases the risk of bowel ischemia, liver failure, and long-term morbidity. This case quantifies the risk of anchoring bias: a 24-hour delay in diagnosis in a time-sensitive vascular emergency directly jeopardized the patient's survival. Clinically, this vignette illustrates how attachment to the past and reputation can override critical new information, narrow the diagnostic framework, and delay the recognition of emergencies. In high-pressure emergency situations where time constraints, cognitive load, and negative emotional bias combine, such attachment can have disastrous consequences. Waldrop (2017) emphasizes that mindfulness and diagnostic thinking, including explicit recognition of cognitive dissonance and deliberate diagnostic pauses, are key strategies for neutralizing attachment, maintaining broad discrepancies, and reducing the risk of life-threatening delays.

A promising solution to address bias in medical decision-making involves the integration of bias-aware algorithmic support systems, as proposed by Ahsen et al. (2019). In their study of mammography decision-making processes, they showed that radiologists' interpretations were

systematically influenced by prior clinical risk information, a clear indicator of bias-based assessment. To mitigate this, they developed an algorithmic prediction framework that explicitly accounts for human bias by modeling both the systematic variation caused by bias and the associated variability in decision-making processes.

By refactoring radiologists' assessments and incorporating unbiased clinical and imaging data, the algorithm produced more accurate cancer risk estimates and improved expected patient outcomes measured in life years. This approach offers a broader solution to anchoring bias: combining human expertise with algorithmic calibration to ensure that initial impressions do not disproportionately determine final diagnoses. In high-risk settings like emergency medicine, similar bias-sensitive decision-support tools can encourage clinicians to reassess early anchors, expand differential diagnoses, and reduce the risk of delayed or missed diagnoses. Anchoring bias will always be a part of human cognition, but its consequences in clinical decision-making are not inevitable. Through conscious deliberation, team-based checks, and algorithmic calibration, clinicians can prevent early anchors from becoming fatal extremes. Combating anchoring bias is not about eliminating intuition; it's about ensuring that intuition is held accountable to the evidence.

4 Conclusion

This literature review examined how two specific cognitive biases—confirmation bias and anchoring bias—impact medical decision-making in both clinical and research contexts. By analyzing emergency medicine cases, Alzheimer's research, and real-world diagnostic failures, the literature review showed how these biases shape physician judgment and contribute to missed or delayed diagnoses. It also evaluated concrete solutions, including decision support tools, diagnostic timeouts, and metacognitive training. Ultimately, the findings suggest that improving clinical outcomes depends not on eliminating intuitive thinking, but on designing systems that support reflective, evidence-based reasoning without ignoring human cognitive tendencies. A balanced approach that respects physician expertise while reducing cognitive error holds the greatest promise for safer, more accurate healthcare.

Many existing debiasing methods fail because they rely on assumptions that are incompatible with physicians' natural ways of thinking and making decisions. As Norman and Eva (2020) emphasize, physicians are often most vulnerable to diagnostic errors when they attempt to override intuitive System 1 thinking by overriding analytical System 2 processes. Successful diagnoses often rely on intuitive judgment rather than formal reasoning, making it difficult to challenge these ingrained cognitive habits. Therefore, effective debiasing approaches must adopt a broader perspective that integrates physicians' expertise and intuition rather than attempting to replace or override them. This requires developing conceptual models and technological tools that are compatible with both the cognitive structures of the human mind and the practical demands of clinical work.

Future research should focus on creating healthcare technologies that facilitate productive interactions between clinicians and artificial expert systems, providing support at every stage of the medical decision-making process. Such tools should support the development of implicit

knowledge and robust intuition, as well as analytical reasoning, and encourage the balanced use of System 1 and System 2 thinking. One promising area is the use of hybrid models, such as fuzzy cognitive maps, that combine human expertise with analytical algorithms. These techniques can increase physicians' awareness of diagnostic cognitive processes and encourage active participation and motivation in the decision-making process. Unlike current debiasing or fully automated data mining approaches, such balanced systems aim to reduce common errors such as premature closure and overconfidence by integrating cognitive knowledge with technological support.

Consequently, debiasing strategies and decision support systems must demonstrate scientific validity and personal relevance to be adopted in daily practice. Raising awareness of cognitive biases should be supported by training and tools that promote a cognitively focused diagnostic process. Clinician collaboration can enhance the effectiveness of decision support tools and foster intuitive diagnostic skills within evidence-based medicine frameworks. This balanced approach offers a path to reducing diagnostic errors and improving patient outcomes without undermining the valuable role of physician intuition.

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Sensor Data Fusion-based Human Detection in Search and Rescue Missions

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Abstract

Computer vision-based human detection is crucial in advanced search and rescue operations, especially in scenarios where it is rather unsafe or difficult for a human to explore the site. While object detection methods are often used in autonomous vehicles and video surveillance, multisensor-based human recognition techniques remain relatively unexplored. Existing systems are often limited in scenarios with low visibility, cluttered environments, noise, or varying thermal conditions. This study aims to improve the accuracy and real time performance of such human identification systems using a combination of thermal and visual imaging techniques. The research presents a novel, brand-independent sensor data fusion approach for object detection, combining image processing and deep learning algorithms. The system achieved significant improvement in detection accuracy compared to existing methods, showing its potential for use in real time and resistance to changes in the environment.

Introduction

Natural and man-made disasters have become more frequent, resulting in greater damage to the environment and communities and increased loss of lives. In 2023, over eighty thousand people died in such disasters, with more deaths compared to previous years (Centre for Research on the Epidemiology of Disasters (CRED)). Therefore, quick and reliable rescue operations are crucial for saving lives and reducing the severe consequences of such events. For a long time, ground search teams of trained personnel and volunteers have been helping to find victims stuck in disaster zones (National Association for Search and Rescue (NASAR)). In addition, K9 search and rescue teams, consisting of dogs trained to respond to disasters, remain one of the most reliable and commonly used rescue techniques (American Rescue Dog Association (ARDA)).

Tech-Enabled Operations

Nowadays, computer vision-based technologies are widely explored and employed for human recognition. For instance, acoustic sensors, ground-penetrating radar, visual sensors, and thermal sensors are used to detect humans, especially in areas inaccessible to people. Acoustic sensors detect people by analyzing sound waves, particularly human voices, breathing, or movement-related noises (Zimroz et al.). Ground-penetrating radar (GPR) is an effective tool for identifying humans trapped under rubble or buried beneath surfaces by emitting electromagnetic waves and analyzing the reflected signals (Hu et al.). Aerial search, cell phone and GPS tracking have greatly contributed to accurately locating people (Lyu et al., Raab et al.), while visual sensors, such as RGB cameras, find people by capturing images and applying machine learning-based object detection algorithms. Finally, thermal sensors improve human detection by capturing infrared radiation emitted by body heat, allowing for identification in darkness, smoke, or dense vegetation (Cruz Ulloa et al.).

Alternatively, the techniques of merging thermal and visual sensor data and the object

detection algorithms have significantly improved over the past decade. In fact, several solutions have already integrated thermal and visual sensor fusion to improve human detection in search and rescue (SAR) operations. For example, the RAPOSA robot, which is equipped with both visual and thermal cameras together with various sensors to detect victims, can provide real-time data for human detection even from debris-laden regions (Marques et al.). Another example is ViDAR (Visual Detection and Ranging) technology (Sentient Vision Systems), which uses both electro-optic and infrared sensors to detect objects and has been used by the Royal Australian Navy on ScanEagle Unmanned Aerial Systems (UAS) and the Australian Maritime Safety Authority.

Despite their advanced abilities, these systems have limitations, such as high costs, dependence on specific hardware setups, and possible performance issues under extreme environmental conditions. These factors show the need to create more affordable and adaptable detection models to increase the effectiveness and accessibility of SAR operations.

Proposed Human Detection Model

This paper presents a novel human detection model that works on combined thermal and visual images to increase detection accuracy in search and rescue operations. The model is specifically designed to address challenging conditions such as smoke, fog, obstructed views, and low-light environments, where traditional methods often struggle. In addition, the system effectively detects humans in scenarios like wildlife search and rescue, crowded environments, and aerial imagery.

Outline of the Paper

In this paper, we present the idea of using multisensor-based data fusion techniques for a robust tool to be used in human search and rescue. Existing methods are discussed in Section 2, along with their strengths, limitations, and current gaps in the field. Subsequently, Section 3 explains the algorithms used to achieve the result, as well as the adjustments made for further improvement. Section 4 evaluates the system by providing test results captured in various scenarios, and the system performance is quantified using the precision, recall, and F1 score metrics. The limitations of the proposed model and suggestions for future work are discussed in Section 5.

Literature Review

Use of Visual Sensors in Search and Rescue

Visual-based human detection has also proven helpful in SAR operations, as optical cameras offer detailed images of the environment. When applied to drone images, algorithms such as YOLO (You Only Look Once) and Faster R-CNN (Region-Convolutional Neural Network) can quickly and accurately identify people in complex environments (Caputo et al.). These techniques work best in situations with good lighting and little visual obfuscation from the environment. Gotovac et al. have shown that visual sensors are especially good at recognizing people from sharp aerial images, which makes them very useful in open and urban

settings. Visual detection systems, however, struggle to detect people in low light and when they are hidden behind objects such as vegetation or debris (Sambolek and Ivasic-Kos). Moreover, image quality can become significantly worse due to weather conditions, motion blur, or varying poses of the person (Caputo et al.). As shown in Figure 1, visual-only detection fails in low-lighting conditions, while thermal and fused approaches provide more reliable results.

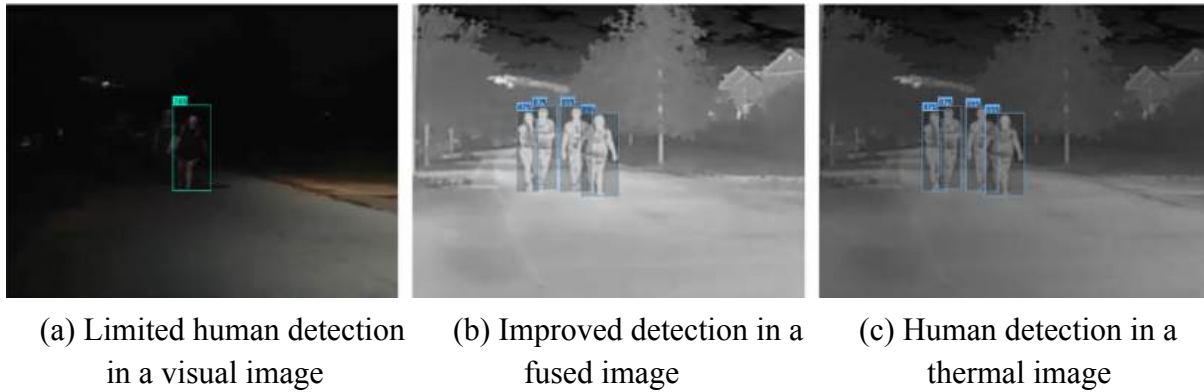


Fig 1: Comparison of human detection in low-lighting conditions

Use of Thermal Sensors in Search and Rescue

Thermal sensors have become a key technology in search and rescue (SAR) missions, primarily due to their ability to detect individuals in low-visibility conditions such as smoke, debris, or darkness. Recent advances in deep learning, such as the YOLOv4 and YOLOv8 models, have significantly improved thermal imaging performance. When trained on large datasets, these models can detect human presence in thermal images with high precision. For example, YOLOv8 achieved 95% precision in human recognition (Rizk and Bayad). However, challenges remain, including the high computational overhead of real-time thermal image processing and the inability to identify victims based on their posture or in situations where thermal signatures are similar to background noise (Tsai et al.). As shown in Figure 2, thermal-only detection struggles in scenarios where noisy heat signatures are present, while the fusion of visual and thermal data significantly improves human detection accuracy.

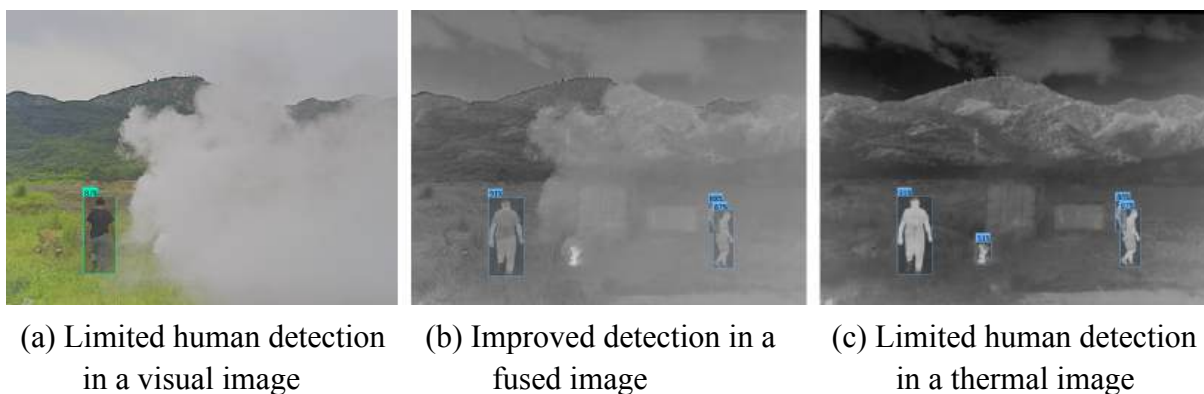


Fig 2: Comparison of human detection under foggy conditions

Sensor Data Fusion

In sensor fusion and object detection, feature extraction algorithms such as statistical anomaly-based extraction (Ben-Shoushan and Brook), channel attention-based fusion (Zhou et al.), and GAN-based misalignment correction (Chauhan et al.) that enable accurate alignment of data from different modalities are commonly used. In addition, edge detection techniques such as Canny edge detection and Hough circle finding improve registration between thermal and RGB-D sensor data by optimizing calibration processes through structural similarity detection. For example, Ozcan and Cetin calibrated a system of sensors using black circular markers with heat-emitting bulbs.

Fusion techniques based on deep learning are also becoming more common due to their high efficiency. For instance, feature refinement, anomaly, and object recognition are often performed by Convolutional Neural Networks (CNNs) to improve precision (Ben-Shoushan and Brook). Zhou et al. used methods including adaptive weight fusion, channel attention mechanisms, and a priori temperature masks to adjust the importance of the features based on lighting conditions. Meanwhile, Chauhan et al. used GANs to generate synthetic images that align misaligned modalities by learning structural consistency and feature mappings from both sensors.

State-space modeling and neural architecture search techniques further optimize fusion processes. Dong et al. integrate state-space channel swapping and dual-state space fusion, where individual feature maps are established within independent state spaces before being merged. Similarly, Liu et al. use multilevel adaptive attention modules that suppress unnecessary information while prioritizing important features.

Implementing hierarchical attention mechanisms alongside complementary mirror structures is also a new approach that has been introduced by transformer-based models. In these architectures, multiscale dilated convolutions preserve both high-level and low-level features while maintaining semantic consistency. For instance, Jiang et al. employed a mirror complementary structure that uses two parallel branches to process RGB and thermal data separately before combining them through a self-attention mechanism. Skip connections and convolutional block attention modules (CBAMs) can improve feature selection across several layers, as demonstrated by Wang et al., who employed an enhanced multiscale encoder that combines spatial and spectral features using attention-based mechanisms to refine object boundaries.

In mobile robotic systems, where computational resources are limited, image processing methods, including stereo vision and heterogeneous fusion models, can significantly simplify the fusion between sensors. For example, Oppliger et al. combined time-of-flight depth sensing and thermal infrared imaging using a probabilistic data association framework, allowing precise object recognition even in visually cluttered environments. Under dynamic environmental conditions, techniques such as modal weighted fusion and region-of-interest scaling increase the fusion efficiency by adjusting the weight contribution of thermal and visible modalities based on the complexity of the scene (Voronin et al.).

Object Detection

Region-based Convolutional Neural Networks (R-CNNs) are commonly used for computer vision-based object detection. For example, Faster R-CNN is implemented in thermal-visible pedestrian detection to identify regions of interest and classify objects within them. In some systems, saliency masks are employed with Faster R-CNN to highlight pedestrian regions and improve detection accuracy. Das et al. integrated multiple saliency detection networks to generate region proposals. This method showed positive results by reducing false positives and enhancing detection in conditions with low visibility.

Another efficient approach is to use the You Only Look Once (YOLO) algorithm, a single-shot object detection model, which is also widely employed for human recognition in airborne imagery—for example, Gallagher et al. achieved a mean mAP of 59.8% using YOLOv7 on paired RGB and Long Wave Infrared (LWIR) image datasets. In addition, Tu et al. introduce contrastive loss functions by combining contrastive learning techniques with YOLO models, thus improving the accuracy in low-light scenarios and small object detection tasks.

Mask-based detection models like Mask R-CNN (which extends Faster-CNN by adding a segmentation branch) are also commonly used. For instance, Khalid et al. combined Mask R-CNN and ResNet-152 using multilayer feature fusion techniques to integrate both modalities at different abstraction levels. Their system reduced the miss rate to 5.25% in the KAIST dataset (Hwang et al.), significantly improving human detection precision compared to other models.

Semantic-aware object detection with integrated Neural Architecture Search (NAS) and adaptive attention mechanisms is another widely implemented method for object detection. One example is the Multilevel Structure Search Attention Fusion Network, which adjusts feature extraction layers based on their input variability. Liu et al. demonstrate this approach by implementing an adaptive multiscale feature selection strategy that adjusts feature importance based on object presence and background clutter and achieved a 0.5% improvement in mAP over FusionGAN.

Research gaps

Despite significant advances in combining thermal and visual imaging for human detection, several research gaps remain, particularly in system performance under real-world, challenging conditions. While many current methods perform well in controlled environments, they often struggle in complex scenarios, such as dense smoke, low light, or obstructed views. The main challenge is that most studies do not provide information on the limitations of their systems, making it difficult to identify areas for further improvement or evaluate how well these approaches work in real-world situations. In addition, many approaches depend on particular sensor models, which limits their adaptability and generic nature of their hardware setup. Furthermore, most research focuses on pedestrian detection in scenarios that mimic conditions encountered during driving, such as burst lighting and clear visibility. This narrow focus leaves a gap in the efficiency of detection methods under disaster-specific conditions, where smoke, debris, and varying environmental factors impact the robustness of the images.

These gaps indicate the need for a more efficient and adaptable fusion method that can

reliably detect humans even in extreme conditions. Addressing these issues requires research that improves the integration of multimodal sensor data and ensures the flexibility and generalizability of detection systems across different hardware setups and environmental conditions. By addressing these issues, future research can greatly improve the efficacy and dependability of human detection systems in actual disaster response situations, ultimately aiding in life-saving efforts

Methodology

Overview

This study employs sensor fusion and object detection models to identify humans in search and rescue (SAR) missions. The fusion process is developed on a convolutional neural network (CNN)-based Attention Network that fuses data from thermal and visual sensors by generating attention maps. These maps contain relevant features and filter out unnecessary data as they highlight significant regions in both modalities. This method contrasts traditional pixel-wise fusion and offers a more effective technique to work with multispectral data instead. The YOLOv11 (Jocher and Qiu), a deep learning-based model known for its high accuracy and fast speed, is used for object detection. It has been fine-tuned using the COCO dataset (Lin et al.) as the initial model, which enabled the use of pre-trained weights for improved detection performance. The dataset for fine-tuning the model contains 2565 original thermal, visual, and fused images. Notably, these images were doubled due to multiple augmentations during dataset preparation. The YOLOv11 provides precise bounding boxes for human recognition and is proven effective in search and rescue missions, where processing time is limited.

Data Collection

The visual images used in the dataset are derived from multiple publicly available datasets containing people in various conditions. The sources include Okutama-Action dataset with aerial views of human actions (Barekattain et al.), the Multiple Pose Human Body Database (LSP/MPII-MPHB) (Cai and Tan), Disaster Occlusion Detection Dataset (DODD) (Zhao et al.), and the AIDER (Aerial Image Dataset for Emergency Response) (Kyrkou). These data are complemented by thermal images obtained from various datasets, including the WIT-UAS dataset (Jong et al.), which captures wildland fire crews from aerial views, and Thermal Image Tracking for SAR with Drones (Yeom). In addition, the Thermal Image Dataset (Kristo et al.) and HIT-UAV dataset (Suo et al.) were used as sources for the dataset used in this study. The paired thermal and visual images come from LLVIP (Jia et al.), a dataset for low-light paired images, WiSARD (Broyles et al.), which is specialized in wildlife search and rescue missions, and M3FD (Fan et al.).

Data Fusion Process

The thermal and visual sensor data fusion method is based on a deep learning model that uses the Attention Network built on a Convolutional Neural Network (CNN) architecture. The system assigns weights between 0 and 1 to different image regions. Higher attention values are

assigned to regions with essential features, while areas with less relevance receive lower attention scores. These weights prioritize critical features necessary for object detection and thus enable us to leave out irrelevant information. Based on the assigned values, attention maps are generated through a series of convolutional layers. Before being sent to the Attention Network, each image goes through preprocessing and is transformed into a grayscale tensor. The attention maps for the thermal and visual images were then made independently. These two modalities' attention maps are combined using the Equation 1 to create a single fused image:

$$I(fused) = \frac{\alpha \times I_1 + \beta \times I_2}{\alpha + \beta + \epsilon}$$

where α and β are the attention maps corresponding to I_1 and I_2 , respectively, which determine the contribution of each image to the fused output, $I(fused)$ is the fused image produced after combining the attention maps and the ϵ is a small constant added to prevent division by zero.

The Attention Network is built on a lightweight CNN model consisting of three convolutional layers, each of which improves the feature extraction and attention computation process. The convolutional layers detect patterns that often appear in important regions (e.g., edges of objects, heat signatures). At the same time, areas with uniform textures or background noise have less influence on the final attention map. Figure 3 summarizes the process of image fusion described in this section.

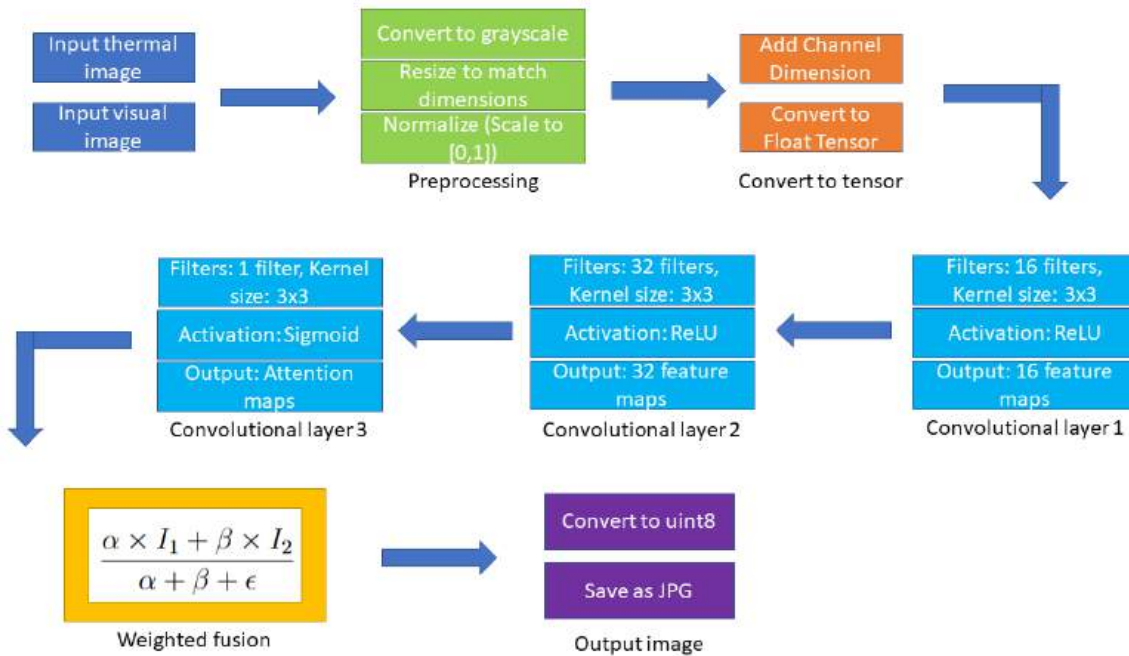


Fig 3: Data fusion process

The first convolutional layer employs a 3×3 convolutional kernel with 16 filters to extract minor features, such as edges and textures. A small matrix called kernel (or filter) slides over the image, while its weights are multiplied by the matching pixel values, and the results are added to identify patterns. This process, known as convolution, helps assign importance values to

different parts of the image.

Each output value at position (i, j) in the feature map is obtained by calculating a sum of weights of the surrounding pixel values in the input image. The process of extracting important patterns is mathematically represented as Equation 2:

$$y(i, j) = \sum_{m=-k}^k \sum_{n=-k}^k x(i - m, j - n) \cdot w(m, n) + b$$

where $x(i - m, j - n)$ indicate the pixel values in the input image, $w(m, n)$ is the kernel weight at position (m, n) , and b is a biased term.

Each filter in the kernel acts as a detector for particular shapes or patterns, such as horizontal, vertical, or diagonal edges. As a result, by employing multiple filters, the system can capture various structures in the image. After the kernel, a ReLU (Rectified Linear Unit) activation function is used to model more complex relationships in the data. It ensures that only positive values pass through while setting negative values to zero, thus introducing non-linearity to the model.

Next, to capture more complex patterns and spatial dependencies, the second convolutional layer applies a 3×3 convolution with 32 filters followed by a ReLU activation function. It expands on the results of the first layer by identifying previously undetected shapes, textures, and structures. The third convolutional layer creates an attention map using a final 3×3 convolution with a single output channel. As a result, a spatial attention map is produced, where each pixel shows the importance of the corresponding image in the input image. The model employs a sigmoid activation function to constrain the values between 0 and 1 for the output to be in a probabilistic range.

The Attention Network is trained using fused images from a prepared dataset. First, the images are loaded and resized to a resolution of 128×128 pixels. The model then undergoes multiple training epochs, using a Mean Squared Error (MSE) loss function and an Adam optimizer. Each epoch refines the model's ability to generate accurate fused images.

This sensor fusion approach has several advantages over traditional techniques. Firstly, instead of uniform weighting, the model highlights important regions dynamically, which reduces the importance of irrelevant background areas. Secondly, it keeps details necessary for object detection, which makes it particularly useful in scenarios typical during search and rescue missions. Finally, this method improves the detection accuracy compared to conventional fusion techniques, enhancing the merging of thermal and visual images.

Human Detection Method

For human recognition in this study, YOLOv11 (You Only Look Once version 11) (Jocher and Qiu), an advanced object detection model hereafter referred to as YOLO, was used. Known for its real-time processing capabilities, high speed, and accuracy, it detects and locates humans in a single pass through the network by predicting the presence, location, and class of each object. YOLO is particularly effective for tasks where both speed and precision are important, making it a good choice for search and rescue missions.

The YOLO architecture was developed on a Convolutional Neural Network (CNN) and uses multiple layers to extract essential features from the input images.

Firstly, depending on its resolution, the image is divided into a grid of cells, with each cell having to predict the presence of an object whose center is located within that grid.

Every grid predicts a probability value, a number between 0 and 1, indicating that an object is present. This is done by looking for patterns in the image, such as human shapes or textures usually associated with humans, that the model can recognize based on the data it has seen during training.

In addition to predicting whether an object is present by looking at its position and scale, YOLO also predicts bounding boxes for each detected object. The bounding boxes are defined by three factors: center coordinates relative to the grid cell, width, and height, which indicate the size of the identified human. These values are normalized with respect to the image size and predicted from the features learned by the network.

YOLO determines the most likely object class by assigning a class probability to each bounding box. For human detection, the relevant class is “human”. Therefore, the model produces a class score that shows the likelihood that the object is a person. This is calculated using a softmax function applied to the predicted classes.

In YOLO, the confidence score is used to combine the probability of the object's presence and the precision of the predicted bounding box. This score plays an essential role in precise object detection, as it represents the probability that the bounding box contains a human and is accurately positioned.

To remove excess predictions, YOLO employs Non-Maximum Suppression (NMS), which helps retain the bounding box with the highest confidence value for each object. It sorts all the predicted bounding boxes according to their confidence scores and then compares each box with others, leaving out those with a confidence score lower than the set value (0.5). This process ensures that each object has only one bounding box. The output includes class labels, confidence scores, and predicted bounding boxes for every detected object (human).

Pre-trained weights from the COCO dataset were used to fine-tune the model, allowing it to improve its ability to identify people in particular scenarios like crowded spaces or blocked views. The model was trained on a custom dataset comprising thermal, visual, and fused images. The images were labeled with bounding boxes that capture humans, and the model was trained to lower the mean squared error (MSE) between the predicted and the true bounding box. The Adam optimizer was used to adjust learning during training, ensuring more accurate detection.

YOLO stands out from other object detection models as it processes the entire image simultaneously, making it more efficient than two-stage models like Faster R-CNN. Moreover, its grid-based detection ensures that objects are identified in a structured way, while anchor boxes help to locate objects and determine their sizes accurately. YOLOv11 further enhances these strengths by using improved feature extraction (through a more advanced backbone network) and better augmentation techniques, as well as handling occlusions and varying scales more efficiently with the help of multiscale prediction methods.

Performance Evaluation

This section analyses how effective and precise the model is for human detection in rescue missions using fused thermal and visual sensor data. The evaluation, with several important metrics, provides a comprehensive overview of the model's performance.

Evaluation Metrics

Precision and recall help in understanding the trade-off between reducing false positives and false negatives and are crucial for evaluating the model's accuracy, especially when one type of error (either false positives or false negatives) may be more significant than the other. This is particularly important for rescue missions, where failing to detect something or giving false alerts can have serious consequences.

F1-Score is the harmonic mean of precision and recall. Precision measures the ratio of true positive results to the total of positive predictions made, and recall determines the proportion of true positive outcomes out of all the actual positives in the dataset.

A ROC (Receiver Operating Characteristic) curve was created to evaluate the model's effectiveness in identifying living beings in varying conditions that displays the true positive rate in relation to the false positive rate at various threshold values. The area under the curve (AUC) provides a summary of the model's performance over all classification thresholds. As shown in Figure 4, the ROC curve demonstrates strong performance with an AUC of 0.9, indicating high accuracy in distinguishing living beings across different conditions.

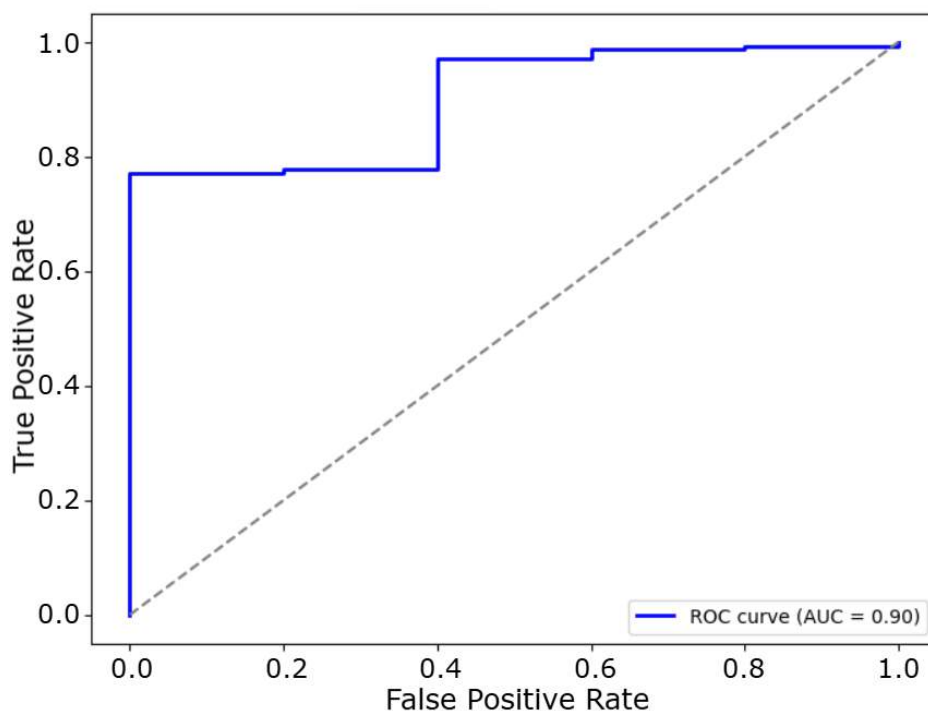


Fig 4: The ROC curve

Performance and Results

With the help of fused thermal and visual sensor data, the system detects humans effectively under conditions frequently met during search and rescue missions. Indeed, the

evaluation metrics verify its robustness under various conditions. The model's precision is 85%, indicating that it effectively reduces false positives while correctly identifying humans. The recall is 80%, confirming that most actual humans are successfully recognized. The F1-score, which reflects both precision and recall, is 81%. Moreover, the high AUC-ROC score further verifies the model's ability to distinguish between human and non-human objects across various conditions. As demonstrated in Figure 5, in challenging environments the fused approach outperforms both visual-only and thermal-only detection.

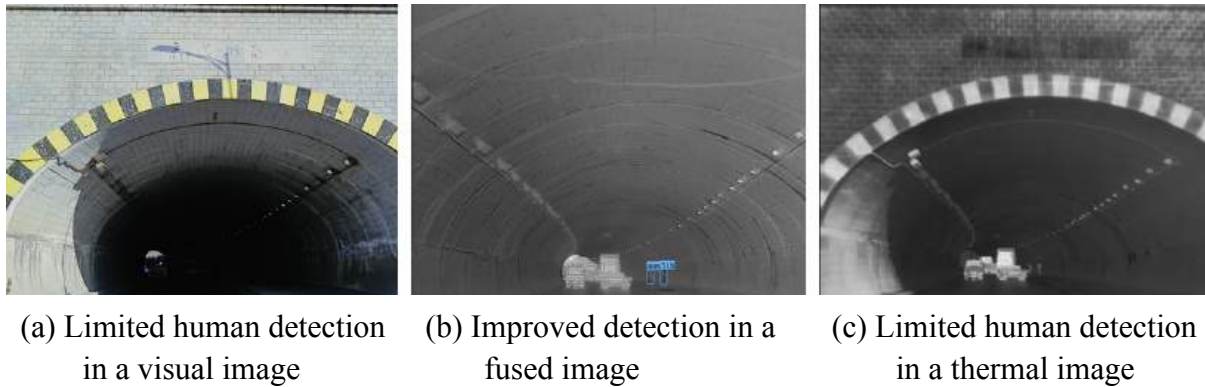


Fig 5: Comparison of human detection in challenging environments

The model performs well in crowded environments by accurately identifying individuals without confusion. It retains high levels of accuracy in low-light conditions by utilizing a combination of thermal and visual data. When used with aerial images, the model can accurately recognize humans from a distance. The system's performance is unaffected by challenging conditions like smoke or fog, as thermal data improves visibility and complements visual data when it produces unclear images. Finally, the model has shown strong results in wildlife search and rescue scenarios and does not misclassify non-human heat sources, such as fires or vehicles, as people. Figure 6 demonstrates the effectiveness of the system in various conditions, including search and rescue of wildlife, obstructed views, and aerial detection.

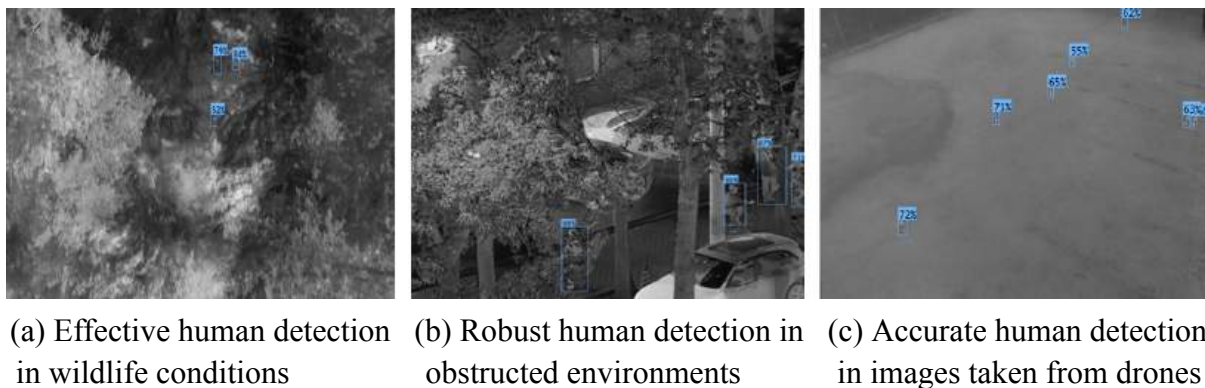


Fig 6: Examples of the system's strong performance in diverse conditions

While the model is highly effective, its behavior depends on the similarity between the two input images. If the images have the same or a highly similar background but differ in

In terms of position or number of people, the fused image includes humans from both input data and inaccurately detects them. However, if the images differ significantly—such as when captured in different locations—the fused output is essentially one of the images in grayscale rather than a true fusion. If the images are only slightly different, the system keeps high accuracy and can still identify humans effectively. Figure 7 illustrates these challenges, showing how the fusion process behaves with similar and totally different input images.



(a) Fusion of similar images with the same background but differing positions and numbers of people



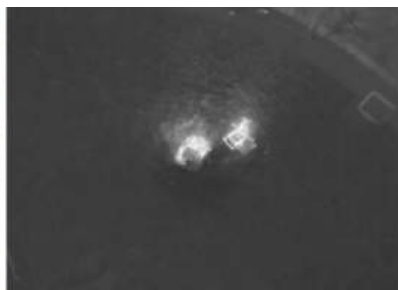
(b) Fusion of totally different images, resulting in an output that primarily reflects one image

Fig 7: Fusing distinct input images

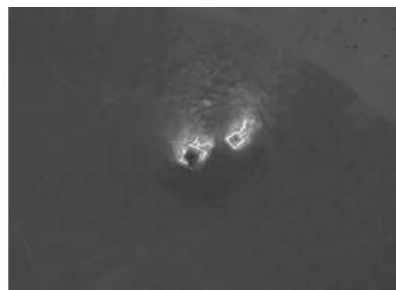
The model's detection accuracy also depends on the presence of humans in the input images. The model successfully detects all individuals if both images contain humans (in the same amount and position). If neither image contains humans, it correctly detects no humans. In cases where one image contains humans while the other does not, the detection outcome depends on the confidence score assigned to the image with humans during the fusion process. Most of the time, the model still detects the person, but in some instances, detection may be affected by how the images are fused. Figure 8, Figure 9, and Figure 10 illustrate these scenarios, showing how the model performs when one, both, or neither of the input images contain humans.



(a) Human detection on a visual image



(b) Human detection on a fused image



(c) Human detection on a thermal image

Fig 8: Comparison of human detection when neither input image contains people



(a) Human detection on a visual image

(b) Human detection on a fused image

(c) Human detection on a thermal image

Fig 9: Comparison of human detection when one input image contains one person and the other contains two



(a) Human detection on a visual image

(b) Human detection on a fused image

(c) Human detection on a thermal image

Fig 10: Comparison of human detection when both input images contain the same number of people

These results confirm that the model is well-suited for real-world rescue operations and demonstrates high reliability across different scenarios and environments.

Conclusion and Discussions

This research shows the efficiency of a model that detects people during rescue operations by combining thermal and visual data. In situations with low visibility or difficult environments like fog or smoke, the integration of thermal and visual data improves the detection capabilities. The model performs well when working with aerial imagery, as it can accurately recognize people even from far distances.

However, there are certain limitations. The detection accuracy of the model decreases in environments where significant obstructions hide more than 75% of the human body, such as dense forests or disaster zones laden with debris. Similarly, performance is affected when multiple individuals are closely packed together, especially in sitting or partially occluded positions. When the quality of input images is too poor to extract features effectively, the number of false negatives increases, lowering the model's accuracy. Figure 11 illustrates these limitations, showing the model's reduced performance in obstructed, crowded, and low-quality conditions.



(a) Lower accuracy in highly obstructed environments (b) Decreased performance in crowded environments (c) Reduced system's accuracy on low-quality input images

Fig 11: Conditions restricting model performance

To address these challenges, several improvements can be considered. Firstly, to determine how well it adapts to various environments, the system should be tested in challenging weather conditions, like heavy rainfall or snowfall. Moreover, to expand the model's detection abilities, it could be trained on data capturing more difficult conditions, such as snow avalanches and cases where individuals are partially hidden under debris.

Another way of improving is by exploring various object detection architectures to identify a model that has higher accuracy while also keeping short processing times. Improving the fusion algorithm to better handle differences in image backgrounds could reduce false positives caused by misalignment. Finally, adaptive image processing techniques could be used to improve decision-making when combining one input image featuring a person with another that does not.

In conclusion, despite its limitations, the system presented in this study offers a reliable solution for human recognition in search and rescue operations. By enhancing detection capabilities in occluded environments, extreme weather, and complex disaster scenarios, the system can become an even more valuable tool during emergency situations, improving the efficiency and success rate of rescue missions.

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How Do Effective Spin Measurements of Gravitational Wave Events Inform the Formation Channels of Compact Object Binaries in the Lower Mass Gap

By Om Kishan Manoj

Abstract

This paper investigates the mass distribution of neutron stars and black holes within observed binary systems and their significance in relation to the lower mass gap, focusing particularly on the effective spin parameter as an indicator of formation channels. The literature review first highlights the stages of stellar evolution leading to the formation of neutron stars and black holes, then explores the properties of these compact objects, the generation of gravitational waves, and the significance of the lower mass gap. In the methods section, the study discusses two primary formation channels—common envelope evolution (isolated binary evolution) and dynamical formation—and employs relevant advanced waveform models to analyze the spin distributions of three gravitational wave events: GW230529_181500, GW190425_081805, and GW200105_162426. The results reveal that the effective spin parameter for these events provides crucial insights into their likely formation mechanisms, with GW190425_081805 showing characteristics consistent with common envelope evolution and GW230529_181500 and GW200105_162426 aligning more closely with dynamical formation. These findings contribute to understanding the types of formation processes that produce candidates in the lower mass gap.

Introduction

Gravitational waves are ripples in the fabric of space-time produced and propagated by cataclysmic events in our Universe like the coalescence of neutron stars and black holes or both. These waves of gravitational energy carry essential information about the masses and dynamics of their sources. The advent of gravitational wave observations has enabled the investigation of mass distribution of neutron stars and black holes within binary systems. This study of the mass distribution, particularly in relation to the lower mass gap, is a research area of substantial significance in astrophysics. The lower mass gap is a mysterious region characterised by uncertainties relating to the masses of neutron stars and black holes. This region between the heaviest neutron star and the lightest black hole is estimated to be approximately $2.5M_{\odot}$ to $5M_{\odot}$. The intriguing gap suggests the existence of underlying astronomical processes that result in difficulty and scarcity in the formation and/or detection of compact objects within this precise range. Understanding this gap is essential for unravelling the complexities of stellar evolution and the end states of massive stars. This research will integrate gravitational wave observation data around the lower mass gap to provide a comprehensive analysis of the mass distribution of neutron stars and black holes within observed binary systems and their implications for the lower mass gap. Fundamental areas of study in gravitational-wave astrophysics also include the formation and evolution of compact objects like black holes and neutron stars. These objects, which were created from the remnants of massive stars, are essential to our comprehension of the cosmos because of the gravitational waves they release when they coalesce. The study aims to

advance our understanding of neutron stars and black hole formation and evolution by amalgamating existing literature, analyzing current data, and further its implications for gravitational physics and cosmology.

The first section (Section I—Background) of this paper includes an extensive literature review, starting with the stages of stellar evolution that lead to the formation of compact objects. The description outlines the progression of a star from its main sequence phase to the final stages of its existence, when, based on its initial mass, it either collapses into a neutron star or forms a black hole. Then we discuss the complex features and attributes of black holes and neutron stars, as well as their mass distributions and significance in relation to gravitational wave astronomy. Then the review delves into the phenomenon of gravitational waves, with a focus on how these spacetime ripples, produced by the coalescence of compact objects, offer a new window into understanding binary systems. The review ends by introducing the lower mass gap: a scarce region between the masses of neutron stars and black holes. Following the literature review section, the next section is the methods section of the paper where we discuss the two main formation channels that are theorized to produce binary systems: isolated binary evolution (common envelope evolution) and dynamical formation. This section also presents the analytical methods used to assess the χ_{eff} distributions of three specific gravitational wave events—GW230529_181500, GW190425_081805, and GW200105_16242. The χ_{eff} is essentially the effective spin measure of a gravitational wave (it is explained in detail in Section II—Methods). We plot relevant waveform models to infer the effective spin parameter of each event.

In Section III—Results and Conclusion, we interpret the values of χ_{eff} plotted for the three gravitational wave events, concluding the likely formation channels of these binary systems. GW230529_181500 and GW200105_162426, with negative χ_{eff} values, appear to align more closely with dynamical formation whereas GW190425_081805, with a positive χ_{eff} , suggests characteristics consistent with isolated binary evolution. These findings provide insights into the types of formation processes that produce candidates in the lower mass gap. Finally, the paper concludes by discussing the implications of these results for our understanding of the formation of compact objects and thus their astrophysical significance of the lower mass gap.

Literature review

Stellar Evolution

To study the mass distribution of neutron stars and black holes in observed binary systems and its significance within the lower mass gap, we must first understand the stages of stellar evolution that ultimately result in the formation of compact objects such as neutron stars and black holes. Every star in the night sky forms in molecular clouds of gas and dust called “stellar nurseries” or “star-forming regions”. These clouds continue accumulating mass over time until they reach “Jeans mass” (1), above which they collapse under their immense gravity. This gravitational collapse leads to the formation of a protostar, the first stage of stellar evolution. The protostar continues to absorb mass from its surrounding environment until it reaches high enough temperatures and pressures to begin nuclear fusion in its core, signifying its transition to the

main sequence. During the main sequence phase, a star's core undergoes fusion from smaller elements to heavier releasing vast amounts of energy that maintains hydrostatic equilibrium by counteracting the inward gravitational forces. The duration of a star's life solely depends on its initial mass. Lower-mass stars (mass less than $2M_{\odot}$) have cool cores and burn their hydrogen fuel slowly thus remaining on the main sequence for tens of billions of years. High-mass stars (mass less than $8M_{\odot}$), on the other hand, burn through their hydrogen fuel far more quickly due to their hotter and more luminous cores. They subsequently do not remain on the main sequence for very long and exit within a few million years. The star exits the main sequence and enters the red giant or supergiant phase after the hydrogen in its core is exhausted, during which it starts fusing helium and heavier elements. When a star with less than $8M_{\odot}$ exits the main sequence, its radius and luminosity increase dramatically with its temperature remaining relatively constant. These stars climb the red giant branch almost vertically (i.e. its luminosity increases significantly while its surface temperature decreases only slightly). Their outer layers finally shed during the red giant phase, leaving behind a dense core that eventually develops into a white dwarf. However, for higher-mass stars, the evolutionary path diverges significantly. They fluctuate back and forth across the top of the H–R diagram (2) with their surface temperatures rising and falling alternately and their radii varying in size while their luminosities remain relatively constant. During their back-and-forth movement in their evolutionary track, these stars fuse not just hydrogen, helium, and carbon, but also oxygen, neon, magnesium, silicon, and even heavier elements like iron as their inner cores continue to contract and their central temperatures continue to rise. The star's luminosity stays roughly constant as its radius increases and its surface temperature drops until it swells to become a red supergiant. As the star exhausts its nuclear fuel, the core's fusion reactions produce elements up to iron, which does not generate energy to counteract the inward gravitational pull. The core then approaches the Chandrasekhar limit (approximately $1.4M_{\odot}$, see (3)) beyond which it can no longer be supported against gravitational collapse by electron degeneracy pressure. This pressure is a phenomenon explained by Pauli's Exclusion Principle (a basic governing rule in quantum mechanics, see (4)) which states that fermions, in this case electrons, strongly resist being squeezed together. It is in this instant that the core collapses catastrophically. Then a spectacular supernova explosion occurs as the star's outer layers collide with its extremely dense core.

Formation of Neutron Stars and Black Holes

The cores of lower-mass stars rely on the electron degeneracy pressure to sustain themselves. Despite that, if the mass of the core exceeds the Chandrasekhar limit, the electron degeneracy pressure is insufficient to halt the collapse of the star. This ultimately results in protons, electrons, and other subatomic particles smashing into one another at such extreme pressures that they combine to form neutrons. The core collapses into a sphere with a diameter of approximately 20 km. Essentially a ball of neutrons, it has a crust of compressed matter and a few uncombined protons and electrons. Following this, a further effect that differs from electron degeneracy known as neutron degeneracy pressure comes into play. Like electrons, neutrons are also fermions and thus also resist being squeezed too tightly together; however, the strength of their pressure is much greater than that of electrons. The collapse hits a wall and comes to a stop if the core is less than or equal to $2.8M_{\odot}$ but still greater than $1.4M_{\odot}$. This produces a huge

shock wave, which, along with an outward-blasting stream of neutrinos, explodes the star. What's left of the core after the shockwave of smoke clears is a neutron star. The end product of a star's evolution is different if its core exceeds the Tolman–Oppenheimer–Volkoff limit (TOV limit is approximately $2.8M_{\odot}$, see (5)); above this mass, not even tightly packed neutrons can withstand the star's gravitational pull. There is no known force that can counteract gravity beyond this point. Thus, if enough material is left behind after a supernova or hypernova explosion that the central core exceeds this limit, or if enough matter falls back onto the neutron star after the supernova has occurred, gravity wins the battle with pressure once and for all, and the central core collapses forever. As the core shrinks and its size drops down to roughly 18km the gravitational pull in its vicinity eventually becomes so great that the escape velocity at its surface becomes equal to the speed of light, thus resulting in an object that nothing—not even light can escape. This object is known as a black hole.

Properties of Neutron Stars and Black Holes

The mass of a neutron star is around a million times that of Earth's or equivalently about three solar masses. The fact that all of this matter is packed into a sphere of only about 20 km in diameter makes a mere cubic centimetre of “neutronium” (matter that makes up a neutron star) have a mass of 400 million tonnes. These fascinating interstellar bodies have an incredibly strong magnetic field ranging from 10^8 - 10^{15} gauss (for reference Earth's field has a strength of 0.25 - 0.65 gauss). This results in the magnetosphere of neutron stars being the strongest in our Universe. The structure of a neutron star consists of an atmosphere ~ 10 cm thick consisting of plasma. Additionally, there is also a “sea of electrons” known as degenerate Fermi gas whose electron degeneracy pressure prevents the atmosphere from collapsing any further. Neutron stars have extremely dense and solid crusts, essentially a crystalline lattice of mostly iron, the last element forged in the core before the collapse. The crystalline structure arises from the ionized nuclei forming a gridlock due to mutual repulsion and extreme gravitational forces of attraction. The deeper you go into the crust of a neutron star; electrons are driven into iron nuclei by a process known as “electron capture”. In this process, electrons fuse with protons to manufacture neutrons making iron nuclei into elements with lower atomic numbers but still the same mass as they are abundant in neutrons. Furthermore, there is another phenomenon known as “Neutron Drip” which is essentially a process in which neutrons leak from nuclei, since they are very neutron-rich, into empty spaces between them. Electron gas (now minimized due to electron capture) is now being replaced by neutron gas and thus the star is supported by neutron degeneracy pressure. When you go even deeper into the neutron star, the numerous nuclei come in contact with one another and rearrange and reshape. This rearrangement results in nuclei forming cylinders of protons and neutrons known as “nuclear pasta” which when squeezed further forms “nuclear lasagna”. Finally, within the core, neutrons of spin pair up to form Cooper pairs (these Cooper pairs have spins of 0 or 1, see (6)) and thus fermions behaving like bosons allow the neutrons to become superfluid, i.e. frictionless. Rare copper pair protons turn the core into a superconductor which is theorized to help in maintaining the star's powerful magnetic field. The state of particles at the exact centre of the core is highly theoretical; possible scenarios include protons and neutrons dissolving into a quark-gluon plasma or hyperon particles being found (particles containing strange quarks) or protons and neutrons remaining as they are.

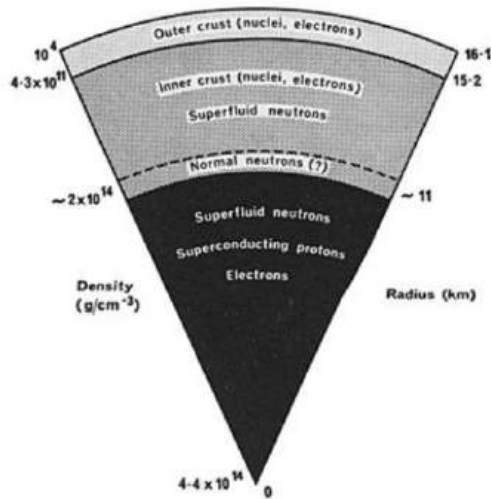


Fig 1-Visual depiction of the structure of a neutron star describing constituent particles at different depths (km) and corresponding densities (g/cm³). Figure taken from NASA

Unlike neutron stars, black holes have no physical surface. When looking at a black hole, what we see is the event horizon, a boundary around the black hole that marks the point at which the escape velocity is equal to the speed of light. The centre of a black hole is called the singularity and is theorized to be the point where all the mass is concentrated in no volume or space. At the singularity, gravity is thus infinitely strong, and the density is indefinite. The radius of the event horizon enveloping the singularity is given by the Schwarzschild radius (7), $R_s = \frac{2GM}{c^2}$, where G is the gravitational constant, M is the mass of the black hole and c is the speed of light.

Depending on their masses, black holes are classified into three types: stellar-mass black holes, intermediate-mass black holes, and supermassive black holes. Additionally, there is a fourth type known as primordial black holes which may be either of the former three. Stellar-mass black holes range from a few to 100 solar masses, and they then can proceed to gain more mass through collisions with stars and other black holes. Most stellar-mass black holes are detected in pairs where the black hole is accreting matter from its companion star. If the black hole pulls enough gas off the star into the disk such that it heats up enough to produce X-rays, the pair is known as an X-ray binary. Intermediate black holes range from 100 to 100,000 solar masses and are believed to be the products of collisions between stellar-mass black holes and accretion from other compact objects or through the collapse of massive star clusters or that they are primordial black holes formed in the Big Bang. There have been several discoveries for potential intermediate-mass black hole candidates; however, these so-called missing-link black

holes have proven difficult to confirm. Supermassive black holes have masses ranging from hundreds of thousands to billions of solar masses and reside in the centres of galaxies. The one at the centre of our very own Milky Way Sagittarius A* has a mass of around 4 million solar masses. Scientists are aware that supermassive black holes can grow by consuming smaller objects such as neutron stars and their stellar-mass relatives, despite the fact their origins remain unknown. When galaxies collide, they can also combine with other supermassive black holes. Finally, primordial black holes are hypothetical black holes theorized to have formed soon after the Big Bang, as in that moment extremely dense subatomic matter pockets were packed so tightly that they caused gravitational collapses which formed primordial black holes without the need for supernovae. They may have masses ranging from 10^{-8} kg to 100,000 solar masses however, primordial black holes with masses below 10^{11} would not survive the present due to Hawking radiation (8). Scientists have not yet found definitive proof these primordial black holes ever existed; however, it is possible that quantum mechanical processes taking place at their event horizons caused them to evaporate as the universe aged.

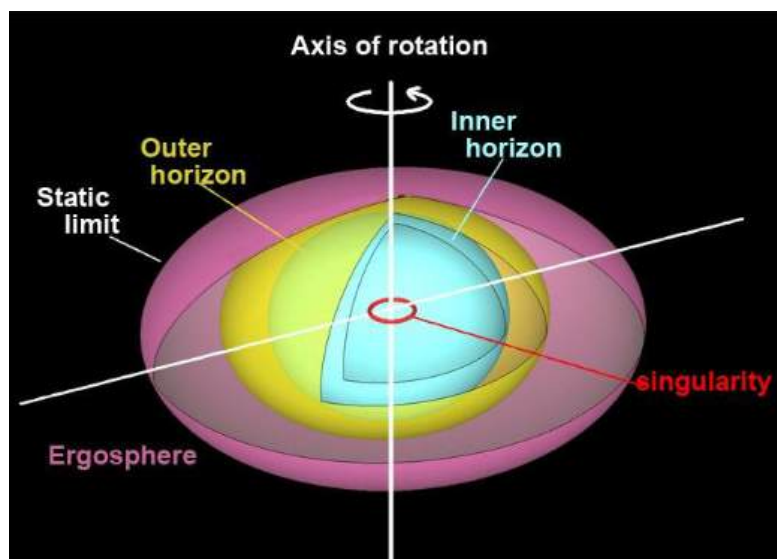


Figure 2- Visual depiction of the structure of a rotation black hole - Scientific Figure on ResearchGate

Gravitational waves

Gravitational waves are ripples in the fabric of space-time produced and propagated by cataclysmic events in our universe like the coalescence of neutron stars and black holes or both as well as supernovae. They are categorized into four types namely: Compact Binary Inspirals, Continuous Gravitational Waves, Stochastic Gravitational Waves and Burst Gravitational Waves. Albert Einstein initially predicted gravitational waves in 1916 in his Theory of General Relativity (9). However, the first evidence of their existence was only found in 1974 when two astronomers, Joseph Taylor and Russell Hulse, discovered a binary pulsar (10) 21000 light years from Earth using the Arecibo Radio Observatory in Puerto Rico. The current primary detectors for gravitational waves include LIGO (11) (Laser Interferometer Gravitational-Wave Observatory) in the United States (Hanford and Livingston), Virgo (12) in Italy and KAGRA (13) (The Kamioka Gravitational Wave Detector) in Japan. In 2015, LIGO made the first direct detection of gravitational waves from the coalescence of two black holes 1.3 billion light-years away. GW150914 (14) was a monumental discovery which opened the door to a new way of observing and studying the universe. This is provided by the fact that these waves convey data about the nature, masses, spins and other features of the merging objects within binary systems. By inferring the data communicated by these waves, we understand the mass distribution of neutron stars and black holes. Another breakthrough observation was GW170817 (15), as it was the first detection of a binary neutron star merger. Further, unlike previous GW observations, it was the first event to be detected in conjunction with electromagnetic signals including gamma-ray bursts, X-rays, ultraviolet, optical, infrared, and radio waves. Ultimately, these intense waves of gravitational energy carry essential information about the masses and dynamics of their sources. The advent of gravitational wave observations has enabled the investigation of mass distribution in neutron stars and black holes within binary systems, especially concerning the lower mass gap.

Lower mass gap

The lower mass gap is a mysterious region characterised by uncertainties relating to the masses of neutron stars and black holes. As mentioned previously, the maximum mass that an NS (Neutron Star) can support before succumbing to gravitational collapse into a black hole is known as the Tolman–Oppenheimer–Volkoff (TOV) mass M_{TOV} . According to (16), recent theoretical and observational constraints on the EOS (Equation of State) have placed $M_{\text{TOV}} = 2.2 - 2.5M_{\odot}$. The current heaviest known neutron star is PSR J0952-0607 with an estimated mass of $2.35 \pm 0.17 M_{\odot}$, therefore observations of massive pulsars set a lower limit of $M_{\text{TOV}} \geq 2M_{\odot}$. The lightest black hole discovered is in the binary system XTE J1650-500 which contains a stellar-mass black hole candidate paired with a star. This black hole was claimed to have a mass of $3.8 \pm 0.5M_{\odot}$. Still, recent fits of the BNS (Binary Neutron Star), BBH (Binary Black Hole) and NSBH (Neutron Star-Black Hole Binary) mass spectrum find a relative lack of objects between $2.6 - 6M_{\odot}$.

Methods

The two formation channels for the evolution of binary systems are formation in isolation—Common Envelope Evolution (CEE) and formation in star clusters—Dynamic Formation (DF) (17).

CEE

The common envelope is not yet fully understood and thus uncertainties may arise. However, what we have discovered so far is that it is a critical stage in the evolution of close binary systems, particularly those that eventually produce compact objects like neutron stars, black holes, or white dwarfs. After the main sequence phase, massive stars may develop stellar radii as massive as several thousand solar radii. Hence, if this star has an orbital separation that is small enough (around a hundred to a few thousand solar radii), the binary system begins with the two stars orbiting one another eventually expanding and filling their Roche lobe (18) and possibly common envelope. When material spills over to the companion star and the mass transfer becomes unstable, the companion star may be unable to accrete all incoming material, resulting in the formation of a common envelope around both stars. This common envelope is essentially a gas that contains the binary system. Now the core of the larger star and the mass-losing star orbit each other within a shared envelope. Friction caused by a strong gas drag from the envelope results in cores losing kinetic energy, inspiralling about each other. The loss of energy causes the envelope to be ejected into space, leaving behind a tighter, closer binary system. Depending on the initial masses and other properties of the stars, the outcome can vary: The envelope ejection can leave behind a close binary made up of a compact object and a companion star or if the spiral-in process is too aggressive, the two cores may merge, resulting in a single, more massive star.

DF

In Dynamical Formation, binary systems involving compact objects are formed by interaction in dense stellar environments like globular clusters, nuclear star clusters, open clusters and young clusters. Such environments imply that the orbits of stars and binary star clusters are constantly perturbed by dynamical encounters with other cluster members, and they then undergo three-body encounters or even multi-body interactions. This process affects the formation and evolution of binary systems. Essentially, dynamical exchanges occur when a binary system interacts with a single stellar object and the latter replaces one of the members of the binary. During these encounters, a more massive compact object can replace a less massive star in an existing binary system using a process known as exchange interaction. This may result in the formation of BBH or NSBH systems.

One of the clearest markers of the underlying formation channels is the spins of the two merging objects. It is common knowledge that systems formed by dynamical interactions in stellar clusters or globular clusters close to active galactic nuclei will have a random distribution of spin angles (see (19)). On the other hand, spins of binaries formed in galactic fields through common envelope evolution are predicted to be preferentially aligned with their orbital angular

momentum. Initial quantitative studies utilizing GW observations to infer the formation channel of binaries had begun with the measurement of individual spin parameters. Since then, it has been found that the measurement of the two-component spins is better when the combination is used rather than either one alone (see (20)). This is the mass-weighted combination of the projection of the two spins along the orbital angular momentum, usually called the effective spin parameter:

$$\chi_{eff} = \frac{S_1/m_1 + S_2/m_2}{m_1 + m_2}$$

Where m_1 and m_2 are masses of two compact objects in the binary system and χ_1 and χ_2 are the dimensionless spin parameters of the two objects (21).

The gravitational wave events— GW230529_181500 (22), GW190425_081805 (23), GW200105_162426 (24) are observations in which one of the compact objects in the detected binary system is close to the lower mass gap. The primary compact objects of events GW190425_081805 and GW200105_162426 as well as the secondary compact object in GW230529_181500 are all candidates that fall into the lower mass gap. Therefore, using the effective spin parameters of the three gravitational wave events GW230529_181500, GW190425_081805, and GW200105_162426, we can figure out whether the distributions are more aligned with CEE formation or Dynamical formation. This further gives us an insight into which formation channel produces candidates within the lower mass gap.

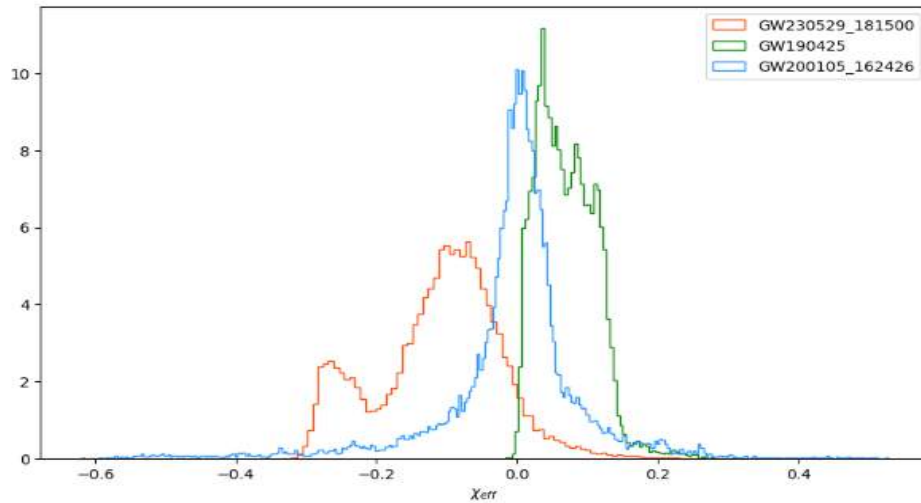


Figure 3- Distribution of effective spin parameter χ_{eff} for three gravitational wave events: GW230529_181500, GW190425_181500, and GW200105_162426. The histograms illustrate the range and density of χ_{eff} values for each event, providing insights into the spin alignment of the binary black hole systems. (The data is normalized to density for comparison).

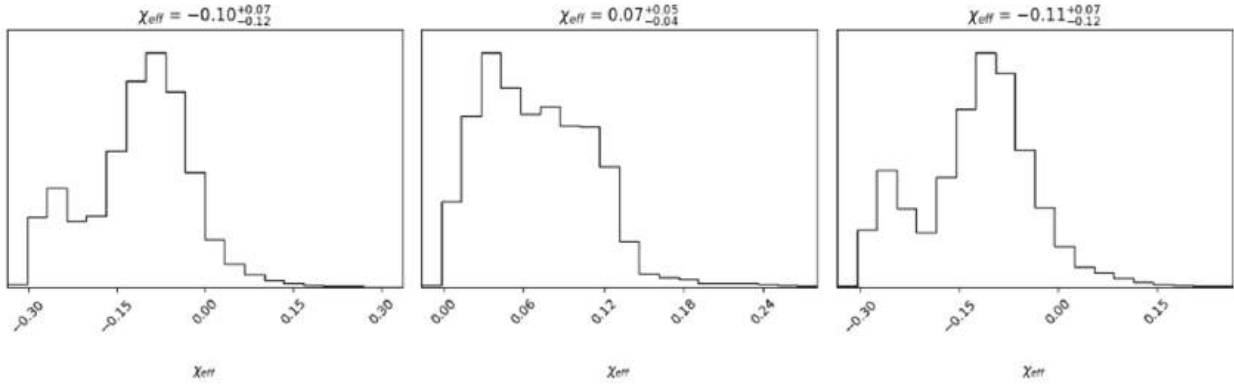


Figure 4- Corner plots for the effective spin parameter (χ_{eff}) of three gravitational wave events: GW230529_181500, GW190425_081805, and GW200105_162426. The plots display the posterior distributions of χ_{eff} for each event, along with their associated uncertainties. GW230529_181500 has $\chi_{\text{eff}} = -0.10 (+0.07, -0.12)$, GW190425_081805 shows $\chi_{\text{eff}} = 0.07 (+0.05, -0.04)$, and GW200105_162426 has $\chi_{\text{eff}} = -0.11 (+0.07, -0.12)$. These distributions provide insights into the likely formation channels of these binary systems, contributing to our understanding of the origins of such events.

In order to extract and compare the effective spin distributions of the gravitational wave events GW230529_181500, GW190425_081805, and GW200105_162426, three different waveform models have been used. Each waveform model offers multiple methods to model the gravitational waves produced by the binary systems. For both events GW230529_181500 and GW200105_162426, the waveform models employed were Combined_PHM_highSpin and C01: Mixed respectively. This is because these models combine aspects of various waveform families to accommodate a range of scenarios, including mixed spin and mass configurations. In particular, Combined_PHM_highSpin is renowned for accurately capturing the waveform when the compact objects are spinning quickly which is relevant to that particular event. However, for GW190425_081805 there were no mixed or combined waveforms available, so the most suitable waveform was C01:IMR PhenomPv2_NRTidal:HighSpin whose incorporation of tidal effects helps in accounting for the interaction between neutron stars.

Results and Conclusion

As previously mentioned, understanding the formation channels of binary systems observed with gravitational waves depends on their χ_{eff} . Negative or almost zero values frequently indicate dynamical formation channels, where the spins are more likely to be misaligned as a result of complex interactions in dense stellar environments. Positive values, on the contrary, typically suggest aligned spins, which can indicate a history of the CEE pathway.

The effective spin for GW230529_181500 is slightly negative with a value of 0.10 and a significant range of uncertainty. The inclination of χ_{eff} being towards the negative implies the spins of the binary components are unaligned with the orbital angular momentum. Such misalignment is more consistent with the dynamical formation channel as it is possible that

interactions of binary components with other stars could have momentarily captured or exchanged them, resulting in unaligned spins. The effective spin for GW190425_081805 is not only significantly positive with 0.7 but also has a narrow range of uncertainty. It is therefore indicated by this substantially positive value of χ_{eff} that the spins of the binary components are aligned with the orbital angular momentum. Such alignment is consistent with the Common Envelope Evolution formation channel as it can be connected that the isolated environment perhaps contributed to allowing the binary components to maintain aligned spins. The effective spin for GW200105_162426 is slightly negative, with a value of 0.11 and a significant range of uncertainty. This implies a degree of misalignment of spin once again, more indicative of a dynamical formation channel. The negative χ_{eff} indicates that the binary components' current misaligned spin orientation may have perhaps also resulted from complex interactions in a dense stellar environment.

These findings imply that the lower mass gap might be populated by objects formed through a mix of both isolated binary evolution and dynamical formation, with the latter potentially being more common for systems with χ_{eff} . The contrasting χ_{eff} values emphasize the diversity in the formation pathways of compact object binaries and highlight the complexity of the processes involved. However, it is important to note that these interpretations are not completely accurate and still highly theoretical. This is because sometimes, complex interactions or supernova kicks can cause the spins of the binary components to become misaligned, leading to negative values in isolated binary evolution. On the other hand, positive values can result from dynamical formation, provided that the objects being captured have aligned spins.

In conclusion, this research advances our knowledge of the formation of compact object binaries and the significance of gravitational waves in examining these systems. The results shed light on the nature of the lower mass gap and highlight the significance of χ_{eff} as a diagnostic tool in identifying formation channels. To further improve our understanding of the connection between spin, formation channels, and mass distribution in the universe, future research should keep investigating a wider variety of gravitational wave events.

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The Role of the Gut Microbiome in Parkinson's and Alzheimer's Disease

By Shreya Sreejith

Abstract

Parkinson's Disease (PD) and Alzheimer's Disease (AD) are prevalent neurodegenerative disorders with significant impacts on patients and healthcare systems worldwide. Affecting millions annually, these diseases lack definitive cures, and their diagnosis remains challenging due to overlapping symptoms and complex pathology. Emerging research on the gut-brain axis (GBA) reveals its critical role in linking gut microbiota imbalances with neurodegenerative diseases.. Alterations in gut microbiota diversity are implicated in neurodegenerative processes such as neuroinflammation, amyloid-beta deposition, tau pathology, and α -synuclein aggregation. These findings emphasize the importance of understanding gut-brain interactions for early diagnosis and helpful treatments. The intersection of PD and AD research with GBA science highlights potential non-invasive strategies like dietary interventions, such as the Mediterranean Diet, to balance gut microbiota and mitigate disease progression. This body of work advances our understanding of the GBA's significance and its therapeutic implications in combating neurodegenerative diseases.

Parkinson's disease

Parkinson's Disease (PD) is a complex neurodegenerative disorder characterized by a combination of motor and non-motor symptoms, making its diagnosis and treatment particularly challenging. The preclinical phase of PD spans 10-25 years, during which symptoms overlap with other neurodegenerative diseases, complicating early diagnosis (Tolosa, 2022). The primary motor symptoms of PD are encapsulated by the acronym TRAP, representing Tremor at rest, Rigidity, Akinesia, and Postural instability. Bradykinesia, a significant symptom identified during neurological examinations, and other motor symptoms such as postural deformities and freezing (motor blocks), can manifest in the early stages (Tolosa, 2022). Non-motor symptoms, including autonomic dysfunction, cognitive and neurobehavioral disorders, and sensory and sleep abnormalities, are also prevalent.

The progression of PD is often assessed using the Hoehn and Yahr staging system, which evaluates the disease from unilateral damage to severe stages affecting daily living activities and motor functions. The genetic aspects of PD reveal that familial forms of the disease are linked to high penetrance pathogenic variants, while sporadic PD is influenced by low penetrance variants and shared genetic-environmental factors. Key genetic mutations, such as those in the α -synuclein gene (SNCA), have been implicated in both familial and sporadic cases, indicating a connection between gene activity, α -synuclein aggregation, and mitochondrial dysfunction.

Pathology of PD

The gut-brain axis (GBA) is a dynamic and intricate system that plays a crucial role in Parkinson's Disease (PD) pathogenesis. Recent research highlights the bidirectional communication between gut microbiota and the central nervous system (CNS), where microbial dysbiosis contributes to the onset and progression of neurodegenerative disorders. In PD, an imbalance in gut microbiota has been associated with α -synuclein aggregation, a defining

pathological feature of the disease. This aggregation often begins in the enteric nervous system and spreads to the CNS via the vagus nerve. Dysbiosis also disrupts the intestinal barrier, increasing gut permeability and allowing harmful metabolites and neurotoxic agents to enter systemic circulation, exacerbating neuroinflammation and neuronal degeneration. These findings underscore the importance of maintaining gut health as a potential therapeutic strategy for PD.

Genetic predispositions further amplify the impact of GBA dysfunction in PD. Mutations in genes like GBA and SNCA impair lysosomal function and α -synuclein clearance, creating a feedback loop of neurotoxicity and inflammation. Studies show that individuals with these genetic mutations often exhibit altered gut microbiota compositions, suggesting an interplay between genetic and microbial factors in disease progression. Furthermore, gut microbiota can influence gene expression through metabolites like short-chain fatty acids, which modulate inflammatory and neuroprotective pathways. This complex interaction offers promising avenues for precision medicine, integrating genetic profiling with microbiota-based therapies, such as probiotics, prebiotics, and dietary interventions. These approaches could provide non-invasive methods for mitigating PD risk and progression, emphasizing the GBA as a focal point in neurodegenerative disease research

Treatments for PD

Currently, there is no cure for Parkinson's Disease, and treatments focus on alleviating symptoms and improving quality of life. Pharmacological treatments include dopamine agonists, catechol-O-methyltransferase inhibitors, and monoamine oxidase B inhibitors, which help manage motor symptoms. However, a significant percentage of PD patients with pain do not receive adequate analgesic treatment, highlighting the need for comprehensive pain management strategies. Non-pharmacological treatments, such as psychokinesis therapy (PKT) and exercise, are recommended to address musculoskeletal pain resulting from stiffness and akinesia. The development of dystonia, a complication of dopaminergic treatment, requires careful management during off periods. Multidisciplinary approaches, integrating both pharmacological and non-pharmacological treatments, are essential for effective PD management. Recent research into the dysregulation of mRNAs opens new avenues for potential treatments targeting PD pathogenesis, offering hope for future advancements in PD therapy.

Alzheimer's Disease

Alzheimer's Disease (AD) is a multifaceted neurodegenerative disorder characterized by significant challenges in diagnosis and treatment due to its heterogeneous nature. It is a brain disorder that slowly destroys memory and thinking skills, and eventually, the ability to carry out the simplest tasks. AD is a disease that affects 50 million people worldwide. It is estimated that this number will reach 152 million by 2050 (Wei, 2024). In most people with Alzheimer's, symptoms first appear later in life. Estimates vary, but experts suggest that more than 6 million Americans, most of them age 65 or older, may have Alzheimer's (Smith 2023). Alzheimer's is currently ranked as the seventh leading cause of death in the United States (Smith et al 2023). There is no effective treatment for AD, which results in symptoms worsening as the condition progresses. AD has been recognized as a global public health priority by the World Health Organization- WHO (Flyer 2021).

Pathology of AD

The neuropathological indications of Alzheimer's are extracellular A β and the formation of neurofibrillary tangles (NFTs). When there is a loss of synapse and neurons, it results in the development of A β and NFTs (Fan, 2020). A β plaques develop initially in the basal, temporal, and orbitofrontal neocortex regions of the brain and eventually spread into the neocortex, hippocampus, amygdala, diencephalon, and basal ganglia (Walker 2020). Many hypotheses have been proposed to figure out the action of the A β plaques and NFTs in Alzheimer's. Some examples are: the amyloid cascade and oxidative stress hypotheses.

An NFT consists of helical and straight filaments which have an abnormally phosphorylated form of the microtubule-associated protein: tau. Tau is mainly found in the neurons of the brain, specifically in the neuronal axis (Mandelkow, 2012). When tau is truncated, it is unable to bind to microtubules, which promotes tau aggregation (Ciesk, 2015).

The progression of AD is marked by neuropsychiatric symptoms (NPS) such as apathy, depression, anxiety, aggression, sleep disturbances, appetite changes, aberrant motor behavior, delusions, disinhibition, euphoria, and hallucinations. These symptoms reflect the underlying neurodegenerative processes and can significantly impact patients' quality of life. The disease advances from mild cognitive impairment to severe dementia, with substantial reduction in amyloid plaques being a key pathological feature. Genetic factors also play a pivotal role in AD, with familial cases often linked to PSEN1 mutations and the APOE ϵ 4 allele identified as the strongest genetic risk factor for sporadic AD. Sporadic AD typically manifests after the age of 65, with proteins such as TREM2 also implicated in disease progression. Despite extensive research, there is no cure for AD. Current treatments focus on managing symptoms, with medications like cholinesterase inhibitors and memantine used to address cognitive decline. Continued research into the molecular mechanisms of A β and tau aggregation, misfolding, inflammation, and oxidative damage is essential for developing more effective therapeutic strategies.

Treatments for AD

Current treatments for AD focus on alleviating symptoms rather than providing a cure, with pharmacological approaches centered around two primary drug classes: anticholinesterase inhibitors (e.g., donepezil, galantamine, rivastigmine) and anti-glutaminergics (e.g., memantine). Anticholinesterase inhibitors enhance acetylcholine levels to support memory and cognitive function, while anti-glutaminergics regulate glutamate activity to prevent neurotoxicity. Although these drugs temporarily stabilize cognitive decline and behavioral symptoms, their effectiveness diminishes as the disease progresses. A major challenge lies in delivering these drugs across the blood-brain barrier (BBB), a protective structure that restricts many therapeutic molecules from entering the brain. Consequently, research is increasingly focused on developing strategies to overcome this barrier, such as nanoparticle-based drug delivery systems.

Emerging technologies, particularly nanotechnology, offer promising solutions for AD treatment. Liposomes and exosomes are innovative nanocarriers capable of crossing the BBB to deliver therapeutic agents directly to affected brain regions. These nanoparticles provide protection for drugs, enhance their bioavailability, and enable targeted delivery to minimize side effects. For instance, liposomes modified with ligands or antibodies can leverage

receptor-mediated transcytosis to penetrate the BBB. Similarly, exosomes, with their natural lipid composition and cellular adhesion molecules, exhibit superior biocompatibility and targeting capabilities. These advancements highlight the potential of nanotechnology to address the limitations of traditional therapies, paving the way for more effective and precise treatment options for AD.

What is the Gut-Brain Axis?

The gut microbiota contains complex communities of micro-organism species that reside in our gastrointestinal ecosystem. It primarily consists of bacteria, fungi, archaea and parasites (Illiano, 2020). Additionally, the number of bacteria in the human gut is nearly equivalent to the number of human cells, significantly expanding human metabolic capabilities (Morais 2020). Its alterations can influence various gut disorders and also central nervous system (CNS) disorders (Jiang, 2017). When imbalances occur in the gut microbiota it can induce inflammation that can be associated with many different diagnoses such as type 2 diabetes and neurodegenerative diseases (Jiang, 2017). Specifically within the GI tract, variations in the microbial density and compositions are influenced by chemicals, nutrition and immunological factors (Picconi, 2022). Furthermore, the gut-brain axis is a complex bidirectional network connecting the gut and brain through communication. The intricate communication involves the coordinated interaction of the nervous, immune, and endocrine systems between the gastrointestinal (GI) tract and the central nervous system (CNS) (Zheng, 2023). It plays an important role in balancing both physical and mental health while controlling homeostasis within the GI tract, CNS, and microbial systems.

Alzheimer's Disease and GBA

Recent evidence suggests that the gut microbiota–brain axis could offer insights into the early diagnosis and treatment of neurodegenerative disorders, including depression and AD (Jiang H, 2015). The gut microbiota's role in AD pathogenesis has been extensively explored, revealing that individuals with AD and mild cognitive impairment (MCI) exhibit a lower gut microbiota diversity index than healthy controls (Aziz, 2024). Also, the gut microbiota is thought to be involved in AD through alterations of at least 5 different pathogenic processes: amyloid-beta deposit, increase tau, phosphorylation, neuroinflammation, metabolic dysfunction, and oxidative stress (Nguyen, 2023). In addition, bacteria populating the gut microbiota can secrete large amounts of amyloids and lipopolysaccharides, which might contribute to the modulation of signaling pathways and the production of proinflammatory cytokines associated with the pathogenesis of AD. A study that was conducted showed that individuals with gut microbiome dysbiosis is due to intestinal disease which puts patients at a higher risk for AD (Chen 2016). Microbiome dysbiosis is where altered gut microbiota composition leads to the production of neurotoxic metabolites and the disruption of gut barrier integrity. Dysbiosis results in increased gut permeability, allowing harmful substances to enter the bloodstream and reach the brain. Approximately 85% of patients with dementia were reported to have alterations of gut microbiota compositions compared to populations of healthy individuals (Paranjaype, 2019). Neuroinflammation is one of the possible mechanisms to explain pathogenesis. It is supposed to be a physiological response to stimuli that maintains homeostasis, but when excessive it becomes harmful to the CNS. The inflammation can result in immense amounts of amyloid- beta being formed

and tau pathology. Changes in the gut microbiota composition can trigger immune responses by activating immune components and regulating levels of pro-inflammatory cytokines in the brain (Fung, 2020). A metabolic imbalance in the gut microbiota can lead to an overactive immune response, damaging neuronal cells and promoting neurodegeneration. The gut microbiota affects metabolic pathways including lipid metabolism and glucose homeostasis (Angelucci, 2019). Gut microbiota can produce bioactive metabolites, such as SCFAs and neurotransmitters which can modulate the immune system and influence brain activities (Rutsch, 2020).

Parkinson's Disease and GBA

The connection between Parkinson's disease (PD) and the gut is increasingly recognized as a pivotal aspect of the disease's pathogenesis. Alterations in the gut microbiome (GM) have been linked to the initiation and progression of PD, with evidence suggesting that α -synuclein aggregates, a hallmark of PD, may originate in the enteric nervous system (ENS) before spreading to the central nervous system (CNS) via the vagus nerve. This mechanism, proposed in Braak's hypothesis, is supported by studies showing that gut-derived microbial products can influence neuroinflammatory pathways and exacerbate neurodegeneration. Dysbiosis in the GM leads to increased gut permeability, systemic inflammation, and oxidative stress, all of which contribute to neuronal damage. Specific microbial metabolites, such as short-chain fatty acids (SCFAs), play a dual role; while some SCFAs exhibit neuroprotective effects, others may promote neuroinflammation, depending on their levels and composition. Furthermore, increased levels of pro-inflammatory markers, including cytokines and lipopolysaccharides, have been observed in PD patients, reinforcing the role of the GM in disease progression. These findings highlight the gut-brain axis as a critical pathway in PD pathology and suggest that therapeutic interventions targeting the GM, such as dietary modifications, probiotics, and gut-brain signaling inhibitors, could provide novel strategies to mitigate disease progression.

The intestinal microbiota in PD is involved in the modulation of α -synuclein aggregation and may further play a role in short chain fatty acid metabolism, α -synuclein pathology and microglial activation (Ilie, 2020). Intestinal microbial overgrowth, which is due to an increase in coliform bacteria, is a common finding in PD patients (Niu, 2016). Additionally, multiple studies reported that patients with PD were found to have significantly reduced levels of bacterial diversity when compared against a healthy population (Yemula, 2021). A recent 2021 meta-analysis by Romano et al confirmed consistent differences between the average gut-microbiota levels between healthy controls and patients with PD (Romano 2020). In the Thy1- α Syn (α -synuclein-overexpressing [ASO]) mouse model, which displays progressive deficits in fine and gross motor function as well as gut motility defects, a notable aggregation of α Syn was observed in the caudoputamen (CP) and substantia nigra (SN), regions of the brain's nigrostriatal pathway affected in both mouse models and human PD. Interestingly, GF-ASO (germ-free α -synuclein-overexpressing) mice displayed appreciably fewer α Syn aggregates, as confirmed by dot blot analysis in the CP and inferior midbrain (Sampson, 2017). This suggests that while not excluding a role for the microbiota during prenatal neurodevelopment, modulation of microglia activation during adulthood contributes to α Syn-mediated motor dysfunction and neuroinflammation, indicating active gut-brain signaling by the microbiota. Furthermore, it was found that microbiota derived from individuals with PD, compared to

healthy controls, promoted increased α Syn-mediated motor dysfunction in mouse models, providing evidence for a functional contribution by the microbiota to synucleinopathies.

Diet Factors Affect on PD and AD

Controlling your diet is very important in the development of PD and progression. Specifically, the Mediterranean Diet (MeDi), characterized by high fiber and polyphenol content, has been shown to positively influence gut microbiota composition, which in turn may impact brain health. Evidence suggests that adherence to the MeDi is associated with a substantial reduction in the risk of PD, with some studies indicating up to a 26% decrease in risk among those with the highest adherence (Solch, 2020). The beneficial effects of the MeDi appear to be mediated through its promotion of beneficial gut bacteria, such as Lachnospiraceae and Ruminococcaceae, which have been inversely correlated with PD. The diet's ability to maintain a balanced gut microbiota may also play a role in mitigating neuroinflammation, a known contributor to PD pathology. Moreover, the production of short-chain fatty acids (SCFAs) by gut bacteria, which is enhanced by the MeDi, has been linked to neuroprotective effects (Solch, 2020). These findings underscore the potential of the MeDi as a non-invasive therapeutic strategy to modulate the GBA and reduce the risk of PD through dietary interventions.

Dietary factors play a critical role in influencing the risk and progression of Alzheimer's Disease (AD). Omega-3 polyunsaturated fatty acids (PUFAs), particularly docosahexaenoic acid (DHA), are essential for maintaining neuronal health and cognitive function. DHA, a primary component of neuronal membranes, supports synaptic plasticity, neurotransmission, and neuroprotection. Studies indicate that diets rich in omega-3 fatty acids, such as those found in fish oils, can mitigate neuroinflammation and reduce amyloid-beta plaque formation, two key pathological features of AD. Early supplementation with DHA has shown promise in preserving memory and reducing cognitive decline, especially when administered during the initial stages of AD. However, its effectiveness appears limited in later stages, underscoring the importance of early dietary intervention.

In addition to omega-3s, other dietary patterns, such as the Mediterranean Diet, are associated with a reduced risk of AD. This diet emphasizes the consumption of fruits, vegetables, whole grains, and healthy fats, which collectively support brain health through antioxidant and anti-inflammatory effects. Key components, such as polyphenols and flavonoids, help combat oxidative stress, a major contributor to neuronal damage in AD. Furthermore, these diets promote gut microbiota diversity, which is increasingly recognized for its influence on the gut-brain axis and overall neurocognitive health. Although further research is needed to fully understand the impact of specific dietary components on AD progression, current evidence strongly supports the role of nutritional strategies in disease prevention and management.

Conclusion

The growing body of research on the gut-brain axis (GBA) underscores its pivotal role in the pathogenesis and progression of both Parkinson's Disease (PD) and Alzheimer's Disease (AD). The intricate interplay between gut microbiota, neuroinflammation, and neurodegeneration highlights the potential for microbiome-targeted interventions in managing these disorders. Understanding the mechanisms by which gut dysbiosis influences α -synuclein

aggregation in PD and amyloid-beta plaque formation in AD paves the way for novel diagnostic and therapeutic strategies.

The implications of these findings extend beyond individualized treatment approaches to broader public health initiatives. Given the modifiable nature of gut microbiota composition, dietary interventions—such as adherence to the Mediterranean Diet—may serve as accessible and non-invasive strategies to mitigate neurodegenerative disease risk. Additionally, microbiome-based therapies, including probiotics and prebiotics, hold promise for future research and clinical applications. These approaches emphasize the necessity of a holistic perspective in addressing neurodegenerative diseases, integrating gut health into neurological care.

Despite these promising insights, several challenges must be acknowledged. A major hurdle in gut microbiome research is the variability in study methodologies, including differences in cohort selection, microbial sequencing techniques, and analytical frameworks. While associations between gut dysbiosis and neurodegeneration are well-documented, establishing causality remains difficult. Many studies rely on animal models, which may not fully replicate human disease pathology. Furthermore, potential biases in the literature, including publication bias favoring studies that demonstrate positive correlations, should be carefully considered.

Future research should focus on large-scale, longitudinal human studies to establish clearer causal relationships and refine therapeutic strategies. Advances in multi-omics approaches, such as metagenomics and metabolomics, will enable a deeper understanding of the functional role of gut microbiota in neurodegeneration. Moreover, personalized medicine approaches that integrate genetic, microbial, and lifestyle factors could optimize intervention strategies tailored to individual risk profiles.

In conclusion, the role of the gut microbiome in PD and AD represents a rapidly evolving field with significant implications for public health and medical science. By bridging neuroscience with microbiology, researchers can unlock innovative pathways for early diagnosis and targeted therapies. Continued exploration of the GBA's influence on neurodegenerative diseases will be instrumental in developing holistic, precision-based treatment paradigms that improve patient outcomes and quality of life.

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Shots Not Taken: The Overlooked Divide in US Adult Pneumococcal Vaccination 2023

By Zhiyu Zhang

Abstract

Although the pneumonia vaccine is effective and widely recommended by the Centers for Disease Control and Prevention (CDC) for high-risk adults, uptake remains suboptimal. We do not know if the socio-economic disparities in vaccination uptake that occurred before the COVID-19 pandemic continued after. We hypothesized that adults older than 65 would have a higher prevalence of vaccination compared to adults between ages 50 and 64 years. The 2023 national health interview survey (NHIS), collected by the CDC, is a nationally representative survey of the US civilian non-institutionalized population, conducted continuously throughout the year. We fit a weighted logistic regression model; the binary outcome was ever receiving the pneumonia vaccine. Covariates included year, age, sex, race/ethnicity, sexual orientation, marital status, poverty level, education attainment, home ownership, usual place of medical care, military health insurance, other government program, medicaid coverage, medicare coverage, self-rated health, BMI category, smoking status, and receipt of flu shot in the past year. Higher education was linked to higher odds of vaccination (OR=1.28; CI: 1.16–1.41) for high school graduates and (OR=1.45; CI: 1.31–1.59) for those with some college, compared to less than high school. Adults who had received a flu shot in the past year had greater odds (OR=4.67; CI: 4.43–4.92) of having ever received the pneumonia vaccine. Compared with non-Hispanic Whites, Hispanic (OR=0.60; CI: 0.54–0.66), non-Hispanic Asian (OR=0.59; CI: 0.52–0.66), and non-Hispanic Black (OR=0.70; CI: 0.64–0.76) adults all had lower odds of vaccination. This cross-sectional study found that disparities in pneumococcal vaccine uptake occur among US adults, particularly by educational attainment, race/ethnicity, and engagement in preventive healthcare such as flu vaccination. Our findings underscore the importance of improving targeted health education and expanding access to vaccination services.

1. Introduction

Pneumonia is an acute infection of the lungs most commonly caused by bacteria, viruses, or fungi, leading to inflammation of the air sacs and potential respiratory failure.¹ In the United States, community-acquired pneumonia occurs at an annual rate of approximately 24.8 cases per 10,000 adults. The US Centers for Disease Control and Prevention (CDC) reported approximately 41,210 pneumonia deaths, with a mortality rate of 12.3 per 100,000 population, and ranks as the eighth leading cause of death². Globally, pneumonia was responsible for around 2.1 million deaths in 2021, with young children younger than 5 years and adults 70 years and older being the most vulnerable populations³. Weycker et al. found the average cost of treating pneumonia requiring hospitalization in the US was \$33,380 for the hospitalization itself plus \$4,568 during the 30-day post-discharge period, with total attributable healthcare expenditures averaging \$68,319 over 3 years per patient⁴.

The first pneumococcal vaccine, the 14-valent pneumococcal polysaccharide, was approved by the US Food and Drug Administration (FDA) in 1977 followed by the 23-valent pneumococcal polysaccharide in 1983⁵. PCV13 (Prevnar-13) was approved in February 2010 for children and later in adults, and PCV15 (Vaxneuvance) and PCV20 (Prevnar-20) received FDA

approval for adults in 2021 and were recommended for pediatric use by 2023⁶. The CDC currently recommends routine pneumococcal vaccination for all adults aged 50 years and older, as well as for individuals with certain high-risk conditions⁷.

Although the pneumonia vaccine is effective and widely recommended by the CDC for high-risk adults, uptake remains suboptimal. Previous studies have shown that disparities in vaccination exist not only by race and ethnicity, but also across other socio-demographic dimensions. For example, Felzer et al. found that adults with lower socioeconomic status, lower education, rural residency, and younger age were significantly less likely to be vaccinated⁸. Similarly, Quinton et al. found that vaccination rates were higher among non-Hispanic White and Latino populations with better insurance coverage, higher income, and higher education levels, while Black participants showed lower rates of pneumococcal vaccination before the age of 65⁹.

The proportion of Medicare beneficiaries aged 65 years and older who received any pneumococcal vaccine increased secularly from 41% in 2010 to 63% in 2019.¹⁰ We do not know if this increase continued in the 2020s, particularly during and after the COVID-19 pandemic. We also do not know if the socio-economic disparities in vaccination uptake that occurred before the COVID-19 pandemic continued after.

To address these gaps, we utilized nationally representative data from the 2020 to 2023 National Health Interview Survey (NHIS), including N = 67,357 respondents aged 50 years and older. We estimated the prevalence of ever having received pneumonia vaccine across years and socio-demographic groups including age, race/ethnicity, income, insurance status and health condition. We then assessed risk factors associated with never having had the vaccine using multivariable logistic regression. We hypothesized that adults older than 65 would have a higher prevalence of vaccination compared to adults between ages 50 and 64 years. Second, adults with higher educational attainment will be more likely to have received the vaccine. Finally, non-Hispanic White adults will have a higher prevalence of ever receiving the vaccine compared to non-Hispanic Black and Hispanic adults.

2. Methods

2.1 Data

The 2023 NHIS, collected by the CDC, is a nationally representative survey of the US civilian non-institutionalized population, conducted continuously throughout the year. Using in-person interviews, often followed by phone calls when necessary, it captures health-related data from individuals living in households across all 50 states and the District of Columbia. The survey uses a cross-sectional design and employs geographically clustered random sampling to ensure that the sample drawn each month accurately reflects the broader population. Interviews typically take place in respondents' homes, and in 2023, more than half were completed partially over the phone. This approach helps monitor health trends efficiently while maintaining national representativeness throughout the calendar year.

Our outcome was never receiving the pneumococcal vaccine. The outcome was based on the following survey question: "A pneumonia shot is also known as a pneumococcal vaccine. Have you EVER had a pneumonia shot?". Covariates included year, age, sex, race/ethnicity, sexual orientation, marital status, poverty level, education attainment, home ownership, usual

place of medical care, military health insurance, other government program, medicaid coverage, medicare coverage, self-rated health, BMI category, smoking status, and receipt of flu shot in the past year. Sampling weights were produced directly by the NHIS. See Appendix Table 1 for details of survey questions, original levels, and levels used in our analysis for all covariates.

2.2 Statistical Analysis

First, we calculated the distribution of the sample by socio-demographic, health-related, behavioral characteristics. Second, we estimated the weighted prevalence of ever receiving the pneumonia vaccine by each of these characteristics. Third, we fit a weighted logistic regression model. The binary outcome was never receiving the pneumonia vaccine. Covariates included year, age, sex, race/ethnicity, sexual orientation, marital status, poverty level, education attainment, home ownership, usual place of medical care, military health insurance, other government program, medicaid coverage, medicare coverage, self-rated health, BMI category, smoking status, and receipt of flu shot in the past year. We utilized R version 4.5.1 for all statistical analyses¹¹. We set the type I error rate at 5%.

3. Results

3.1 Characteristics of Study Sample

The study included 67,357 participants across four survey years: 2020 (27%), 2021 (24%), 2022 (23%), and 2023 (25%). Participants were aged 50–64 years (45%) or 65–84 years (49%), with a small proportion aged 85+ (6%). Females represented 56% of the sample, and males 44%. The majority were non-Hispanic White (75%), followed by non-Hispanic Black (10%), Hispanic (9%), and non-Hispanic Asian (4%). In terms of marital status, most participants were married or living with a partner (50%), followed by divorced or separated (20%), and widowed (17%). Regarding education, 64% had at least some college, while 26% had completed high school, and 9.7% had less than high school education. Sixty-three percent of participants had received a flu shot in the past year. Self-rated health status was most frequently reported as good (32%) or very good (32%), while 16% rated their health as excellent, 15% as fair, and 5% as poor. For body mass index (BMI), 37% of participants were classified as obese, 35% as overweight, 27% as having normal weight, and 0.8% as underweight. By smoking status, 56% reported never smoking, 32% as former smokers, and 12% as current smokers.

3.2 Prevalence of Ever Receiving Pneumonia Vaccine by Characteristics

The proportion of adults who reported ever receiving pneumonia vaccine was approximately constant across years (Table 2). The proportion increased across age: 20.2% among adults aged 50–64 years, 65.2% among those aged 65–84 years, and 70.2% among those aged 85 years and older. Also, female adults (44.9%) were more likely to report having received the pneumonia vaccine compared to males (38.2%). Disparities were also evident across race and ethnicity, with the highest prevalence among non-Hispanic White adults (45.9%), and lower rates among Hispanic (27.3%). With respect to educational attainment, individuals with some college education had the highest reported coverage (42.6%) compared to those with a high school

diploma or equivalent (42.1%) and less than a high school education (37.0%). Access to a usual place of medical care was also associated with greater uptake (43.1%) compared to those without one (14.1%). In terms of self-rated health, individuals who rated their health as poor (55.2%) or fair (51.0%) were more likely to report receiving the vaccine than those in excellent health (31.1%). Lastly, vaccination coverage was significantly higher among those who received a flu shot in the past year (56.5%) compared to those who did not (19.3%).

3.3 Logistic Regression Results

Compared to adults aged 50–64, those aged 65–84 (odds ratio, [OR]=3.28; confidence interval, [CI]: 3.01–3.58) and 85+ (OR=3.45; CI: 3.02–3.94) had significantly higher odds of ever receiving a pneumonia vaccine. Males had lower odds than females (OR=0.76; CI: 0.72–0.80). Compared with non-Hispanic Whites, Hispanic (OR=0.60; CI: 0.54–0.66), non-Hispanic Asian (OR=0.59; CI: 0.52–0.66), and non-Hispanic Black (OR=0.70; CI: 0.64–0.76) adults all had lower odds of vaccination. Higher education was linked to higher odds of vaccination (OR=1.28; CI: 1.16–1.41) for high school graduates and (OR=1.45; CI: 1.31–1.59) for those with some college, compared to less than high school. Adults who had received a flu shot in the past year had greater odds (OR=4.67; CI: 4.43–4.92) of having ever received the pneumonia vaccine.

4 Discussion

We reached three central findings. First, we found that higher educational attainment was associated with increased odds of pneumococcal vaccination, with individuals who had at least some college education being significantly more likely to report ever receiving the vaccine compared to those with less than a high school education. Second, receiving a flu shot in the past year increased odds of pneumococcal vaccination. Third, we observed significant differences by race and ethnicity, with Non-Hispanic White adults more likely to be vaccinated than Non-Hispanic Black, Hispanic, and Asian adults.

Our findings align closely with prior research demonstrating that socio-demographic factors profoundly influenced pneumococcal vaccination uptake. For instance, Gatwood et al. found that urban residence, higher health literacy, and receiving a flu shot were positively associated with vaccination among high-risk adults, while poverty and limited internet access were negatively associated¹². Our study also shows that individuals who had received a flu shot in the past year were significantly more likely to report ever receiving the pneumococcal vaccine. Additionally, Trent et al. reported that awareness of eligibility, perceived disease risk, and doctor recommendation significantly increased vaccine uptake, especially among high-risk adults¹³. Fix et al. found that current smoking and lower education were linked to lower pneumococcal vaccination rates, consistent with our findings regarding education and health behavior¹⁴. Moreover, a scoping review by Nasreen et al summarized that barriers across individual, social, and contextual domains consistently affect older adults' vaccination¹⁵. Our findings also showed that factors such as educational attainment, self-rated health, and access to a usual place of care each contribute to vaccination disparities, reinforcing the multi-level nature of barriers.

Our research also extends the literature by exploring factors associated with vaccine uptake not commonly addressed in prior work. While most studies focus on adults aged ≥ 65 years, our analysis includes those aged 50–64 years, uncovering middle aged adults as an important population with lower vaccine uptake. For example, Nowalk et al. documented persistent racial disparities in vaccination among adults aged ≥ 50 , but did not break out the 50–64 age group specifically or explore behavioral correlates like preventive care engagement¹⁶. Fix et al. considered self-rated health status and found that fair or poor health did not increase the likelihood of vaccine uptake. In contrast, we found that adults self-reporting poor or fair health were more likely to receive the pneumococcal vaccine than adults self-reporting good health.

These findings suggest that targeted vaccination efforts among lower-educated groups and those who forgo annual flu shots could improve equity. Our study supports policies to integrate pneumococcal vaccination with flu clinics, and to prioritize educational outreach and reminder systems, especially in underserved communities. Evidence shows that combining vaccination services can enhance efficiency and increase uptake, particularly when delivered in familiar settings like primary care clinics or community health centers¹⁷. Furthermore, culturally tailored education and personalized reminders have been shown to improve vaccination rates among minority and low-income populations¹⁸.

A key strength of our study is that we utilized large nationally representative survey data. Nevertheless, limitations include that vaccine receipt was self-reported and may be subject to recall bias or social desirability effects. Jackson demonstrates that relying on self-reported vaccination status can introduce significant bias due to recall errors and social desirability effects, potentially leading to misclassification and inaccurate estimates of vaccine effectiveness¹⁹. Also, while we identified broad patterns in vaccine uptake, the NHIS does not provide information on specific barriers to vaccination, such as cost concerns, access to providers, or vaccine misinformation.

This cross-sectional study found that disparities in pneumococcal vaccine uptake occur among US adults, particularly by educational attainment, race/ethnicity, and engagement in preventive healthcare such as flu vaccination. Individuals with higher education levels and those who received a flu shot in the past year were significantly more likely to report having received the pneumonia vaccine. In contrast, lower coverage among minority groups and those with less formal education highlights the need to address persistent access and awareness gaps. Our findings underscore the importance of improving targeted health education and expanding access to vaccination services. These efforts are critical to reducing disparities and increasing overall coverage of adult pneumococcal vaccination.

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Financial Literacy and Young Adult Indebtedness in Bulgaria: Structural Trends and Digital Strategies By Yani Ovcharov

Abstract

Youth over-indebtedness has risen sharply in Bulgaria amid persistently low financial literacy. Indicative administrative data suggest that approximately 30% of Bulgarians aged 25–30 were subject to enforcement actions by the end of 2024, underscoring the scale of the problem. This study analyzes the main drivers of widespread indebtedness and evaluates remedies. International and domestic literature review is complemented by a policy and implementation review of Bulgaria's National Strategy for Financial Literacy (2021–2025) and its annual progress reports, and by an analysis of secondary statistics on household credit, enforcement activity, regulatory reports, macroeconomic and demographic trends, and digital-banking adoption. We document a sizable competence gap among adolescents, alongside the rapid uptake of high-cost fast loans and opaque digital marketing. The paper proposes a two-track response: strengthening curriculum-embedded financial education to build medium- and long-term capabilities; and leveraging Bulgaria's rapid adoption of digital banking to deliver practical, just-in-time education that reduces near-term harm. The study concludes by outlining avenues for future research, including securing age-disaggregated data on the youth share of non-bank lending and developing a more granular profile of young debtors; prototyping and evaluating digital-banking delivery models; and assessing the need for tighter policy and enhanced supervision of the fast loan market.

Keywords financial literacy, youth indebtedness, Bulgaria, fast loans, digital banking, consumer protection, behavioral finance

1. Introduction

The term “financial literacy” is most commonly accepted as being financially aware while also possessing the necessary knowledge, skills, and behavior to make sound financial decisions which ultimately achieve individual and societal financial well-being, according to the Organization for Economic Cooperation and Development (OECD, "International Network on Financial Education (INFE) | OECD"). The main benefits that arise from a country's population being, on average, regarded as highly financially literate include: greater economic growth, improved social inclusion, poverty reduction, as well as enhanced financial well-being (OECD, "OECD/INFE 2023 International Survey of Adult Financial Literacy"). In contrast, the predominant downsides that low financial literacy leads to involve widening social inequality, lower economic productivity, higher vulnerability to fraud and scams, and mass over-indebtedness (Lusardi and Mitchell).

This research paper examines the sharp rise in indebtedness among young people in Bulgaria and its links to gaps in financial literacy. It synthesizes evidence on youth financial capability, past and current attempts to improve it, traces the mechanisms that channel young people into high-cost credit, and advances potential solutions to address the challenge of indebtedness.

The paper consists of five main sections. The “Methods” section provides context on how and when the research was conducted and clarifies the author’s standpoint. The “Context” section describes Bulgaria’s financial literacy baseline, highlights the scarcity of assessments for youth and young adults, and summarizes the government’s official plans to improve it. The “Findings and Discussion” section reviews the literature and examines the recent sharp rise in indebtedness in greater depth. By presenting and analyzing available statistics, it identifies the principal drivers while also disproving some common assumptions and hypotheses. The section also proposes potential solutions—utilizing both the standard school curriculum, and the rapid adoption of digital banking. Finally, the “Limitations” and “Directions for Future Research” sections discuss the study’s constraints and outline avenues for subsequent work.

2. Methods

This research was conducted over a five-month period, from April to August 2025, and applies a mixed qualitative and secondary quantitative approach to analyze the financial literacy of Bulgarian youth and its connection to rising indebtedness. The design combines a review of academic literature, a policy and institutional document analysis, secondary statistical data analysis, and a reference to an NGO’s published findings of a survey in whose design the author took part himself.

The literature review, primarily assisted by Google Scholar, incorporated both international and Bulgarian sources, with inclusion criteria centered on studies that examined financial literacy levels, indebtedness, and digitalization, specifically focusing on Bulgarian youth (ages 15–24) and young adults (ages 25–30). Other demographic cohorts are occasionally discussed, but only for background context or comparative purposes.

Policy and institutional analysis focused on the National Strategy for Financial Literacy of the Republic of Bulgaria (2021–2025) and its Action Plan, as well as the annual progress reports (2021–2024) prepared by the Bulgarian Ministry of Finance. These documents provided insight into the current government efforts to strengthen financial literacy in the country and how youth were targeted as a distinct group.

Secondary quantitative data from the Bulgarian National Statistical Institute and Eurostat were examined to contextualize the economic environment, particularly demographics, employment, purchasing power trends, and household consumption patterns. Complementary data from the Bulgarian National Bank and the Consumer Protection Commission were also reviewed to trace trends in youth credit usage, fast loans, and enforcement procedures.

At last, findings from the literature, policy documents, statistical data, and survey results were all systematically compared and organized. A structured analysis was applied to (1) identify drivers and causes of youth indebtedness, (2) assess structural deficiencies in financial literacy education and their impact, and (3) discuss potential measures and solutions to alleviate the trend of rising youth indebtedness in Bulgaria.

Media-reported estimates of the number of young adults in active enforcement proceedings were corroborated via direct e-mail correspondence with a senior official at the Bulgarian Chamber of Private Enforcement Agents (personal communication, 8 July 2025).

An expert consultation with an executive director at ProCredit Bank Bulgaria provided initial feedback on the proposed use of the digital-banking channel for financial education and

offered the bank's perspective on fast loan market dynamics (personal communication, July–August 2025).

2.1. Researcher Positionality and Subjectivity

This study was conducted by a high school student in Bulgaria, enrolled in an entrepreneurship-oriented curriculum during the final years of secondary education. The author's position as a young person within the same age cohort that is the focus of the research provides a unique insider perspective on the challenges of financial literacy and the risks of indebtedness. This perspective helps the author see more clearly how young people interact with financial products, digital platforms, and peer pressure.

At the same time, as a member of the demographic under study, the author's interpretation of literature and policy documents may be shaped by personal experience, including being raised in a family with above-average financial literacy and intending to major in economics and finance, which increases exposure to the topic. To mitigate this, findings were cross-checked across multiple sources—national and international surveys, government strategies, and independent academic research. In this way, conclusions are not based solely on personal impressions. Rather, they are supported by broader research while also benefiting from the authenticity of a youth perspective, especially in suggesting fresh approaches to address the challenge.

3. Context

Historically, Bulgaria has consistently scored poorly in all financial literacy assessments compared to European standards. For instance, the S&P Global FinLit Survey conducted in 2015 showed that only 35% of Bulgarian adults could be considered financially literate, which ranked Bulgaria among the lowest participants in the EU (Standard & Poor's / GFLEC).

It wasn't until 2018 however, that Bulgaria first participated in a youth-specific study on this matter by taking part in PISA's third assessment of financial literacy. The study, this time focusing solely on 15-year-olds, revealed that Bulgaria again scored in the bottom quintile, specifically in 16th position out of 20 participating economies worldwide (OECD, "PISA 2018 Results (Volume IV): Are Students Smart about Money?"). Moreover, Bulgaria also ranked last out of all ten European countries that were involved. The PISA financial literacy assessment uses five proficiency levels (Levels 1–5), with Level 2 recognized as the threshold for basic competence. Figure 1 compares Bulgaria with other countries by showing the share of students below Level 2 versus those at or above Level 2.

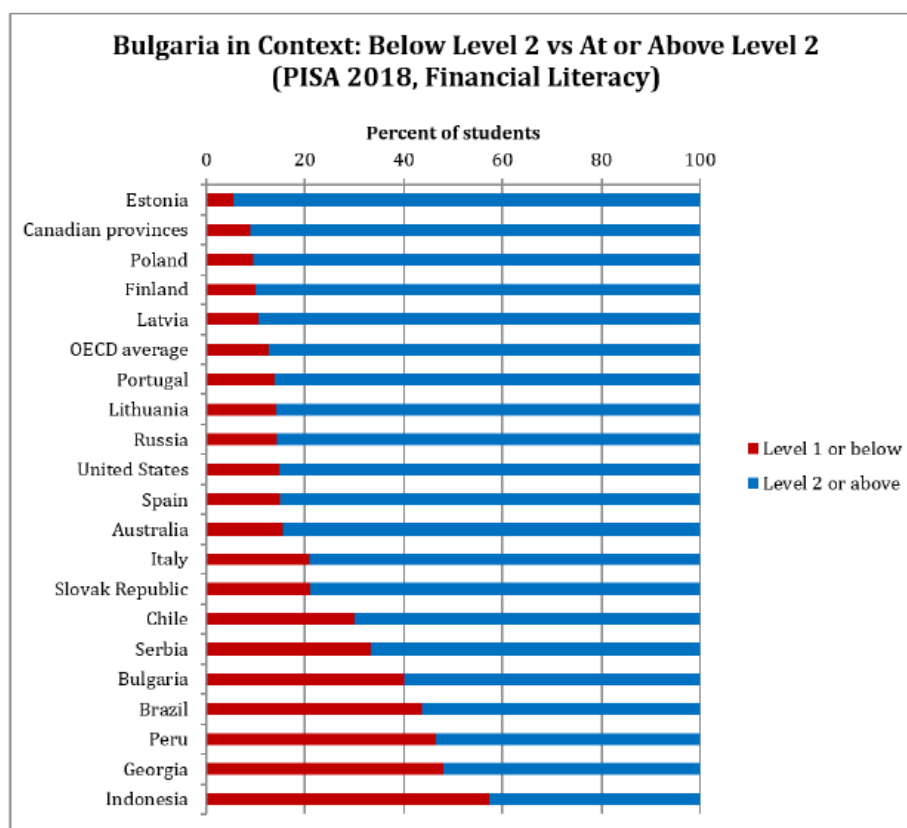


Figure 1. Bulgaria in Context: Below Level 2 vs At or Above Level 2 (PISA 2018, Financial Literacy). Source: OECD, "PISA 2018 Results (Volume IV): Are Students Smart about Money?" Table IV.2.2, p. 55.

This PISA survey indicates that Bulgaria's low financial literacy isn't limited to adults only and likely develops during adolescence, due to the absence of finance and economic education in most of the country's secondary schools.

Due to the relative scarcity of recent research on this topic, a self-administered survey conducted by the paper's author, under the "Financial Literacy Matters" project, was conducted in May–June 2025. Reaching over 400 young people aged 14–24 from more than 25 cities across Bulgaria, the study confirmed the persistence of these gaps at the youth level (VoxTUA). We'll refer to the findings of this study at various points across the following pages.

The Ministry of Finance of the Republic of Bulgaria recognizes the importance of financial literacy and integrates it as part of its Economic Policy (Ministry of Finance, "Economic Policy").

According to the Ministry of Finance, financial literacy is essential for individuals, businesses, and overall financial sector stability, and depends on knowledge, behavior, and personal attitudes toward money (Ministry of Finance, "Importance of the Financial Literacy"). It is a priority for both EU member states, including Bulgaria, and global organizations such as the Organization for Economic Co-operation and Development (OECD), the World Bank, and the G20. Financially literate individuals are more capable of managing their finances and contributing to a more stable society. The Ministry of Finance notes that with the rapid digitalization of financial services, there is a growing need for continuous development of

financial and digital skills, as well as for promoting financial literacy from a young age. It also refers to the OECD Methodology for Measuring Financial Literacy, where financial literacy is presented through the following three main components: financial knowledge, financial behavior and financial attitudes:

- Financial knowledge refers to understanding financial concepts and applying basic calculations to make informed and independent decisions about managing personal finances
- Financial behavior involves the everyday actions and decisions individuals make that affect their financial well-being and long-term resilience, such as budgeting, timely bill payments, and responsible borrowing
- Financial attitudes reflect an individual's mindset and values toward money, savings, and future planning, which significantly influence their financial decisions and habits.

In 2021, the Bulgarian Ministry of Finance for the first time created a National Strategy for Financial Literacy and also an action plan that covers the period 2021–2025 (Ministry of Finance, "National Strategy for Financial Literacy and Its Action Plan (2021-2025)").

According to the National Strategy for Financial Literacy, the level of financial literacy in Bulgaria is lower compared to most other EU Member States as well as OECD countries (Ministry of Finance, "National Strategy for Financial Literacy of the Republic of Bulgaria (2021–2025)" 8). It also notes that young people have the lowest overall financial literacy score – 53%, compared to 61% for people aged 30–60 and 57% for those over 60. The strategy document suggests that targeted and effective policies and programs are needed to improve financial literacy in the country, which should be oriented both toward immediate actions and long-term perspectives.

The National Strategy for Financial Literacy also notes that digital technologies are entering all areas of modern life, but the population in Bulgaria still does not use them enough in the field of financial services. We would like to note that this observation by the Ministry of Finance was made in 2021. What we found out as part of this research is that this trend has rapidly reversed in the past few years. We'll further analyze this change in this paper, along with the opportunities we believe it presents.

The Action Plan (2021–2025), part of the National Strategy for Financial Literacy, includes the following four priorities and measures:

- 1) Development of a competency framework in the field of financial literacy
- 2) Development of content and provision of free access to educational and informational resources, as well as their promotion
- 3) Improving the financial literacy of high school and university students
- 4) Improving financial literacy and promoting financial inclusion of vulnerable and other groups in society

Before analyzing the published yearly reports (2021–2024), it is important to mention that the National Strategy says the Action Plan does not specify concrete financial resources for the implementation of each measure. It instead suggests that the funding for the specific measures and activities should be provided by the budgets of the respective institutions and organizations responsible for their implementation. We recognize this as a risk for the general plan implementation and desired results.

After analyzing the Action Plan yearly reports (2021–2024), we can summarize that according to the reports between 2021 and 2024, Bulgaria made good institutional and structural progress in advancing its National Strategy for Financial Literacy (Ministry of Finance, "National Strategy for Financial Literacy and Its Action Plan (2021–2025)"). National financial competence frameworks for adults and youth were developed and aligned with EU and OECD standards to support future education and policy initiatives. A centralized digital platform was launched to provide free financial education resources, and teacher training was initiated to support the integration of financial topics within existing school subjects. Targeted programs were implemented for vulnerable groups, through workshops, online training, and awareness campaigns delivered in cooperation with ministries and NGOs.

That said, it's worth noting that while a framework of monitoring tools and evaluation methods seems to be established, no national or international study has been run yet to measure and confirm actual improvements in financial literacy.

4. Findings and Discussion

This section synthesizes evidence across four domains: (1) youth financial literacy and its determinants; (2) the rise and mechanisms of over-indebtedness; (3) tests of alternative explanations (demography, labor market, purchasing power); and (4) fast loan market dynamics and regulatory signals. Together, the subsections weigh this evidence to identify the primary drivers of youth over-indebtedness in Bulgaria.

A 2023 study of university students found that financial literacy levels among students were primarily driven by personal factors rather than the education curriculum: taking any of the currently available finance courses had no measurable effect on financial literacy (Marinov, "Financial Literacy: Determinants and Impact on Financial Behaviour"). This is not an intuitive or expected result which puzzled the author of the study himself and we will refer to his interpretation:

One possible explanation is that there might be a discrepancy between the academic content of the subject taught at university and the scope of the questions used to calculate the financial coefficient. Another possible explanation may be the assumption formulated above, that building a certain attitude and viewpoint regarding personal finance in Bulgaria takes place at an early age; during the years of secondary education and when they attend university, young people have already formed these attitudes and views. (Marinov, "Financial Literacy: Determinants and Impact on Financial Behaviour" 109)

For our research we will summarize this result in two aspects: (1) the educational content being provided in universities might not be adequate; and much more importantly (2) the earlier

kids are educated, the better. University age might be too late—financial literacy needs to be addressed in the early years of school. Supporting this, the author’s “Financial Literacy Matters” survey indicates limited exposure to structured learning: 70% of respondents reported never taking any extracurricular course in economics, business, or personal finance (VoxTUA).

On digitalization and its impact on financial products and solutions: while digitalization is acknowledged as a key environmental factor, its role in financial education or literacy acquisition is not directly investigated or tested in Marinov’s study. It is only in the study conclusion though where the author makes an important comment recognizing the financial institutions as stakeholders “in two different roles: as business entities offering financial products aimed at students, and as stakeholders interested in raising the level of student financial literacy” (Marinov, “Financial Literacy: Determinants and Impact on Financial Behaviour” 112).

In our research we will further explore the second suggestion, namely that financial institutions are expected to be interested in taking proactive actions to improve the level of financial literacy.

4.1. Rising Levels of Indebtedness

Recent reporting shows that the debt-collection company EOS Matrix found the share of debtors in Bulgaria aged under 25 soared from 7.2% in 2021 to 21% by September 2024, marking a three-fold increase in just three years (Dimitrova).

Sharpening this picture, recent data from the Chamber of Private Enforcement Agents show that by the end of 2024 over 120,000 Bulgarians aged 18–30 were debtors in already active enforcement proceedings (Bulgarian Chamber of Private Enforcement Agents, “Annual Enforcement Report 2024” 28–29). From those, around 4,000 are aged 18–20; 36,000 fall into the 20–25 year-old category; and over 80,000 are aged 25–30.

To analyze and highlight the severity of the situation and its implications for the country’s future, we benchmark the enforcement count against cohort size. The National Statistical Institute reports 270,718 residents aged 25–29 at the end of 2024 (National Statistical Institute, “Population by Age: Time Series Table 6.1.2”). Set against “over 80,000” 25–30-year-olds already in active enforcement, this implies that about 29–30% of the entire cohort is currently subject to enforcement ($\approx 80,000 / 270,718 \approx 29.6\%$), or roughly three in ten young adults. Although the indicators are not perfectly aligned (enforcement registers vs. population totals; 25–30 vs. 25–29), the magnitude is alarming. Referring back to the findings of the Bulgarian company EOS Matrix, this rapid rise in youth indebtedness is primarily attributed to low financial literacy, with many young adults lacking basic money-management skills, causing them to be often driven by impulsive purchases, such as taking loans for mobile phones, electronics, and sporting goods (Dimitrova).

The fact that about 30% of all individuals aged 25–30 in Bulgaria are already subject to legal proceedings due to unpaid debts is deeply alarming and necessitates a more in-depth investigation into the underlying causes.

This is a striking indicator of a growing structural problem with potentially far-reaching implications. While some level of debt accumulation might be expected in young adulthood, the scale observed in this age cohort suggests a broader pattern of financial vulnerability. At the

individual level, such early exposure to legal and financial distress can hinder access to credit, housing, and employment opportunities, and may discourage long-term financial planning or entrepreneurial risk-taking. These limitations can delay key life transitions such as forming a household or investing in further education. On a societal level, the indebtedness of a substantial share of the upcoming workforce could reduce overall economic productivity, weaken consumer spending, and place pressure on social support systems. If not addressed, this trend may hinder the development of a financially resilient and economically active younger generation, which is essential for the country's long-term growth and demographic sustainability.

4.2. Drivers of Youth Over-Indebtedness: Micro-, Meso-, and Macroeconomic Context

4.2.1. Consumer Credit and High-Cost Fast Loans

To better understand the accelerants accounting for the youth indebtedness crisis, it is essential to first examine the broader context of household debt in Bulgaria. According to data from the Bulgarian National Bank, total household debt reached BGN 50.05 billion (approximately EUR 25.59 billion) as of May 2025, representing a significant 20.7% increase compared to BGN 41.48 billion (EUR 21.21 billion) in May 2024 (Јеков). A substantial portion of this debt—BGN 19.92 billion (EUR 10.18 billion) is concentrated in consumer loans, which grew by 14% year-on-year. This sharp expansion in personal, non-mortgage borrowing supports the observation that household financial stress is intensifying, particularly through credit instruments typically associated with short-term consumption rather than long-term investment.

Here it would be an appropriate time to explain how consumer loans and predatory loans differentiate and operate within Bulgaria's current society. Firstly, consumer loans are funds extended to individuals for financing personal, family, or household needs, covering instruments such as credit cards, installment loans, and unsecured personal loans, and are repaid on a scheduled basis (Federal Deposit Insurance Corporation, "Consumer Lending"). Predatory lending, which often involves the usage of fast, payday loans, while not an officially classified product category, denotes practices that impose unfair or abusive terms (National Association of Consumer Advocates, "Predatory Lending"). Examples include: hidden charges, repeated rollovers, or disproportionate penalties, which exploit borrowers' urgency or limited financial literacy and can convert short-term borrowing into persistent indebtedness. The distinction between a fair fast loan (a short-term, unsecured loan) and a predatory one is subtle and easy to miss, which is exactly what deceptive lenders hope the consumers will misinterpret. In Bulgaria specifically, aggregate consumer borrowing has increased in recent years, younger cohorts have shown strong uptake of options like microloans and Buy Now Pay Later services, and now, consequently, the Consumer Protection Commission (KZP) has stepped up oversight of nonbank fast lenders exhibiting predatory features.

We will now trace the mechanism through which fast loans escalate into indebtedness and enforcement. Fast loan providers in Bulgaria are aggressively marketed online, including on youth-heavy social platforms, and commonly advertise 'ID-card-only' applications with approval 'in minutes'. Many initially borrow for gadgets and trips without fully grasping repayment risk (Novinite.bg). When a single installment is missed, standard acceleration clauses

allow the lender to declare the entire remaining balance immediately due, and to launch the order-for-payment procedure under the Civil Procedure Code (GPK). In many small-ticket deals, borrowers also sign a promissory note, allowing the creditor to seek an immediate order and further shorten the path to enforcement. Once the order is served, the debtor has 14 days to file a simple objection; many do not, and the order becomes final, clearing the way for bailiff action. Although courts and the Consumer Protection Commission frequently deem flat “penalties” and add-on fees unfair or attempts to circumvent legal caps, such terms persist in practice and inflate balances. Enforcement by a private enforcement agent then results in wage and account attachments plus fee-based costs, causing the total due to jump beyond the original principal. In combination, rapid acceleration, a brief objection window, fee-loaded enforcement, and persistent unfair charges together turn modest missed payments into outsized, long-lasting debts. Compounding the problem, aggressive marketing encourages “loan stacking” with several fast loans taken in parallel; this raises the probability of a first missed installment, after which the sequence above can quickly snowball into an avalanche of arrears and enforcement.

According to ProCredit Bank Bulgaria, in an email to the author dated 16 July 2025, the fast loan portfolio in Bulgaria exceeded EUR 3 billion in 2024, representing approximately 3.5% of GDP. They estimate the segment grew by about 22% in 2024 and continued to expand in 2025. More than 190 fast-credit companies are currently registered and active. Annual percentage rates frequently surpass 40%, and the bank reports a rise in non-performing fast loans in 2024. In their assessment, ProCredit Bank highlights a “significant lack of knowledge about personal finance management in the country,” and reports challenges in protecting consumers from irresponsible borrowing behavior. These “so-called fast loans,” they emphasize, are predominantly used for consumption. Taken together, these observations reinforce the paper’s argument that limited financial literacy can impair young borrowers’ ability to distinguish predatory credit from prudent, purpose-specific consumer loans.

Further referring to this problem while specifically focusing on Bulgaria’s youth, respondents from the author’s “Financial Literacy Matters” survey identified their main personal financial challenges as difficulty saving, difficulty managing a personal budget, and a lack of sufficient knowledge about finance, economics, and investment opportunities (VoxTUA). What’s more, when asked about which behaviors they would prioritize, 36% said they would focus on saving while only 13% indicated they would prioritize borrowing responsibly, and many also cited financial independence as a primary financial goal. Ultimately, these patterns reinforce the belief that budgeting skills among the youth are also weak, which continues to predispose them to unnecessary consumption borrowing.

4.2.2. Testing Alternative Hypotheses: Demography, Labor Market, and Purchasing Power

Before continuing with the discussion and exploration of potential measures, we would like to check various hypotheses that could potentially lead to such an alarming trend of youth indebtedness, like for example demographic change, unemployment trends, or economic changes.

An examination of National Statistical Institute’s Population Table shows that the 15–29 age cohort has remained effectively stable over the past three years, rising only from 854,074

individuals in 2022 to 880,414 in 2024, which we assess as ordinary demographic fluctuation (National Statistical Institute, "Population by Age: Time Series Table 6.1.2"). The underlying size of the young-adult population has not undergone any dramatic shifts that would be necessary to potentially trigger any changes in borrowing volumes. Accordingly, demographic change in this age bracket is unlikely to be a factor for increasing youth indebtedness.

Using the National Statistical Institute's Labor Force Survey annual results, the unemployment rate among 15–29-year-olds in Bulgaria declined from 10.4% in 2021 to 7.9% in 2022, remained relatively steady at 8.0% in 2023, and eased to 7.7% in 2024 (National Statistical Institute, "Labour: Time Series Table 3.2.3"). Over the same period, the aggregate unemployment rate for the whole country's population fell from 5.3% (2021) to 4.2% (2024). There's one minor nuance in this trend: among those with lower secondary education it rose from 10.7% in 2023 to 12.6% in 2024. This subgroup may be more vulnerable to income volatility and may rely on short-term credit, which could potentially be related to increased youth indebtedness despite a tight overall labor market. Notwithstanding this exception, the overall pattern suggests that unemployment dynamics are unlikely to be a primary driver of rising youth indebtedness.

We evaluate Bulgaria's economic context as a potential factor for increased indebtedness by tracing recent changes in purchasing power. The National Statistical Institute (NSI) and Eurostat report Actual Individual Consumption (AIC) per capita for Bulgaria and all other EU members. According to Eurostat the Actual Individual Consumption (AIC) is the value of everything people actually consume: both what households buy themselves and the individual services they receive from government and non-profits (European Commission, Eurostat, "Glossary: Actual Individual Consumption (AIC)"). Because it captures use rather than who paid, AIC is the preferred metric for household consumption in international comparisons. Unlike GDP per capita (a production/income metric), AIC per capita better reflects the material welfare of consumers.

NSI/Eurostat reports the following AIC values for Bulgaria expressed in PPS–Purchasing Power Standard units as defined by Eurostat (National Statistical Institute, "Actual Individual Consumption: Time Series Table 5.3"; European Commission, Eurostat, "Purchasing Power Parities (PPPs), Price Level Indices and Real Expenditures for ESA 2010 Aggregates"):

- 2021 year: 67 PPS
- 2022 year: 69 PPS
- 2023 year: 70 PPS
- 2024 year: 74 PPS

Given that the AIC per capita reflects the material welfare and consumption capacity of households, its upward trend in Bulgaria from 2021 to 2024 indicates an improvement in purchasing power. Therefore, we may conclude that the economic conditions are unlikely to be a driver of the rising indebtedness among Bulgarian youth.

4.2.3. Fast Loan Market Dynamics and Regulatory Findings

Let us now explore the dynamics in the fast loan landscape in Bulgaria. According to

official data from the Bulgarian National Bank (Bulgarian National Bank, "Дружества, Специализирани в Кредитиране — Таблици (Excel)") the total loan claims of non-bank lending companies have expanded sharply in the last three years:

- Dec 2022: BGN 4.427 billion (EUR 2.263 billion)
- Dec 2023: BGN 5.536 billion (EUR 2.831 billion)
- Dec 2024: BGN 6.577 billion (EUR 3.363 billion)
- June 2025: BGN 7.065 billion (EUR 3.612 billion)

The growth trend is significant: year-on-year growth reached 25% in 2023 and 19% in 2024, followed by a further 7.4% increase in just the first half of 2025. Taken together, the accumulated growth between December 2022 and June 2025 amounts to 59.6%.

Examining the market structure, the number of licensed banks has remained stable at 23 institutions over the last five years (Bulgarian National Bank, "Регистри За Кредитните Институции (Банков Сектор)"). In contrast, the population of non-bank lending companies exhibits different dynamics. The same Bulgarian National Bank statistical releases report the following counts of registered lending corporations:

- Dec 2022: 177
- Dec 2023: 177
- Dec 2024: 190
- June 2025: 190

The most pronounced change occurred in 2024, when the number of non-bank lenders rose by 13 companies (a bit over 7%).

Figure 2 presents a concise overview of the two key trends: total loan claims and the number of non-bank lending companies.

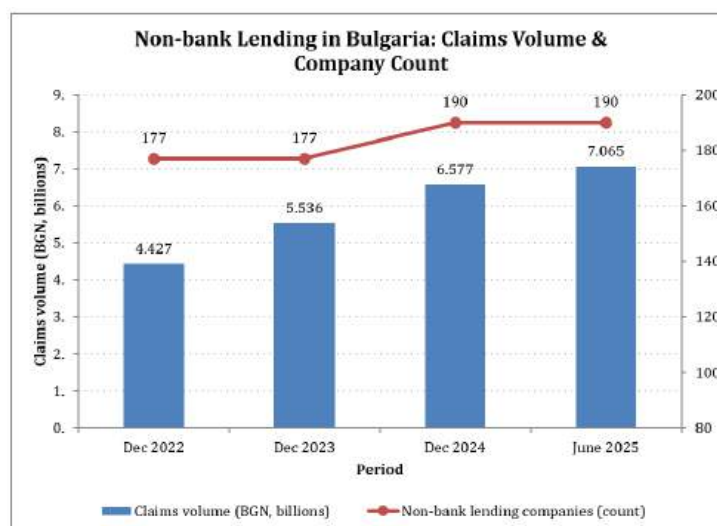


Figure 2. Non-bank lending in Bulgaria: claims volume (BGN, billions, left axis) and number of lending corporations (right axis), Dec 2022–Jun 2025.

As shown in Figure 2, lending volumes have risen steadily over the past 2.5 years, and the number of market participants spiked in 2024. Although these series are aggregate (all ages) and not age-disaggregated, they document a rapid expansion of fast loan supply and marketing reach. We therefore use Figure 2 as supply-side context for the youth credit environment rather than youth-specific evidence; its trajectory is consistent with increased exposure among younger borrowers discussed in this paper.

Exploring factors that may be driving the growth in fast loan volumes, we find a disturbing pattern of regulatory signals pointing to aggressive and misleading offerings and promotions. In a series of press releases from November 2024 to May 2025, the Consumer Protection Commission reported the following:

- 1) On 5 November 2024, Bulgaria’s Consumer Protection Commission (KZP) announced that, for the first time, it reviewed all non-bank financial institutions and their standard contracts, finding widespread unfair terms and unfair commercial practices in fast loan products. Examples include “express review” fees, excessive late-payment penalties, automatic acceleration for minor delays, promissory notes and other over-broad securities, and unilateral interest/currency changes. KZP gave firms 14 days to amend contracts and said it would issue prohibition orders with immediate effect and pursue collective claims against non-compliant lenders (Commission for Consumer Protection, "Комисията за защита на потребителите установи нелоялни практики и неравноправни клаузи в договорите за бързи кредити").
- 2) On 11 March 2025 KZP reports that some fast loan companies are evading prior orders by shifting unfair terms from contracts into side documents such as fees, annexes, and price lists—sometimes despite earlier court rulings. The Commission states that it will initiate collective claims and notes that many prohibition orders already have immediate effect or have been confirmed for preliminary execution, warning of tougher sanctions for non-compliance (Commission for Consumer Protection, "Председателят на КЗП Мария Филипова: Фирми за бързи кредити се опитват да заблудят КЗП, че са привели дейността си в съответствие с потребителското законодателство").
- 3) On 12 May 2025 KZP reported new unfair practices in the non-bank consumer-credit market. Inspectors found lender websites that conceal key price elements—including APR, interest rate, repayment schedule, and fees—while using marketing that emphasizes “ease” and “speed”. KZP also documented aggressive collection tactics, including threatening messages and pressure to refinance. The update also comments on a draft version of the new Consumer Credit Act, which aims to transpose Directive (EU) 2023/2225. This directive will tighten rules on advertising, pre-contract disclosure, creditworthiness checks, digital platforms, and protections for vulnerable consumers (Commission for Consumer Protection, "Председателят на КЗП Мария Филипова: Комисия за защита на потребителите установи нови нелоялни търговски практики на пазара на потребителските кредити").

Taken together, the Nov 2024–May 2025 KZP releases indicate an inflection point in 2024: intensified, aggressive digital promotion paired with unfair and in some cases, unlawful terms. These fast loan terms raise the effective cost of credit and plausibly encourage repeat borrowing among vulnerable consumers. The regulator’s progression from market-wide inspections to prohibition orders and collective claims signals persistent non-compliance. In short, this is a sector-level problem rather than isolated breaches, consistent with the concurrent surge in fast loan volumes.

Having excluded demographic, labor-market, and purchasing-power factors, the evidence indicates that low youth financial literacy, combined with aggressive and opaque fast loan promotion, greatly increases vulnerability and directly contributes to rising indebtedness. Addressing these gaps in youth financial literacy through targeted measures is therefore critical to reducing harmful credit uptake and repeat borrowing among young people.

Figure 3 charts the pathway to Bulgarian youth and young adults’ over-indebtedness.

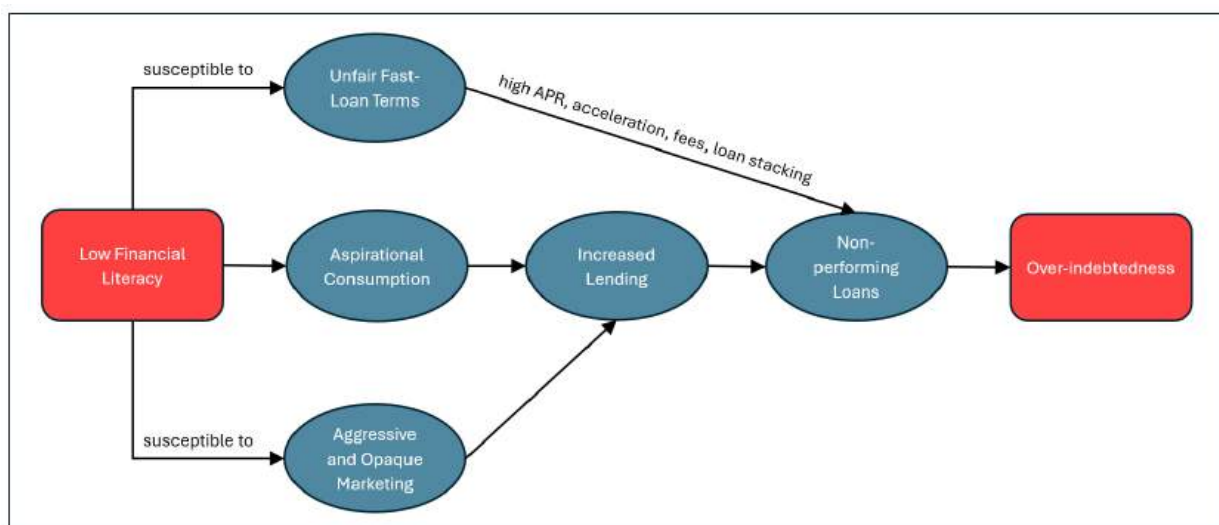


Figure 3. Pathways to youth and young adults' over-indebtedness in Bulgaria (conceptual flowchart)

4.3. Potential Solutions

4.3.1. Long Run: Strengthening Curriculum-Embedded Financial Education

To sustainably tackle Bulgaria’s mass youth indebtedness in the long term, we need to educate students in schools in applied personal finance, including budgeting, saving, responsible credit use, and digital-banking safety. The National Strategy for Financial Literacy and its accompanying Action Plan (2021–2025) recognize this and explicitly call for embedding financial literacy across all stages of formal education (Ministry of Finance, "National Strategy for Financial Literacy of the Republic of Bulgaria (2021–2025)" 18). This aligns well with Marinov’s finding that high school and university-level interventions may come too late,

emphasizing the importance of early education (grades I–VII) as well (Marinov, "Financial Literacy: Determinants and Impact on Financial Behaviour" 109). For elementary and middle school students, the strategy calls for the integration of financial literacy topics specifically into the subject Technology and Entrepreneurship, accompanied by updates to the national curriculum and the development of supporting digital and hybrid learning resources. For high school students, the strategy and its action plan promotes the inclusion of financial literacy topics within the existing curricula of general education subjects such as Technology and Entrepreneurship, Geography and Economics, Mathematics, and Civic Education. This is to be supported by regular methodological training for teachers and the development of optional and elective modules that reinforce financial knowledge and skills relevant to young people's everyday lives.

However, it remains uncertain whether these measures will be sufficient or effectively implemented at scale. Their impact has not yet been externally evaluated. Based on the findings of this research regarding the alarming level of youth indebtedness, we recommend that the national strategy be revised for the post-2025 period by taking bolder steps—most notably, by introducing a dedicated subject on financial literacy into the school curriculum, starting from middle school. As the results of the 2025/26 OECD/INFE International Survey of Adult Financial Literacy are expected to become available in the coming months, we suggest using this data to assess the broader effectiveness of existing measures and to further validate whether international benchmarks support such curricular reforms. With regard to the younger generation, it should be noted that no OECD-led international survey focused on youth financial literacy is currently scheduled before the next PISA Financial Literacy Assessment in 2029, leaving a significant interim data gap.

In support of our proposal, the author's "Financial Literacy Matters" survey found that 90% of all respondents believe finance and economics courses should be taught in school, and more than one-third of those participants explicitly said they want help acquiring deeper knowledge in this area (VoxTUA). Complementing this curricular argument, the survey additionally shows that the main sources young people turn to for financial knowledge are informal and digital: 89% rely on family and friends, 65% on social media, 42% on online articles, 39% on school lessons, and only 27% on books or textbooks (respondents had the option to select multiple sources, thus the total percentages exceed 100%). This data also suggests that any other effective intervention outside of integrating finances into the standard education must engage digital channels.

Based on our findings, we recommend focusing youth financial literacy efforts on the following areas:

- Money & transactions. Accounts, cards, transfers, digital payments, common fees, reading bank statements; intro to taxes and pay slips
- Budgeting & resilience. Cash-flow calendar, spending categories (needs/wants/saving), emergency buffer, goal-based saving, and inflation/real vs. nominal.
- Borrowing—core concepts. Simple vs. compound interest, APR, fees, amortization, and total cost of credit.

- Product comparison & rights. How to use the Standard European Consumer Credit Information (SECCI) to compare offers.
- Contracts & enforcement basics. Calculating true cost from the contract; recognizing acceleration clauses and promissory notes; late fees; order-for-payment timeline and the 14-day objection.
- Hidden pricing and unfair terms. Red flags identified by the regulator (e.g., “express-review” fees, hidden pricing, automatic acceleration, promissory notes); how “easy & fast” marketing frames risk.

Our proposal of financial literacy areas aligns with the OECD/INFE methodology for measuring financial literacy and covers all three components—financial knowledge, financial behavior, and financial attitudes. It is, however, calibrated to Bulgaria’s youth-indebtedness context, placing greater emphasis on financial behavior to address the main causes and drivers identified in our research.

4.3.2. Near Term: Delivering Practical Financial Education via Digital Banking

While curriculum reform is a necessary foundation for long-term change, it does not address the urgent needs of young people who are already out of school—the demographic currently most exposed to over-indebtedness. Although the National Strategy for Financial Literacy and its accompanying Action Plan (2021–2025) include measures targeting adults, such as the development of a national digital platform, awareness campaigns, and training programs through public institutions and NGOs, there is currently little evidence of a measurable impact. These efforts remain fragmented, and no national evaluation has yet confirmed improvements in financial behavior or outcomes among this vulnerable group.

To address this gap, we propose an innovative approach that is aligned with the high-level direction mentioned by Marinov in his study’s conclusion (engage the financial institutions), but grounded in detailed findings from our own research into digital behavior trends among Bulgarian youth. By analyzing data from the National Statistical Institute, we identified a sharp and sustained increase in the use of internet and mobile banking services—a trend that remains unaddressed in the current National Strategy for Financial Literacy and its Action Plan. Unlike existing measures, which focus on general digital resources, our proposal considers how financial education can be integrated directly into the digital banking environment. This interdisciplinary perspective—combining insights from digital user behavior, technology adoption, and education policy—offers a promising new channel to reach those already outside the formal education system. In the following section, we present the specific data that form the empirical basis for this proposal.

According to an industry-report summary of the Association of Banks in Bulgaria (ABB), by the end of 2024 digital channel usage accounted for 76% of all banking transfers in the country (Novinite.com). Additionally, the 73% decrease in paper-based transfers in 2023 again signals the beginning of a mass consumer readiness to embrace e-banking. What’s more, data from the National Statistical Institute of Bulgaria reveal that in the last 6 years internet and mobile banking adoption in the country has achieved a fourfold increase from just 8.6% of the population in 2019 using internet bank services to 31.3% by the end of 2024 (National Statistical

Institute, "Individuals Using the Internet by Purposes: Time Series Table 1.1.6"). The gradual progression of this spike is as follows: 12.6% usage in 2020; 14.9% in 2021; 22.4% in 2022, 23.4% in 2023, and 31.3% in 2024. This indicates a very high level of adoption already and also high confidence in the continuity of this trend for the next few years.

When zooming in on the youth, we see that as early as 2018, more than half of Bulgarians aged 18–29 were using internet banking, which is over ten times the rate among older adults (Parusheva). It is therefore reasonable to expect that by 2024 the proportion of young Bulgarians using internet banking is well above the national average of 31.3%.

Given the broad adoption of online financial services among young people, a pragmatic short-term step might be to integrate practical money-management lessons directly into banks' digital platforms. One possible approach is to introduce simple gamified elements, such as progress-based rewards for completing modules. By applying this or a similar method, banks can encourage young clients to engage with financial education. Different banking institutions could tailor their own incentives to better match their customer base. Banks have clear incentives to make such investments: they are likely to strengthen loyalty among young customers and, more importantly, to equip them to recognize and avoid predatory loans, thereby protecting clients and ultimately supporting sustainable business growth.

As Bozhinova and Ganchev (39–40) highlight, the digitalization of financial services in Bulgaria has already led to the development of youth-oriented banking and payment products, such as children's accounts offered by fintech platforms and debit cards for minors provided by commercial banks. At the same time, the authors warn that young people are increasingly exposed to financial narratives through social media and celebrity influencers—sources that are unregulated and may be manipulative, or misleading.

This dual reality presents both a challenge and an opportunity. While traditional institutional channels struggle to reach Gen Z effectively, digital banking platforms already serve as trusted and frequently used tools in their financial lives. Embedding financial education into these platforms—designed with interactive, gamified and socially engaging elements—offers a way to deliver authoritative knowledge in a format that resonates with the behavioral patterns of young users.

It is important to acknowledge that the rapid migration to digital banking introduces cybersecurity risks. Digital channels can expose users to phishing, social engineering (including money mule recruitment), account takeover, and investment scams. Accordingly, any digital-banking-embedded curriculum should pair financial skills with core cyber-hygiene: enabling multi-factor authentication, practicing device/app security basics, recognizing and reporting scams, and providing clear escalation paths to trusted providers and authorities.

To validate the viability of using digital banking platforms as an educational channel, in July 2025 the paper's author contacted ProCredit Bank, one of the most digitized banks in Bulgaria. ProCredit Bank serves SME and retail customers but operates without physical branches, relying almost entirely on digital channels. The feedback was very positive. The bank acknowledged that, despite rising non-performing fast loans and increasing 18–35 adoption of digital onboarding and daily banking through the mobile application, its past and current marketing campaigns have not targeted this cohort. They have already shared this proposal with their product design and marketing strategists and emphasized that gamified learning modules

could significantly boost user engagement, foster a culture of saving, and improve personal budgeting skills among young adults. This response gives the author confidence that this idea is worth further exploration and testing in the real world.

5. Limitations

There are important empirical constraints to this study that shape how its findings should be interpreted.

First, recent, nationally representative data specifically measuring youth financial literacy in Bulgaria are scarce. Consequently, the analysis relies on a mix of older international assessments, administrative statistics, third-party reports, regulator reports, and a short, author-conducted convenience survey collected during May–June 2025. This mix limits precision and therefore findings are directional rather than definitive population estimates.

Second, the data reported by the Chamber of Private Enforcement Agents is approximate and should be interpreted as indicators of overall trends, rather than exact figures. The author contacted the Chamber of Private Enforcement Agents asking for more detailed data and historic trends, but they responded that they do not have a well-structured data set. The lack of detail and breakdown data limits further analysis about the structure of the non-performing fast loans and constrains the design of tightly targeted measures. The Chamber of Private Enforcement Agents noted they are working to update these data, including by judicial district, but progress may be slow because the Central Register of Debtors was not designed to allow easy extraction of such information.

Finally, the proposed online banking embedded micro-lessons are a design concept, not a tested intervention. Evaluating effectiveness will require prospective pilots.

6. Directions for Future Research

Building on the limitations above, future research on youth over-indebtedness in Bulgaria could focus on the following areas:

- 1) Age-disaggregated non-bank lending claims. Obtain a detailed breakdown of non-bank lending claims by age group. While not available in the Bulgarian National Bank's published statistics, the BNB could be approached for custom age-band tabulations. Such data would enable a more granular understanding of lending dynamics among youth and young adults in Bulgaria.
- 2) Profiles of debtors in active enforcement. Examine historical trends and current characteristics of debtors in active enforcement proceedings handled by Private Enforcement Agents (PEAs)—e.g., average debt size, loan categories, debtor attributes (age, region), number of other credits, and length of arrears. This evidence would support deeper analysis and the design of better-targeted measures.
- 3) Piloting and evaluating digital-channel measures. In partnership with banks, pilot an in-app, gamified learning path for ages 20–30: micro-lessons/videos triggered by routine activity, brief quizzes, and a points-based progression with non-monetary recognition. Evaluate effects on engagement and loyalty, and on financial behaviors (savings frequency and reduced uptake/rollover of quick loans).

- 4) Policy tightening and enhanced supervision in the fast loan market. Conduct a focused literature review and a systematic assessment of the current legal and supervisory framework to identify gaps and potential failure points. Track ongoing legislative and regulatory initiatives by the Commission for Consumer Protection and other competent authorities and evaluate how well they address the identified gaps.

7. Conclusion

This paper examines evidence on the financial literacy of Bulgarian youth and young adults, explains the recent and pronounced rise in over-indebtedness in this cohort, and identifies practical levers for change. By combining international and Bulgarian literature, administrative statistics, regulatory documents, and the published results of a small author-run survey, the analysis shows that the epidemic levels of over-borrowing among youth are not simply a product of macroeconomic pressures. Rather, it emerges from the intersection of uneven financial capability formed during adolescence, the proliferation of unfair fast loan offerings, and their aggressive, opaque promotion.

Three findings are central. First, Bulgaria's youth and young adults exhibit gaps in core financial concepts—consistent with PISA evidence and domestic policy assessments. Second, a fast growth in household credit has occurred outside traditional banks, where pricing opacity (high effective APRs, add-on fees), unfair terms and persuasive digital marketing elevate uptake among inexperienced, vulnerable consumers. Third, digital channels have expanded rapidly with internet and mobile banking adoption accelerating over the past 12–24 months—a largely untapped venue for intervention. In a context where institution-led financial literacy education initiatives have yet to demonstrate a measurable impact, these channels offer new practical opportunities.

Based on these findings and analysis, the paper proposes a dual-track response to the widespread over-indebtedness of young Bulgarians. Track one is educational: adopt bolder policy steps to integrate specific financial subjects into the national curriculum, beginning in middle school. Track two is digital, faster to deploy and yields tangible results: delivering financial education concepts as micro-lessons and just-in-time nudges within banking and fintech applications. The digital track also enables engagement tools, such as light gamification and progress feedback, that resonate with the digital-native young generation.

The two proposed tracks are expected to deliver short-term relief and long-term improvement. Given the severity of the problem and its potential consequences for Bulgaria's future economic and financial resilience, immediate action is needed; this paper proposes specific measures. These measures are not exhaustive, however, and there is substantial scope for further research. Priorities include: (i) securing age-disaggregated evidence on non-bank lending claims; (ii) developing a more granular profile of young debtors; (iii) piloting and evaluating digital-channel measures; and (iv) assessing a complementary third track not covered here—policy tightening and enhanced supervision in the fast loan market.

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Feasibility Study on Dynamic Brain Imaging and Video Generation Using EEG and fMRI Data By Heather Lee

Abstract

This feasibility study explores the simultaneous integration of electroencephalography (EEG) and functional magnetic resonance imaging (fMRI) for dynamic brain imaging and video generation, supported by artificial intelligence (AI). By combining EEG's high temporal resolution with fMRI's precise spatial mapping, the study investigates the potential for multimodal methods such as fMRI-guided EEG source localization and independent component analysis to visualize real-time brain activity. High-frequency EEG signals, including high gamma oscillations and high-frequency bursts, were shown to align with BOLD signals, enhancing the precision of dynamic brain mapping. AI tools demonstrated the potential to generate video representations of brain states, deploying applications in neurofeedback, early diagnosis of neurological conditions, and personalized cognitive training. However, technical and ethical challenges such as artifacts from simultaneous recordings, synchronization issues, safety concerns, data privacy, algorithm transparency, and underrepresentation in training datasets remain. Nevertheless, dynamic brain imaging through EEG-fMRI fusion is a viable and transformative method to revolutionize how the brain is understood, monitored, and visualized in real time.

Introduction

The human brain is home to over 86 billion neurons, forming a vast array of neural connections that provides individuals with a unique spark of personality. The rapidly evolving field of modern medical technology allows researchers to further explore the complexities of brain function and structure. Dynamic brain imaging is one major technological advancement that supplements brain scanning technology with artificial intelligence to capture and analyze the changes in brain activity over time. The two most prominent imaging technologies used are functional magnetic resonance imaging (fMRI) and electroencephalography (EEG). The proposal of combining EEG and fMRI data into a singular powerful modality, with the enhancement of AI, challenges the individual potential ceiling of either method and avails the creation of dynamic brain imaging tailored to adapt to a variety of different neural patterns for fully personalized results. This feasibility study explores how dynamic brain video imaging can revolutionize characterized neural insights, emphasizing real-world applicability and the benefits of integrating validated technologies.

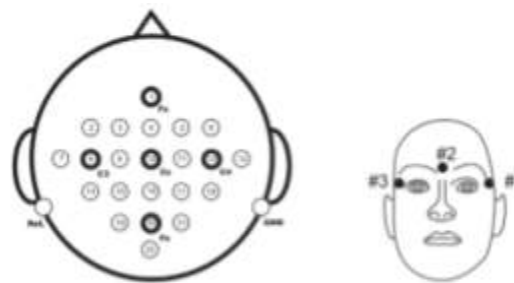


Figure 1. Standard EEG electrode placement and channel labeling on the scalp

EEG is a non-invasive method of recording electrical signals through small sensors attached on the scalp, as shown in Figure 1. Known for its high temporal sensitivity, EEG tracks rapid neural processes and electrical activity of the brain to reveal patterns, fluctuations, and abnormalities in brain waves. However, EEG lacks strong spatial resolution, making it difficult

to determine the exact brain regions that are activated by a response [1]. In contrast, fMRI has higher spatial sensitivity to localize precise regions where the brain is active, accessing blood oxygenation level dependent (BOLD) signals with the flow of paramagnetic oxygenated hemoglobin in the brain. An increase in blood flow in a specific area indicates that neurons are requiring more oxygen to function, in which fMRI's magnetic field detects where these changes occur [2]. Whereas EEG's data is displayed as waveforms, the data collected by fMRI helps generate high resolution, 3D visual maps of the brain. Despite their clarity, it takes a longer time to process the data into activation maps because BOLD signals change relatively slowly compared to how quickly neurons are responding [3].

Methodology and Data Integration Approaches

Data acquisition can be obtained through both simultaneous and nonsimultaneous EEG and fMRI recording. Simultaneous EEG-fMRI has developed into an analytical measurement technique and has contributed to many research fields today. Synthesizing these methods have provided an insight into the brain function that cannot be measured by one modality on its own. The simultaneous EEG-fMRI, allowing for brain activities to be monitored simultaneously with high temporal and spatial resolution, can aid in eliminating habituation effects, reducing the overall time for experiment and creating an identical sensory environment (See Figure 2). Simultaneous EEG-fMRI recording allows for the acquisition of two complementary datasets capturing the identical brain activity [4]. During combined recordings, the same neural activity contributes to both the EEG and fMRI data each trial. On the other hand, the non simultaneous recording method consists of post integration of EEG and fMRI data following separate recording sessions.

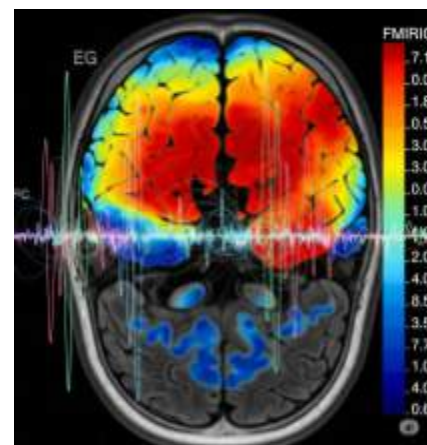


Figure 2: Simultaneous EEG and fMRI imaging

Following the collection of EEG and fMRI data utilizing its respective techniques, such data can be integrated through two different methods: model-based approaches and data-driven approaches. The former method involves the creation of mathematical models that capture the relationship between EEG and fMRI signals, often using fMRI-guided EEG source localization. This technique incorporates high spatial resolution of fMRI to improve the accuracy of EEG source localization, which has advanced temporal resolution but lacks spatial accuracy. The model-based approach has a symmetrical approach involving the integration of both modalities into a joint analysis and an asymmetrical approach using one modality to predict or constrain the other. The asymmetrical method generally uses fMRI data as the basic framework of this analysis. In addition, EEG source localization algorithms are better and more precisely able to locate the specific location of brain activities, especially in the deeper brain regions [5].

Data-driven approaches employ algorithms resembling independent component analysis (ICA) and canonical correlation analysis (CCA) to identify shared correlations between the two datasets [6]. This approach begins with independent component analysis (ICA) degrading spatiotemporal EEG data into a linear combination of scalp potential maps and time courses.

Then, the time course of each independent component (IC) is used to construct a regressor fitting the fMRI time series. The resulting fMRI map feeds back as a spatial constraint to score distribution estimation underlying the corresponding IC's scalp map. The product of the source distribution and corresponding IC time sources are summed across all ICs, resulting in a reconstructed spatiotemporal brain activity [7].

There have been different frameworks that propose the use of ICA for multimodal data fusion. Joint ICA first processes differing biosignal modalities separately then examines the relationships between data types, merging fMRI statistical maps and ERP data into a single matrix. While the unimodal case either temporally (EEG) or spatially (fMRI) reveals independent components, the multimodal case provides a joint spatiotemporal decomposition with joint independent components corresponding to electrophysiologically measured responses (indicating the timing of signal changes) alongside associated clusters of active regions (indicating spatial origins of signal changes) [5].

High frequency imaging is crucial to synchronize better with EEG signals, effectively capturing rapid brain dynamics. In addition, high frequency provides a smoother and more accurate representation of real-time neural activity. Ultra-high frequency of EEG over 100 Hz can contain crucial information like high gamma oscillations involved in attention and memory. HFBs (high-frequency bursts) at approximately 600Hz in human EEG recordings have proved to show spiking activity in primary somatosensory cortex while in somatosensory stimulation, supplying a noninvasive way to monitor human population activity [8]. Positively, high frequency imaging enhances the temporal resolution of fMRI, making it compatible for dynamic video generation. It also bridges the gap between the static nature of traditional fMRI and the dynamic needs of real-time applications [9].

The complementary advantages of EEG and fMRI machines are evident in their cost efficiency, reliability, and compatibility with AI analysis and other neuroimaging equipment. EEG's high temporal resolution captures rapid data down to milliseconds for reliable assessments of real-time brain responses. EEG machines are also less expensive than fMRI and can adapt to both clinical and medical settings. Despite fMRI's higher initial cost and narrowed niche, fMRI scanners excel in spatial resolution, better able to distinguish and describe images.

Moreover, EEG and fMRI have the capacity to be implemented with AI and other generative softwares, offering immense ease to the medical industry. Pulling out patterns in patient data sets can increase precision and accuracy in the identification and diagnosis of different neurological events. AI is capable of combining and interpreting fMRI and EEG data into personalized, dynamic video images. In addition, AI can extract important information from EEG signals to create images. Advances in AI models now enable the processing of text, images, and videos, addressing arising difficulties from traditional EEG data analysis. Incorporating IG (Integrated Gradients) can further improve understanding and analysis of these advanced models. Furthermore, AI can support personalized medicine by considering patient demographics and medical histories, thereby tailoring treatment plans to individual needs following brain imaging [10].

Finding on EEG-FMIR Fusion and AI Application

The integration of EEG's high temporal resolution with fMRI's high spatial precision enables comprehensive visualization of brain dynamics. Both model-based and data-driven approaches, such as EEG-informed fMRI and ICA, have shown precision in the identification and localizations of brain patterns. High frequency EEG signals, including high gamma oscillations and high frequency bursts, align well with BOLD signals captured by fMRI, enhancing the detail and accuracy of dynamic brain mapping. AI-enhanced tools further facilitate the processing and interpretation of these complex multimodal datasets [11].

In event-related tasks such as visual stimulation or motor responses, simultaneous EEG-fMRI allows for real time mapping of brain activities and patterns over time and across different brain regions. AI models also demonstrated the ability to generate a continuous video representation of different brain states, proposing potential applications in the studies of neurofeedback, early neurological diseases or mental early diagnosis, and cognitive training.

However, despite such benefits, technical challenges such as the presence of artifacts, signal asynchronization, and privacy and safety concerns during simultaneous recordings hinder widespread application of this technique in different fields of neuroscience. Gradient and pulse artifacts remained despite the use of hardware adjustments and RF-induced heating during fMRI recording posed safety concerns with solutions like carbon fiber leads and current-limiting resistors only showed partial effectiveness in risk reduction.

Discussion

Moreover, multiple digital filters must be applied to EEG data to remove external electrical activity impairing brain frequencies, possibly eliminating its original signal. However, such multimodal imaging techniques present significant difficulties such as disruptions in the MRI scanner's magnetic fields due to the presence of the EEG system inside the scanner, safety concerns, and poor data quality. While a typical EEG places the electrical conductive materials near the patient's head, the simultaneous EEG-fMRI system places the materials inside static magnetic fields (B_0) in which strong switching gradient fields and radio frequency (RF) fields are used during scanning. The safety concern that follows such a system is heating of the components and the tissues as the radio frequency fields and the switching gradient fields induce electromotive forces. To address such impediments when combining EEG and fMRI data, incorporating current-limiting resistors in the electrodes, using carbon fiber leads, and applying new conductive ink technology have shown to reduce heating during MRI scans. A major concern for fMRI integration with EEG data is the risk of adverse events and incorrect selection of the appropriate fMRI sequence. Although the use of low RF MRI sequence has shown to significantly decrease heating, constraining the MRI sequences interfere with MRI data regarding temporal and spatial resolution. Not only are there safety concerns following the combination of fMRI and EEG data, there are also concerns regarding the data quality of these scannings. EEG recorded in the scanner includes artifacts like eye movements, muscle tension, and electrical interferences from devices used in the scanning room, as shown in Figure 3. In addition to common artifacts, major concerns such as changes in magnetic fields, movement of EEG components within the static field, gradient artifacts, pulse-related artifacts, and motion-related artifacts are primarily caused by electromagnetic induction [5]. Signal filtering is important as it removes noise and artifacts from EEG and fMRI data to enhance accuracy.

However, signal filtering can possibly complicate the data by removing necessary information from the signal and adding artifacts to the data. In Average Artifact Subtraction (AAS), artifact templates are calculated through averaging adjacent artifact epochs. Consequently, templates are subtracted to reduce artifacts. Despite the good performance of AAS, artifact residuals typically remain in EEG after its application. However, there are 3

assumptions of AAS. The first assumes that EEG possesses zero mean, meaning that after averaging EEG epochs, they would cancel each other out. The second assumption states that the artifact is repetitive, so one can separate the EEG data into artifact epochs. The last assumption expresses that the artifact stays constant through adjacent artifact epochs. Concerning the first two assumptions, one can attain zero mean through high pass filtering and one is able to accurately divide the gradient artifact into epochs determined by the MRI scanner sequence repetition time. However, the third assumption can be extremely problematic, as head motion can alter artifact shapes, making complete removal challenging [12].

In signal integration, synchronizing EEG (millisecond-level) and fMRI (seconds-level) data is challenging as the highly sensitive nature of EEG is highly sensitive to fMRI's magnetic field, distorting the resulting signals and images. Given EEG's high temporal resolution and fMRI's high spatial resolution, bridging the gap between these factors poses major difficulty. Other technical difficulties include the difference in artifacts, where fMRI artifacts are minor and without substantial effects on sensitivity to signal changes. However, EEG possesses strong gradient artifacts from the magnet's gradient switching. Additionally, when ballistocardiographic (BCG) pulse artifacts (due to the small movements of the body and electrodes because of cardiac pulsation) merges with the Hall Effect, the construction of a possible difference across an electrical conductor when a magnetic field is perpendicularly applied to the current's flow, there are also strong gradient artifacts being formed [13]. Dynamic brain imaging generates unprecedented volumes of data due to its simultaneous use of both EEG and fMRI. When both processes are functioning independently, they measure two distinct types of data at two different scales. EEG captures rapid electrical activity down the milliseconds. Meanwhile, fMRI records changes in blood flow over a given region while lacking the capability to collect information at specific time frames. However, as dynamic imaging creates a broader dataset, they provide a more detailed visualization of brain function than either imaging method used alone. This feeds into the artificial intelligence algorithm, which thrives on larger, diverse datasets to make efficient and accurate predictions. Training AI models is resource-intensive due to their heavy reliance on large datasets, which enable efficient analysis but also require significant computing. As the amount of data increases, increased storage is needed for future use. While technological

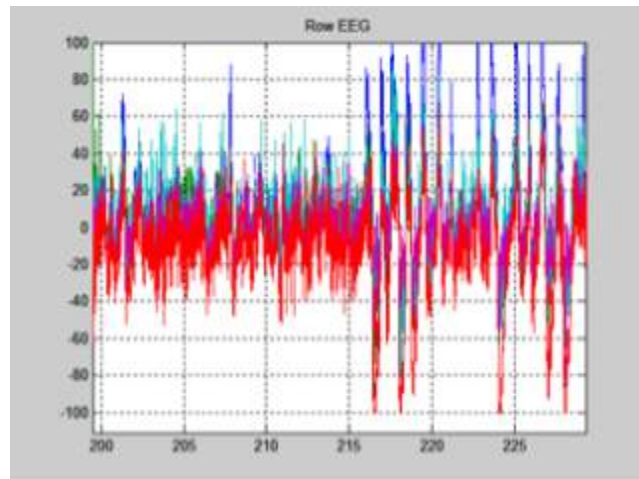


Figure 3. Raw EEG signals displaying high-amplitude artifacts and noise

advancements have made data collection and storage more accessible, accurately integrating data remains a challenge. For example, EEG relies on specific events to analyze, whereas fMRI operates more slowly, making it harder to align with specific events.

Alongside the advancements and advantages following the implementation of AI in brain imaging techniques, concerns are raised regarding data privacy and security. For many AI integrated neuroimaging systems, the specific process in which they arrive at their conclusions are unknown. Additionally, in order to train these AI models to aid in brain imaging processes, a massive amount of information regarding demographics and imaging data are required. Such acquisition of personal data to develop a powerful AI model threatens patients' privacy and autonomy.

One safety concern is radiofrequency (RF) power, which causes heating in EEG leads and electrodes. Exposure to radiofrequency heating is able to induce neuronal firing without causing heat injury. The blood-brain barrier is also negatively infected and can allow harmful substances into the brain. Increased temperatures can trigger inflammation of tissue, further disrupting the normal brain's function. Long-term exposure to RF potentially leads to heat stroke and heat exhaustion through increasing the skin's blood flow and sweating for heat dissipation.

Neuroimaging can improve mental health care as it can provide early, tailored intervention and has access to resources by image representation of the disease processes. However, premature technology transfer poses significant risks such as misunderstanding and misrepresentation of results that can ultimately result in inappropriate patient care. Especially among the marginalized population, the potential risk of data underrepresentation can result in inaccurate treatment plan or patient care. The use of deep learning techniques can aid in facilitating identifications of clinical results from a specific data set that may not be visible by mere inspections of the images. Recent advancements in machine learning can likely accelerate recognition and identify subtle patterns within the imaging data set. Furthermore, the incorporation of a computational model to analyze brain imaging data of each individual patient ensures effective and precise treatment intervention for mental health, preventing the need for trial and error in selecting the appropriate treatment.

Wearable EEG devices enable continuous monitoring of brain activity, allowing users to track their cognitive states (See Figure 4). Thus, performance can be enhanced by recognizing periods of peak cognitive thinking and periods of mental fatigue. Additionally, EEG devices can monitor sleep quality and patterns, supporting better sleep and cognitive function [13]. Because EEG data can dynamically adjust game difficulty and content based on the player's cognitive state, it helps maintain a favorable level of

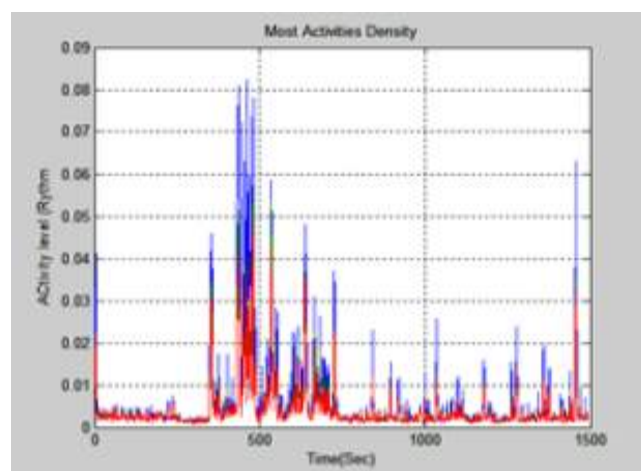


Figure 4. Spikes in activity density over time reveal dynamic fluctuations in brain activity.

challenge and engagement [13,14]. In education, EEG can monitor student attention levels and cognitive load, enabling tailored pacing and content selection [15].

Conclusion

This feasibility study justifies the viability and transformative role of dynamic brain imaging through the integration of both EEG and fMRI data supported by the use of artificial intelligence. The complementary strengths of EEG and fMRI allows for real time tracking, spatial recognition, and the measurements of both neuronal activities and hemodynamic changes. Coupled with artificial intelligence and advanced computational and analysis models, such dynamic brain imaging techniques can produce a revolutionary modality for personalized brain mapping and imaging.

Despite challenges-including artifacts, safety concerns during simultaneous recordings, and privacy concerns associated with the utilization of AI-this integration promotes the widespread application of real-time, personalized brain imaging video, paving new pathways for advanced applications in mental health, education, and medicines or treatments for neurological diseases. Currently, simultaneous EEG and fMRI brain imaging techniques have provided a more comprehensive understanding of the brain activity in the studies of resting state networks, neurofeedback, emotion localization and regulation, and epilepsy research.

Future studies should aim to mitigate issues regarding artifacts, refine safety protocols for simultaneous acquisition of EEG and fMRI data, and develop a framework for secure data management. With the continuous development in the technological field and through continued interdisciplinary collaboration, dynamic brain imaging using simultaneous EEG and fMRI data holds potential to redefine how people interpret, understand, and visualize neuronal activities, offering unparalleled insights to neurological diseases, human cognition, and mental health.

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Determining Planet Nine's Position Using Celestial Evidence By Jonathan D. Epstein

Abstract

This paper is a review of the Planet Nine hypothesis, including its initial announcement in 2016 and how it has changed over the last decade. Many of the discussed modifications include the estimates for Planet Nine's planetary parameters. The topics discussed in this paper include the history of the Kuiper Belt, its discovery, the objects that reside there, and the ETNOs, whose parameters were the biggest piece of evidence for Planet Nine. I also explore the gravitational influences that Planet Nine may induce on these bodies, which includes the Kozai Effect, as well as the use of Adaptive Optics that could aid in the detection of Planet Nine. My conclusions show that Planet Nine likely does exist and that more time should be given on powerful optics such as the James Webb Space Telescope (JWST) to look for it.

Introduction

Planet Nine is a hypothesized major planet located in the most distant reaches of the solar system. It is believed to be so distant that it would spend most of its orbital period beyond the heliopause. When it was first predicted, it was estimated to be $\sim 10\times$ the mass of Earth, with an orbital period of $\sim 18,000$ years and an aphelion, or furthest point from the Sun, of 1149.4AU (Astronomical Unit, 1AU = 93,000,000 miles, the average Earth-Sun distance) [Batygin & Brown 2016]. When discovered, Planet Nine will be one of the biggest finds in the fields of astronomy and planetary science since Clyde Tombaugh discovered Pluto nearly a century ago.

Planet Nine was first predicted by a group of astronomers and researchers at the California Institute of Technology. The team, led by Michael E. Brown and Konstantin Batygin, first published their hypothesis for Planet Nine in January 2016 [Batygin & Brown 2016]. Brown and Batygin formulated their estimates for Planet Nine based on some unusual similarities shared by many Extreme Trans-Neptunian Objects (referred to from here on out as ETNOs). The observed patterns between these ETNOs included the clustering of the objects' perihelion, having highly eccentric orbits and extremely long orbital periods [Batygin et al. 2016]. After a thorough investigation by Brown and Batygin into the possible causes of these unusual patterns, they decided that the only logical explanation was that an undiscovered, major ninth planet was lurking in the distant reaches of the solar system, and that it likely had significant gravitational influence.

The detection of Planet Nine would answer longstanding questions about the very early history of the solar system as well as about ETNOs. Some of these include whether or not Planet Nine had been ejected from the inner solar system during its formation, captured by another star, or just formed in its current orbit. Further questions about the planet's gravitational influence on the Trans-Neptunian Objects (or TNOs⁴⁹), including how each body could be influenced by Planet Nine differently from each other, and if it was a combination of Planet Nine's gravity and something else that produced the orbital patterns in the solar system we see today.

This research paper will feature material on the Kuiper Belt, including the major objects that reside there, how they were found, and how the population of ETNOs have parameters that

⁴⁹ These can also be referred to as Kuiper Belt Objects, or KBOs, after the region of the solar system where these objects reside

have baffled astronomers for many years. There will also be content about Planet Nine's gravitational influence and the possibilities that come with it, including the possibility of Neptune working with Planet Nine to induce the Kozai Mechanism on certain KBOs, and finally, using ground-based optics to aid in Planet Nine's detection and the challenges associated with it.

This paper will have the following sections in addition to the abstract and this introduction: Theory, Discussion, and Conclusion.

Theory

The Kuiper Belt

Following Clyde Tombaugh's 1930 discovery of Pluto [Pickering 1931], many in the scientific community, including Tombaugh, began to speculate that there were even more planets that lay beyond Neptune. Tombaugh continued to search for more Trans-Neptunian Objects throughout the mid-late 1930s and World War II, eventually retiring from the Lowell Observatory, the place where he discovered Pluto, in 1945.



Figure 1A-C: A photo collage showing the tools and images used by Clyde Tombaugh in the discovery of Pluto

Top Left (1A): The Lowell Observatory's 13-inch Astrograph in which Tombaugh scanned the stars, looking for a moving point of light.

Top Right (1B): The "Blink Comparator" machine used by Tombaugh as seen today on display at Lowell Observatory. Tombaugh used this device to compare the images he took on moonless nights, usually 5-6 days apart. As you peered through the machine's eyepiece and blinked quickly, you would see if any of the dots shifted positions. This technique would give away a planet's hiding spot because a planet would be moving as it orbits the Sun, while a star would not shift at all.

Bottom (1C): "The Pluto Discovery Photographs," taken by installing glass plates into a slot in the 13-inch Astrograph and exposing the two to the starfields for about an hour. During the exposure, the positions of all the dots in the sky are engraved into the plates. These particular plates were taken of the constellation Gemini, 6 days apart on January 23rd and 29th of 1930.. When Tombaugh first noticed the dot of Pluto shifting back and forth, he decided to double-check what he saw in order to confirm his find. After taking measurements and checking plates taken by a different telescope at the exact same time, he was certain of his discovery. After informing Carl Lampland, one of his colleagues, the two rushed into the observatory director, Dr. V.M. Slipher's office. Then, trying his best to keep his composure, Tombaugh announced, "I have found your Planet X."

(Source: The Lowell Observatory)

Pluto was only known to be a faint dot in the sky until 1976. That year, Cruikshank et al. 1976 used infrared detectors on a Kitt Peak telescope and found signs of methane (CH_4) ice on Pluto's surface. Two years later, in May and June 1978, astronomers Jim Christy and Robert Harrington [Christy & Harrington 1978] were analyzing recently taken images of Pluto at the U.S Naval Observatory when Christy suddenly spotted a bump on one of the ends of Pluto. When the pair went back to check a month later, the "elongation" had suddenly disappeared. Christy and Harrington eventually came to one conclusion: They had just witnessed an eclipse. Pluto had a Moon that would subsequently be named Charon.

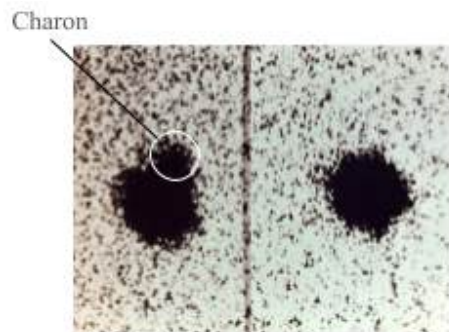


Figure 2: Charon Discovery Image (Source: ADAPTED FROM Christy & Harrington 1978)

Throughout the 1980s, many astronomers began to investigate a theory first proposed by Dutch planetary astronomer Gerard Kuiper in 1951. Kuiper suggested that the solar system had a

“disk” of other worlds beyond the Eighth and Ninth Planets. However, many had gotten used to the idea that the Solar System most likely ended with Neptune and Pluto.

Pluto remained the only known world beyond Neptune, even 60 years after its discovery. Then, in 1992, the fields of astronomy and planetary science took a major step forward. A very small, icy world had been discovered by astronomers David Jewitt and Jane Luu [Jewitt & Luu 1992]. This KBO, designated 1992 QB₁, was the first object found beyond Neptune in 62 years. Jewitt and Luu had been using a newly developed style of planet hunting, but their technique had been the same one used by Tombaugh in the discovery of Pluto in 1930: Take two images of the sky at different times, usually a few days apart, and then look to see if any of the dots move against the vast starfields. While Tombaugh had used glass plates and an Astrograph to take his images, along with a “Blink Comparator” to manually compare the two images, Jewitt and Luu had been using newly developed CCDs, which have since been compared to the sensors in a 2010s digital camera. After the discovery of the first KBO, approximately 1000 more were discovered between 1992 and 2006.

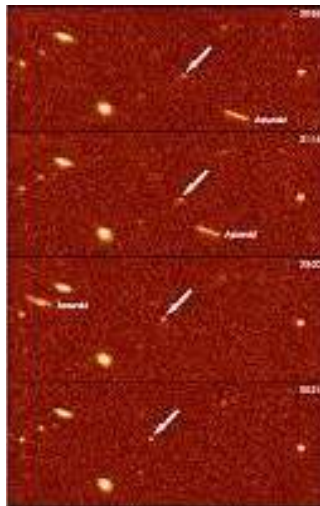


Figure 3: The discovery Images of the first Kuiper Belt Object (KBO), designated 1992 QB₁.
(Source: David Jewitt, University of California Los Angeles)

However, the eventual discovery of some of the larger KBOs, such as Eris [Brown et al. 2005], Makemake [Brown et al. 2006], and Haumea [Brown et al. 2007], not only sparked curiosity amongst astronomers, but also controversy. This was especially true in the wake of Eris’ discovery in 2005 [Brown et al. 2005]. Further analysis of Eris by the Hubble Space Telescope (HST) revealed that it was close in size to Pluto and was 1.27x Pluto’s mass [Brown & Schaller 2007]. As a result, Eris was originally slated to become the Tenth Planet. However, the discovery of a larger mass than Pluto sparked a big debate among planetary scientists about what makes a planet a planet. This debate eventually found its way to the 2006 convention of the International Astronomical Union (IAU). The IAU decided to reclassify Pluto from planet to the newly created category of “Dwarf Planet” - a body that is round and orbits the Sun, but does not have the gravitational power to “clear the neighborhood of its orbit.” The public was outraged at this and surprised to see that many famous astronomers, including Neil deGrasse Tyson and Mike Brown, Eris’ discoverer, were actually in favor of the IAU’s decision to demote Pluto.

However, the discovery of the Kuiper Belt, and especially the 2003 discovery of Sedna, made scientists begin to question the nature of these bodies. The main issue at hand was that several of the ETNOs, such as Sedna, 2000 CR₁₀₅, and 2010 GB₁₇₄, shared similar orbital patterns. The scientists were especially questioning the object's argument of perihelion. This means that when these KBOs reach perihelion, or the closest point in their orbits to the Sun, they are all at about the same angle to a plane of reference. This pattern raised a lot of eyebrows among the scientific community, especially after it was realized that this parameter should be random for each KBO.

It was already known that the newly found KBOs acted as "fossils" - showing us a snapshot of early planetary formation.. These small icy bodies are the "relics" left over from the creation of the solar system. At around the same time, NASA had just approved funding for the New Horizons mission, which was to perform a flyby of Pluto. When the space probe performed its Pluto encounter on July 14, 2015, some of Pluto's landscapes, as seen in the images that were being sent back, had mission controllers' and scientists around the world's jaws dropping. Many of the people who'd worked on the New Horizons mission were especially surprised to see that Pluto had similar geologic features to those on Earth.



Figure 4: New Horizons Principal Investigator Dr. Alan Stern (in shock), along with Dr. John Spencer (at the computer), and others look at recently transmitted images the day after the Pluto encounter

(Source: The Johns Hopkins University Applied Physics Laboratory, NASA)

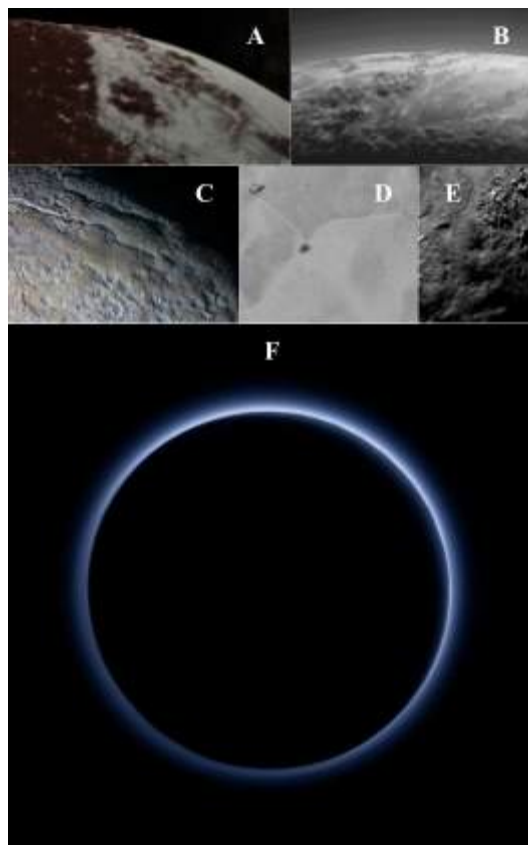


Figure 5A-F: A photo collage showcasing some of the best finds that were made during New Horizons' Pluto encounter.

Top Left (5A): The diverse landscapes of Pluto include many regions. All with different geologic features and chemical compositions. This flyover image shows Sputnik Planitia, Cthulhu Macula, Tartarus Dorsa, Pioneer Terra, and Voyager Terra. ****NOTE****: All names of Pluto's regions are not official

Top Right (5B): Taken 15 minutes after closest approach, this image shows most of the rugged Plutonian landscapes of Norgay Montes and Hillary Montes. Many of the mountains shown in the photo are over 10,000 feet tall and are mostly made of Water (H_2O) ice.

Middle Left (5C): As New Horizons approaches the Day/Night line over Pluto's surface, it was able to capture images of more ice mountains near Tartarus Dorsa.

Middle Center (5D): New Horizons captured active glacier flows of Nitrogen (N_2) and Methane (CH_4) ice

Middle Right (5E): Dr. Stern called Wright Mons "the most amazing find we made at Pluto." Wright Mons is an ice volcano, which was active at some point during Pluto's early history. The divot in the center of the photo is the caldera of the volcano.

Bottom (5F): From the vicinity of the Pluto system, New Horizons turned its detectors back at Pluto, capturing the Sun's rays passing through Pluto's Nitrogen atmosphere, forming the blue ring around Pluto.

(Source: The Johns Hopkins University Applied Physics Laboratory, NASA)

The biggest shock from New Horizons was the discoveries of the water ice mountains and the nitrogen glaciers, which led the New Horizons science team to a shocking conclusion: Pluto is geologically alive after four and a half billion years. This finding, as Dr. Stern later said, "upended many geophysical theories that did actually predict that small icy planets would cool off and die early in their history and just be a frozen relic of that time. This finding told us that our ideas on how planetary engines work were flat wrong. And that we now had to rethink them. [DCODE: NASA's New Horizons Mission to Pluto]"

The discovery of many ETNOs in the years leading up to the New Horizons Pluto flyby, which revealed active geology on Pluto, indicated that we still had much to learn about the most distant reaches in the solar system. In late 2016, a few months after Brown and Batygin had formulated and published their Planet Nine hypothesis, other groups of astronomers, including Scott Sheppard and Chadwick Trujillo, performed surveys on the orbits of two ETNOs: Sedna and 2012 VP₁₁₃ [Sheppard & Trujillo 2016]. Their surveys scanned 1080² degrees of the sky to see if the orbits of the ETNOs could give any insight as to Planet Nine's location in the night sky. They then examined the orbits of two more ETNOs, 2014 SR₃₄₉ and 2013 FT₂₈, using the same surveying techniques and came up empty. However, Sheppard and Trujillo do admit that results from computer simulations showed that their survey would have failed to detect a "distant, eccentric planet" 99% of the time. They stated that this was likely because "the possible hypothesized planet's large eccentricity implies that it spends most of its time near aphelion, which would make it very faint and a significant fraction of its time in the northern sky if it is anti-aligned with the main grouping of ETNOs [Sheppard & Trujillo 2016]."

As impossible as Planet Nine's existence may seem, the idea of predicting and finding new planets like this is nothing new. Neptune had been predicted mainly through math, mere months before its actual discovery via telescope in 1846. And even more recently, NASA's exoplanet hunting Kepler mission had determined that Neptune-sized planets at the edge of other solar systems are extremely common throughout the Milky Way galaxy.

Gravitational Influences

As stated by Brown and Batygin in their original 2016 paper, the biggest piece of evidence that they had for the existence of a major ninth planet was the unusual orbital clustering among ETNOs. There are two main patterns that Brown and Batygin observed. As previously stated, many of the ETNOs had a common argument of perihelion. The other main similarity that was observed was that all of the ETNOs' orbits were right next to each other in the "same plane in the solar system." And as shown in Figure 6 below, the orbits of six ETNOs are all tilted away from the ecliptic by ~20°. Furthermore, these orbits are not only extremely elliptical, but they swing outwards from the Sun in the same general direction. Normally, these objects trace out in such a way that their orbits look like flower petals. It was a big indication that something had

“manipulated these objects’ orbits in such a way that they clustered in space together, and that the something had significant gravitational influence [The Verge].”

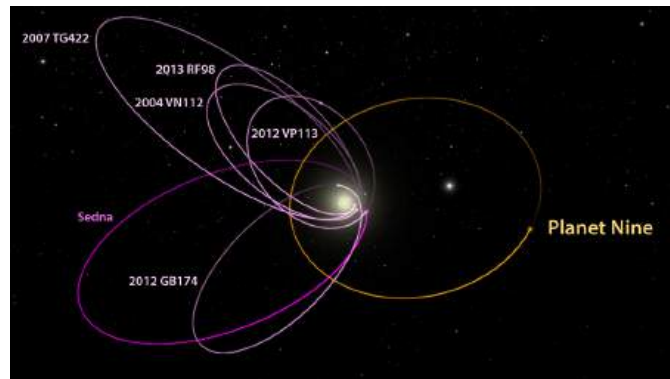


Figure 6: A 2016 diagram showing the orbits of six ETNOs, Sedna, 2004 VN₁₁₂, 2012 VP₁₁₃, 2013 RF₉₈, 2007 TG₄₂₂, and 2010 GB₁₇₄ in relation to the predicted orbit of Planet Nine (Source: California Institute of Technology, Caltech)

Other researchers have come up with further explanations as to ETNO's strange orbital clustering. Becker et al. 2017 came up with a theory about Planet Nine's influence on ETNOs that said that it is not only possible that Planet Nine could be influencing small icy bodies like Sedna and 2012 VP₁₁₃, but Planet Nine could be influencing each ETNO in an entirely different way. Their paper also suggested that it is highly possible that Planet Nine could be sharing its influence on these worlds with Neptune. Furthermore, the work done by Downey & Morbidelli 2020 proved that, after examining the orbits of Sedna, 2004 VN₁₁₂, 2012 VP₁₁₃, and 2000 CR₁₀₅ and running computer simulations, it was shown that 2004 VN₁₁₂ is "the body most prone to instability."

The original estimates for Planet Nine's mass in Brown and Batygin's January 2016 paper estimate Planet Nine to be ~10x the mass of Earth, with this number remaining constant throughout more papers written that year [Brown & Batygin 2016, Batygin & Brown 2016]. Later estimates for Planet Nine's mass by Brown and Batygin decrease slightly, to 5x the mass of Earth in an April 2021 paper [Batygin & Brown 2021], followed by 6.2x the mass of Earth in a January 2022 paper [Brown & Batygin 2022].

If Planet Nine were to have a mass of 8-12 times the mass of Earth, it would easily have a big enough gravitational field to manipulate these ETNOs. There are many such theories about other major planets manipulating small icy bodies. The best example that has been seen in the solar system is Neptune's largest moon, Triton. After Voyager 2's flyby of Neptune and Triton in August 1989, it was found that, as Dr. Bonnie Buratti [The Year of Pluto - NASA New Horizons Pluto Mission Documentary] later said, "Triton is almost a twin of Pluto. It's about the same size and the same brightness." Given that Pluto is the KBO we know the most about, many scientists now believe that Triton started its history as a KBO with an orbit of its own around the Sun, but early in its history, it started to get influenced by Neptune and eventually wound up getting captured by its gravitational field [Hammond & Collins 2024].



Figure 7A-B: A comparison of the original Triton and Pluto images

Left (7A): Triton as seen by Voyager 2 during its August 25, 1989 encounter with Triton

Right (7B): Pluto as seen by New Horizons the night before its July 14, 2015 encounter with the Pluto system

(Source: The Jet Propulsion Laboratory, The Johns Hopkins University Applied Physics Laboratory, NASA)

Even though Brown and Batygin claim to have strong evidence for Planet Nine, to some astronomers and researchers, the unusual clustering of the ETNOs' orbits is not enough evidence to claim Planet Nine does indeed exist. Since the 2016 publication of the original hypothesis, other theories have come into play over the ETNOs clustering. These theories include 1) The ETNOs' orbits had been shaped by a "rogue" planet's gravity. This planet would have been temporarily captured by the sun and soon thereafter ejected from the solar system. 2) The ETNOs' orbits were disturbed by a passing star. 3) The combined masses of all the ETNOs together equal $\sim 10x$ the mass of Earth, which was the original mass estimate for Planet Nine. This theory proposes that the combined gravitational effects of all the ETNOs are basically fighting and disturbing each other.

The "rogue planet" theory, as described in Socas-Navarro 2023, talks about a meteoroid that impacted Earth in 2014 that had likely been "flung at Earth by a gravitational encounter." Navarro went on to state that by using computer simulations to backtrack the meteoroid's trajectory, it was shown to have come from the region where Planet Nine is "likely to reside." This paper shows that a rogue object being thrown at another is nothing new, and many back up this theory, saying that such an occurrence could explain the ETNOs' orbits.

The second major theory to explain the orbital clustering of ETNOs is that these bodies were disturbed by a passing star. The work done by Clement & Kaib 2020 involved running computer simulations that "approximate the effects of the passing stars." However, at the end of their conclusions, Clement and Kaib write, "while the Planet Nine hypothesis remains the most viable explanation for the observed orbital clustering in the distant solar system, still more detections of extreme objects are required to confidently infer its existence."

The final major theory to explain the clustering essentially involves the ETNOs influencing each other. Muñoz-Gutiérrez et al. 2021 took the parameters of the 34 biggest objects in the Kuiper Belt and “explored the dynamical influence that these objects (...) have on the orbital evolution of light TNOs.” Their conclusions show that, of the 34 major KBOs tested, six of them are ‘resonant’ (defined by the authors as when a majority of their simulated orbits remain within a known resonance); of the 28 nonresonant objects, 17 are ‘stable’, while 11 are ‘unstable’ (where many of their orbital simulations change drastically in at least one of their main orbital parameters).”

Muñoz-Gutiérrez et al. 2021: KBO Influence Test Results

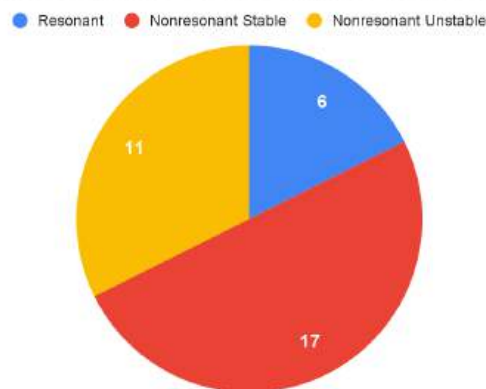


Figure 8: A chart showing the results of computer simulations testing the various “states” (stable/unstable) for the 34 largest KBOs. Data from Muñoz-Gutiérrez et al. 2021

The Kozai Mechanism

The Kozai Mechanism (or the Kozai Effect) is a method of influence in which two large bodies, such as Neptune or Planet Nine, work together to manipulate the entire orbit of one or more small bodies, mainly KBOs. As explained in Kaib & Sheppard 2016, the Kozai Mechanism works when Planet Nine uses its gravity to gradually tilt the orbits of KBOs onto their sides. Eventually, Planet Nine’s gravitational field will encounter that of Neptune, and when that happens, the affected KBOs wind up orbiting the Sun in the opposite direction of most other bodies.

The best example of the Kozai Mechanism being induced on a KBO is 2011 KT₁₉, or “Niku.” During the work done by Brunini 2023, computer simulations were used to find “possible effects that the inclusion of the giant planets could have on the orbital evolution of Trans-Neptunian Binaries.” As displayed in Figure 9 (see below), the simulations showed that over time, the mutual inclination of the Trans-Neptunian binaries increases.

In addition, there are many patterns that astronomers look for in terms of the Kozai effect. The main of which is looking to see if objects are, 1) Near Neptune mean motion resonances, or MMRs. 2) Have inclination angles greater than 20°. As discussed in Sheppard et al. 2016, the astronomers discovered a series of KBOs: 2014 FZ₇₁ and 2015 FJ₃₄₅. It was found that these objects “are mostly near Neptune mean motion resonances) and have significant inclinations.” The researchers go on to mention that they now believe that “these moderate

objects likely obtained their unusual orbits through combined interactions with Neptune’s MMRs and the Kozai resonance.”

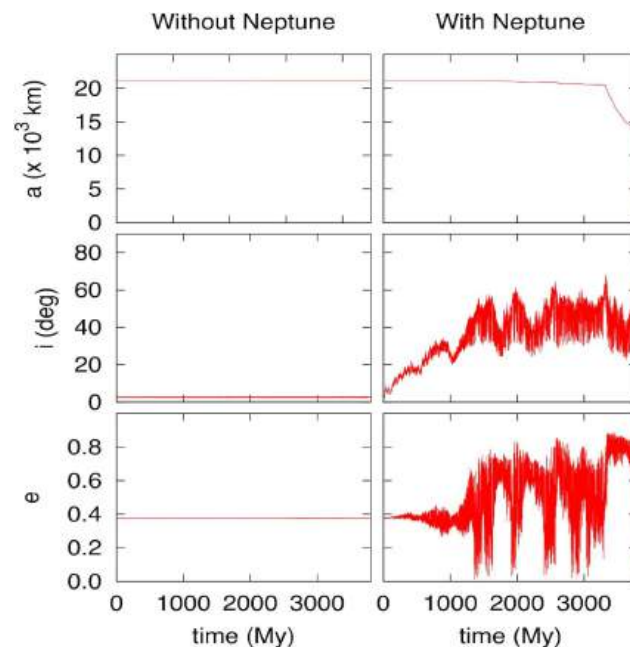


Figure 9: A chart showing the results of computer simulations that were designed to show “the evolution of the mutual inclination shown with and without the presence of Neptune.”

Source: FIGURE 3 From Brunini 2023

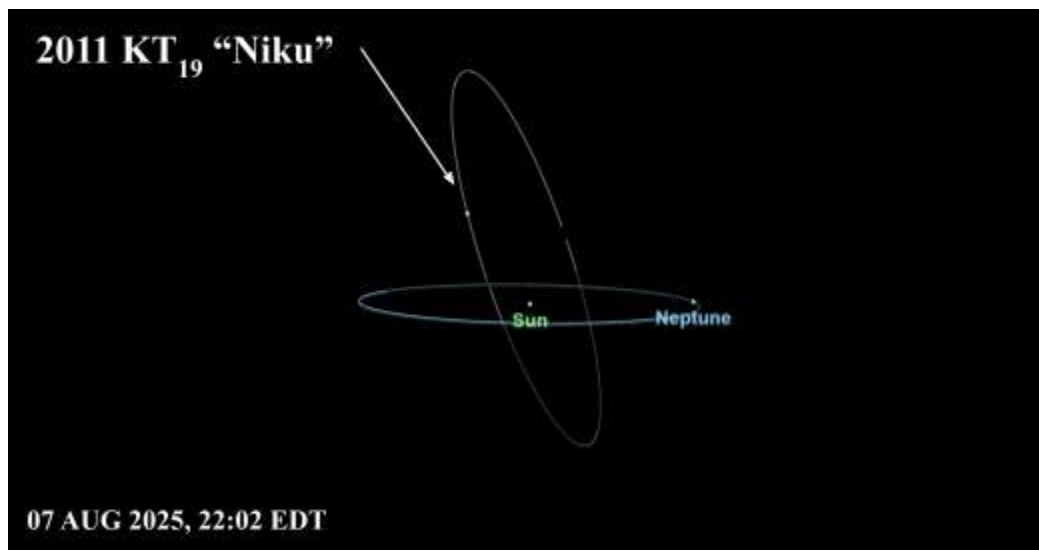


Figure 10: A diagram showing the orbits of Neptune and the KBO 2011 KT₁₉ (“Niku”). Notice how Niku’s orbit (White) is almost completely tilted on its side.

NOTE: Orbital Positions as of Thursday, August 7, 2025, at 10:02PM ET

(Source: The Jet Propulsion Laboratory, Small Body Database Lookup and Orbit Viewer)

Adaptive Optics

Recently, many astronomers have discussed using techniques to aid in the possible detection of Planet Nine. When people on Earth look at the stars, the Earth's atmosphere significantly distorts the view into deep space. For example, the fact that the stars appear to twinkle is due to atmospheric distortions: the stars do not, in fact, twinkle. Scientists have found ways to correct for these distortions using lasers, mirrors, magnets, and other technology. The range of materials, devices, and technology that scientists use to correct for distortions in what space looks like from Earth is collectively called Adaptive Optics (AOs).

As explained in Rao et al. 2024, "Adaptive Optics is the technology that integrates optics, mechanics, electronics, computer technology, and automation and control technology to compensate for optical aberrations that vary with time and space." In astronomy, AO systems are used to "correct for distortions in light caused by atmospheric turbulence, primarily to improve observations." In Perdelwitz et al. 2018, the researchers used adaptive optics to "re-analyze data acquired by WISE, an all-sky survey well suited for the detection of SSOs." Throughout the paper, the KBO Makemake was used to "illustrate the challenge of moving object detection and as a proof-of-concept of our method." However, when their AO technique was applied in a search for Planet Nine, they came up empty.

Furthermore, in Basden et al. 2018, the astronomers discuss a new technique to use Adaptive Optics. The researchers ran into a problem where they realized that the AOs "cannot be used to observe the whole sky since one or more natural guide stars of sufficient brightness must be found within the telescope field of view for the AO system to work." The researchers go on to mention a possible workaround by saying, "We introduce a technique to overcome this problem by using rotary unmanned aerial vehicles (UAVs) as a platform from which to produce artificial guide stars."



Figure 11: A Before/After picture of Neptune showing just how big a difference Adaptive Optics can make.

(Source: Scientific American)

Adaptive Optics could be extremely helpful in the search for Planet Nine because it is known amongst astronomers that, as Dr. Marc Buie once said, "The basic problem is that the

Earth’s atmosphere is just a mess at these kinds of scales. There’s a limit. And that’s what we often beat our heads against.” AOs are used to take that factor out of the picture and observe the stars as if the Earth’s atmosphere never existed.

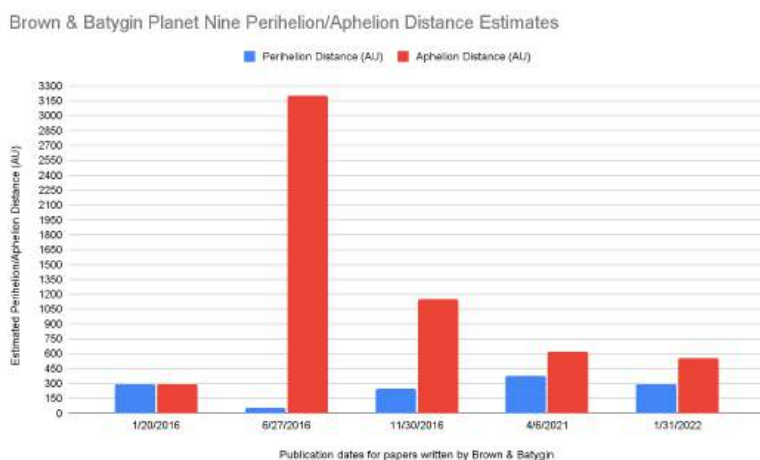


Figure 12: A bar chart showing Brown and Batygin’s estimates for Planet Nine’s perihelion and aphelion distances in Astronomical Units (AU) over six years. The dates on the horizontal axis represent dates on which Brown & Batygin published papers that included estimates for Planet Nine’s Perihelion and Aphelion distances.

Discussion

Evaluating Evidence for Planet Nine

There are two strong observational/dynamical arguments that currently support the existence of Planet Nine. The first of these is the fact that, when Holman et al. 2025 used a computer simulation to test the “Planet Nine reference population first described by Brown and Batygin, the simulation predicted that we would have discovered 75,769 out of 100,000 of the synthetic Planet Nine objects at 50% confidence.” This number shows that the idea of Planet Nine existing is not completely baseless. Furthermore, the paper goes on to state that they “could combine our results with those of Brown et al to place tighter constraints on the existence of Planet Nine.” One of the figures from their paper (See Figure 13) shows the density of the objects in the Planet Nine reference population that were not ruled out by Holman et al. 2025 (Figure 13A) or by Brown et al. 2024 (Figure 13B).”

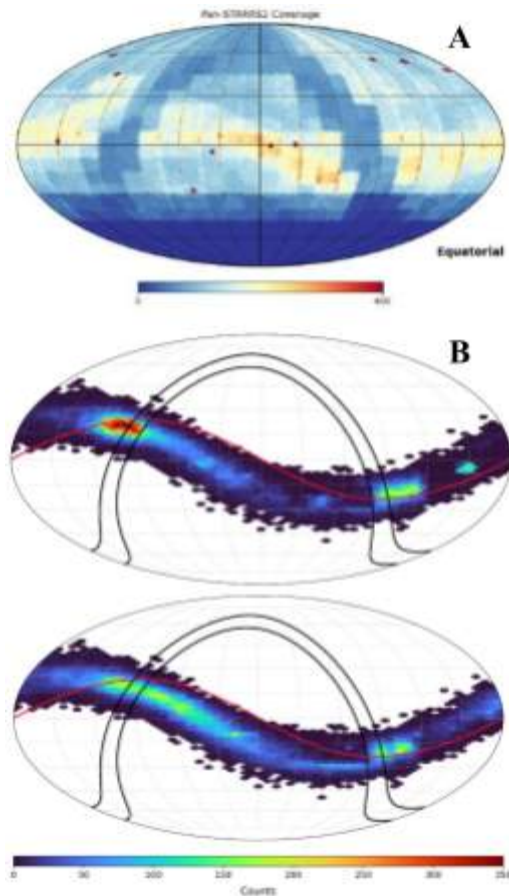


Figure 13A-B:

Top (13A): A diagram showing the “The coverage of the Pan-STARRS1 data used in this search, from 2009 April 2 until 2017 November, shown in a Mollweide projection in equatorial coordinates (R.A. = 0° is at the center of the plot, with R.A. increasing to the left). The original caption notes that “Each [Medium Deep Field] has thousands of exposures; we cap the maximum at 600 to keep those fields from dominating the color scale. The median number of exposures is ~ 150 . A fraction of the sky was not observed at all, and a few regions were observed more than ~ 400 times.” The color scale at the bottom of the figure denotes “the number of exposures that cover the region.”

Bottom (13B): A diagram showing the “On-sky density of the objects in the Planet Nine reference population” of studies conducted by Brown et al. 2024 (top) and Holman et al. 2025 (bottom).
(Source: FIGURES 1 & 9 From Holman et al. 2025)

The other main observational/dynamical argument that supports Planet Nine’s existence has been stated in many scientific papers, including Brown et al. 2024. In this paper, it is written that “While the existence of Planet Nine remains the most satisfactory explanation for a range of phenomena, true detection of the planet will be required to firmly discount these or other

alternatives.” This basically is saying that there’s just no way that planetary parameters like the ETNO clustering are simply a coincidence. There has to be a real reason behind it. And although the authors agree that Planet Nine is the best explanation for these strange patterns, Planet Nine would actually need to be detected in order to be certain of this.

The primary method used in searching for Planet Nine is conducting sky surveys backed up by computer simulations. However, these means of searching for Planet Nine could very well be flawed. For one thing, computers are just imperfect. Furthermore, many previously conducted computer simulations have shown that Planet Nine, if it is out there, is so dark and so far away that detecting it against many bright stars would be extremely difficult. Migaszewski 2023 writes that “the hypothesis of Planet Nine is justified by the anomalous structure of [the] trans-Neptunian solar system. The first indication of the planet’s existence was the detachment of the perihelia of Sedna and several other ETNOs from the gravitational influence of the known planets. Nevertheless, the existence of Planet Nine would be problematic if the detachment of the perihelia were the only evidence for it, since the proposed orbit of Planet Nine is itself detached from the giant planets.” Migaszewski’s interpretation is that the orbital clustering of the ETNOs is not enough to truly determine if Planet Nine exists. However, the paper goes on to state, “it was proposed that the planet was first scattered and then its orbit was circularized by planetesimals forming an extended disc up to $\sim 1000\text{AU}$. The chain of proposed solutions to the ETNOs detachment problem is then as follows: to explain detached ETNOs – a distant detached Planet Nine is proposed; to explain detached Planet Nine – an extended detached disc of planetesimals is proposed. The addition of more and more objects only seems to shift the problem, and without more evidence, the Planet Nine hypothesis would be in trouble.” This statement indicates that the authors believe that the addition of more ETNOs is only making the search of Planet Nine increasingly complicated.

Alternative Explanations for Planet Nine

As previously mentioned in the Theory section, three major ideas can explain the observed ETNO clustering other than the existence of Planet Nine. These are as follows:

1. Rogue Planet
2. Passing Star
3. ETNOs fighting each other

These theories show how known celestial phenomena can be applied to major astronomical mysteries like the ETNOs’ orbital clustering, and prove that we still have much to learn about the mysteries of the universe.

The Role of the Kozai Mechanism and Other Resonances

In the Theory section, I discussed the role of the Kozai Effect and Mean Motion Resonances in influencing the orbits of KBOs. However, I believe that if we are going to prove that Planet Nine is in fact working with Neptune to induce the Kozai Effect on these bodies, more evidence is needed, which could be obtained by further examining the KBOs’ orbits in addition to evidence from other theories about Planet Nine’s disturbances in the solar system. This includes the unusual 6° axial tilt of the Sun, which, as explained by Bailey et al. 2016 is believed to be caused by Planet Nine.

Observational Challenges and Biases

Previously in this paper, I explored how Adaptive Optics could be used to aid in the Planet Nine search (see Adaptive Optics in the Theory Section). However, as with using computer simulations to run Sky Surveys, the plan by many astronomers and researchers to use telescopes with AOs is also likely flawed. Many active Sky Surveys have constraints such as sky coverage and magnitude limits. The telescopes that conduct these surveys can only observe a small fraction of the night sky due to their location on Earth as well as potential obstructions that might block the view into deep space. Magnitude constraints would involve the sensors on a given telescope only being able to detect objects that give off enough light to reach the telescope. In addition, Planet Nine and the ETNOs it is believed to influence have very high magnitudes, making detection even harder. However, this is not to say that detection of these distant bodies is impossible. Sedna was discovered in November 2003 with technology from the 1990s [Brown et al. 2004]. If Sedna could be detected with that kind of computers and software, I believe that we could easily find Planet Nine with our current computers if we program them correctly to look in the right places.

Recent Developments and Debate

There has been much debate over the possibility of Planet Nine since the publication of Brown and Batygin's paper in 2016. Some of the more recent discussions on Planet Nine include the following scientific papers:

1. Siraj et al. 2025, who acknowledge that the ETNOs clustering “may have a mixture of origins.” After running a computer simulation which assumes that “the Kuiper Belt is the dominant source for objects with a semimajor axis < 1000 AU, but if the inner Oort cloud contributes an appreciable amount, the expected orbital properties of the unseen planet would differ.” The simulations showed that “in such a case, the expected eccentricity of the planet may increase, possibly making it harder to detect.”
2. Brown & Mathur 2023, who write in their paper, “On long timescales, it is not valid to treat the orbit of Planet Nine as fixed. It should evolve slowly in response to perturbations by the four known giant planets. In the analysis of the interaction of Planet Nine and a KBO, it is therefore better to use a fixed plane such as the mean ecliptic as the reference plane rather than the orbital plane of Planet Nine as we have done above.” This is saying that they think that Planet Nine's orbit might have also been manipulated by the known gas giant and ice giant planets.
3. Belyakov et al. 2022, who say, “Using the full orbital elements of 11 distant KBOs with perihelion distance > 42 AU and associated observational biases, Brown & Batygin 2021 write a likelihood function for detecting each KBO with certain parameters with a known fixed semimajor axis and eccentricity for each KBO, given a Planet Nine with a certain mass, semimajor axis, and other orbital parameters.” This is saying that if we use the data we have about the ETNOs, and then account for flaws in that data, we could calculate Planet Nine's planetary and orbital parameters.

Conclusion

Summary of Key Insights

The most compelling reasons to continue the search for Planet Nine include,

1. Investigating Planet Nine could unlock even more “mysteries of the universe” than it has already.
2. As mentioned in the Theory section, some of the discoveries that the New Horizons spacecraft made at Pluto changed the way we think about planetary engines. Continuing to search for and investigate Planet Nine will continue the adventure that humanity began 100,000 years ago, as our ancestors first walked out of Africa.
3. The search for Planet Nine promises to continue the legacy of generations of astronomers who have made their contributions to the field.

I think that the Kozai Mechanism and the clustering of the ETNOs are the best clues we have for Planet Nine’s existence.

Remaining Uncertainties

The biggest gaps in our current understanding of Planet Nine include a consistent estimate for Planet Nine’s orbital and planetary parameters, as well as figuring out how much gravitational force Planet Nine has, which would be needed in order to determine if Planet Nine really could be using its gravity to mess with the entire solar system.

These questions could be answered by running more advanced sky surveys (as technology advances) to further narrow down Planet Nine’s exact position in the sky, in addition to using tools like the world’s largest telescopes like the Keck and Subaru telescopes in Hawaii and the Magellan telescope in Chile, as well as the Hubble and James Webb Space Telescopes to directly observe the stars in search for Planet Nine.

Implications for Planetary Science/Call to Action

During the search for Planet Nine, we have made countless discoveries about our solar system and beyond, including the recent discovery of Uranus’ 29th moon (Moutamid et al. 2025), among other wonderful discoveries. One of the most compelling lessons from the ongoing search for Planet Nine is the enduring importance of patience, persistence, and creative problem-solving. I hereby call for more time on powerful optics like the James Webb Space Telescope dedicated to the search for Planet Nine, as well as more computerized sky surveys and more advanced search techniques to be found and applied to aid in the search.

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The Association Between Depression and OGM By Allison Xu

Abstract

OGM (Overgeneral Autobiographical Memory) is a phenomenon that causes an individual to recall less detailed memories and instead remember more general occurrences. This circumstance is often associated with depression; thus, this review aims to elucidate the relationship between the two. The method of selecting the research papers consists of filtering “OGM” and “depression” on the database ScienceDirect from the years 2000-2025. The multitude of researchers used various surveys and techniques to measure OGM and depression, including the AMT, CESD, HDRS-17, BDI, and SCEPT to derive their conclusions. The findings deduced that OGM is a predictor of depression, as well as rumination being associated with OGM and depression too. However, further research is needed to concretely state these findings, as several limitations were present in the articles, such as differing versions of questionnaires, varied levels of depression within subjects, and the education level of the participants. In addition, further research is also suggested in exploring the relationship between other mental disorders besides depression, such as PTSD. In summation, understanding memory and OGM is important as past experiences define an individual’s identity and allow people to learn from their past mistakes. Additionally, a better understanding of the correlation between OGM and depression can allow researchers and therapists to improve treatments and possibly prevent depression.

Introduction

Autobiographical Memory (AM) refers to an individual’s memory of their own life, including both specific personal experiences (episodic memory) and general factual knowledge (semantic memory) (Williams et al., 2007). These memories play a central role in shaping personal identity, since past experiences influence personality, emotions, and self-identity (Sumner, 2012). For instance, recalling a specific past success can enhance confidence and self-image, while a negative experience may harm one’s outlook and emotional well-being.

Overgeneral Autobiographical Memory (OGM) refers to the reduced ability to recall detailed, specific memories, which are typically defined as a memory that occurred at a particular place and lasted less than a day (Williams et al., 2007). Instead, the person tends to retrieve generalized summaries of events rather than precise recollections (Liu et al., 2016). For example, a person might remember a “trip to China” but struggle to recall a specific moment, such as visiting the Great Wall. OGM often involves overgeneralizing repeated events or events spanning a long period of time (Rawal and Rice, 2012). Over the past 25 years, research has identified associations between OGM and several mental health conditions, such as post-traumatic stress disorder (PTSD), anxiety (Liu et al., 2016), and especially depression (Sumner et al., 2010).

Major depressive disorder (MDD) is a common psychiatric condition, affecting almost 20% of American adults during their lifetime (Kessler and Wang, 2008), with a higher prevalence during adolescence (Stange et al., 2013), and a high recurrence rate (Solomon et al., 2000). Given its widespread impact, identifying and understanding risk factors for depression is

crucial for prevention and early intervention. In recent years, OGM has been proposed as a potential cognitive risk factor for depression (Liu et al., 2016).

Despite these advances, important questions remain unanswered. Various factors heavily impact study results, such as trauma history, clinical vs self-diagnosed MDD, remitted MDD, differing severities of depression, subject's education level, and age (Hermans et al., 2004; Wessel et al., 2001). For example, Kuyken and Brewin (1995) found that depressed women who reported experiencing child sexual abuse retrieved more overgeneral memories than those who did not have this history, suggesting that childhood trauma may play a role in the recall of autobiographical memories. However, Wessel et. al (2001) contrasted this notion, as their results did not support the idea that trauma is an important precursor to OGM and also noted that the variable of differing intensities of depression (e.g., more suicide attempts, self-harm, more severe depression) was not accounted for in the previous study. Therefore, all of these factors led to differing outcomes in numerous articles, resulting in inconclusive findings.

Due to the growing interest in cognitive markers, such as OGM, that could signal depression (Williams et al., 2007), this literature review is significant in recognizing this sign of depression to allow for early intervention and prevention (Rawal and Rice, 2012). Throughout the past years, OGM has been thought to have been linked to depression as decreased access to personal memories is associated with mood disturbance (Rawal and Rice, 2012).

This review aims to synthesize current research on the relationship between OGM and depression, drawing on findings from several experimental and observational studies. In addition, it will compare common methods used to measure OGM and examine the different results. This review first focused on explaining the multiple questionnaires and techniques to measure OGM and depression, then analyzed the various claims that oppose these tests. The key results and findings were shared, along with the limitations of the studies and this review. Finally, a conclusion was derived. By doing so, the review seeks to provide a clearer understanding of whether OGM represents a modifiable risk factor for depression and how this knowledge could inform prevention and intervention strategies.

Methodology

A systematic search was conducted in the ScienceDirect database using the keywords "Overgeneral autobiographical memory" AND "depression". The search was limited to peer-reviewed research articles published in English between January 2000 and July 2025. The initial search yielded 97 articles. Titles and abstracts were screened for relevance to the review topic, resulting in 24 articles selected for inclusion. The final selection was completed on July 25, 2025.

Results

1. Table of results

Table 1 shows the specific articles (with authors' names and dates) used in the review, along with some of the techniques that each article implements within its methodology, and finally, whether they disagree or agree with the existence of a relationship between OGM and depression. (Due to differing article objectives, the term "Other" was used in the methods used

category when none of the questionnaires explained earlier were used, and instead, the study uses other methods of measurement. In addition, the term “Inconclusive” will be used to declare the conclusion of the association between OGM and depression as unknown due to differing goals of each article. For example, Raes et al. (2008) aimed to investigate the relationship between rumination and OGM, focusing less on depression.)

Authors & date	Methods used	Agree or disagree	Authors & date	Methods used	Agree or disagree
Beyderman and Young, 2016	AMT (modified with 18 cue words)	Disagree	Phung and Bryant, 2013	BDI-II, AMT	Disagree
Frampton et al., 2018	Other	Inconclusive	Raes et al., 2008	SCEPT, BDI-II	Inconclusive
Graham, Herlihy, and Brewin, 2014	AMT (modified with 16 cue words)	Agree	Rawal and Rice, 2012	AMT	Agree
Griffith et al., 2012	AMT (3 versions), SCEPT	Inconclusive	Rimes and Watkins, 2005	BDI	Inconclusive
Hakamata et al., 2025	fMRI, AMT	Agree	Robinaugh et al. 2013	SCEPT	Disagree
Hermans et al., 2004	AMT, BDI, HDRS-17	Agree	Stange et al., 2013	AMT	Agree
Hitchcock et al., 2016	AMT, BDI-II	Inconclusive	Sumner et al., 2010	Other (meta-analysis)	Agree
Kaczmarczyk et al., 2018	AMT	Disagree	Takano et al., 2017	AMT, CES-D	Inconclusive
Kong et. al., 2015	CES-D, AMT (modified oral 12 cue words)	Agree	van Vreeswijk and de Wilde, 2004	Other (meta-analysis)	Agree
Liu et al., 2016	HDRS-17, AMT (Dutch)	Agree	Watkins and Teasdale, 2004	BDI, AMT	Inconclusive
Liu et al., 2017	HDRS-17, AMT, fMRI	Agree	Wessel et al., 2001	AMT	Agree
Matsumoto, Takahashi, and Hallford, 2023	AMT	Inconclusive	Zhu et al., 2012	CES-D, AMT (Dutch), fMRI	Agree

2. Methods to detect OGM and depression within patients

The Autobiographical Memory Test (AMT), created by Williams and Broadbent in 1986, was commonly administered to subjects throughout the papers selected for this review. The main goal of using this test is to assess the specificity of autobiographical memory via cue words. Before the test, subjects were given two practice words to familiarize them with the procedure. In the AMT, 12 emotional cue words (six positive and six negative adjectives) were presented (orally or on flashcards) to the participants. Afterwards, subjects were given one minute for each card to retrieve and present a specific memory to the word. However, if the participant was

unable to retrieve a specific memory, they were prompted to describe a particular time or place, and the time was recorded. Each response was timed, recorded, and categorized to either “specific” or “categorical”, with the latter referring to OGM (Kong et al., 2015; Liu et al., 2016). A few different modified versions of AMT (such as the Dutch version used by Zhu et al. (2012)) were used throughout the studies (Table 1). An example of the new, modified version of the AMT includes using 9 cue words (three positive, three neutral, and three negative) instead of the original 12 (Stange et al., 2013).

The 17-item Hamilton Depression Rating Scale (HDRS-17) was created by Hamilton in 1960 and is another test that was commonly given to subjects to assess depression severity. The questionnaire contains 17 questions inquiring about the subject's emotions and physical symptoms on a scale from 0 to 4; higher scores indicate higher severity of depression (Hermans et al., 2004; Liu et al., 2017).

The Center for Epidemiological Studies Depression Scale (CES-D) was created by Radloff in 1977, and it consists of 20 items, each describing depressive symptoms. Participants self-report how often they experience each symptom over the past week from a scale of 0 to 4, with 0 indicating no days and 4 indicating 5-7 days of the week. Like the HDRS-17, higher scores denote harsher depressive symptoms (Kong et al., 2015; Takano et al., 2017).

The Beck Depression Inventory (BDI), created by Steer et al. (1993), is a self-report questionnaire containing 21 items on a 4-point scale measuring how participants felt during the last week, similar to the CES-D. The BDI-II, created by Beck et al. (1996), was also used in a few articles, with both measuring the severity of depressive symptoms in subjects (Hitchcock et al., 2016; Phung and Bryant, 2013; Raes et al., 2008; Rimes and Watkins, 2005; Watkins and Teasdale, 2004).

The Sentence Completion for Events from the Past Test (SCEPT), created by Raes et al. (2008), is a task where subjects complete 11 sentence stems that connect to past experiences. The responses are then categorized as either specific or general and elicit a higher amount of OGM in nonclinical, healthy individuals compared to AMT (Robinaugh et al., 2013).

Functional magnetic resonance imaging (fMRI) is a powerful in vivo brain imaging technique that measures brain activity by detecting differences in blood flow. Experiments that used this approach conducted brain scans on the subjects while being shown a visual stimulus (fearful vs neutral faces) or subjects were prompted to think of an AM (Hakamata et al., 2025; Liu et al., 2017).

3. CaR-Fa-X model

Williams et al. (2007) developed the CaR-Fa-X model, detailing the processes (capture and rumination (CaR), functional avoidance (FA), and impaired executive capacity and control (X)) contributing to overgeneral memory. The cognitive model also shows the independent or combined effect of these processes on the subject's cognition and behaviour (e.g., problem solving). To this day, this model is one of the most prevalent figures used to demonstrate the process of OGM in particular relation to depression and was referenced numerous times (Graham, Herlihy, and Brewin, 2014; Liu et al., 2016; Phung and Bryant, 2013; Raes et al., 2008; Stange et al., 2013).

However, Phung and Bryant's (2013) findings contradicted this popular model that was frequently referenced throughout the other articles as supportive evidence (Graham, Herlihy, and Brewin, 2014; Liu et al., 2016; Phung and Bryant, 2013; Raes et al., 2008; Stange et al., 2013). They found that avoidance strategies (e.g., emotional suppression and inhibition) led to fewer categoric memories, which contrasted with CaR-Fa-X. Therefore, they stated that the model may need some revision and further research, perhaps weakening our understanding of this process between OGM and depression.

4. Outcomes

These various questionnaires, surveys, and techniques were assigned to the participants, usually ranging from 20 to 100 people. Overall, a majority of the articles supported the notion that OGM predicts depression; people who recall vague memories rather than specific events are more likely to develop depression or relapse into it (Frampton et al., 2018; Graham, Herlihy, and Brewin, 2014; Hakamata et al., 2025; Liu et al., 2016; Matsumoto, Takahashi, and Hallford, 2023; Rawal and Rice, 2012; Stange et al., 2013; Sumner et al., 2010; Wessel et al., 2001).

On the other hand, there were a few articles that didn't fully agree with this concept, particularly doubtful of the methods that led to this conclusion. Specifically, the AMT has been unfavored by some researchers for many reasons (Griffith et al., 2012). For example, Robinaugh et al. (2013) used the SCEPT in their research as AMT was hypothesized to be inadequately sensitive to detecting OGM in non-clinical subjects. However, van Vreeswijk and de Wilde (2004) found evidence to support the usage of the AMT. Other findings rejected the association between OGM and depression entirely (Beyderman and Young, 2016; Kaczmarczyk et al., 2018).

Discussion

With the essential association between OGM and depression being that OGM predicted the occurrence of depression, the plethora of science articles also displayed a few other relationships between the two experiences. One of the main key findings in this review includes the involvement of rumination in OGM. Rumination is the repetitive and passive constant thinking about the individual's own causes, consequences, and symptoms of depression (Nolen-Hoeksema, 1991). This style of thinking is typically present in those with depression and plays a role in predicting depression too (Rimes and Watkins, 2005). Kong et al. (2015) found that individuals who tend to use ruminative coping techniques tend to have more OGM, potentially leading to OGM playing a mediator role between rumination and depression (Liu et al., 2016). Additionally, Raes et al. (2008) compared abstract (maladaptive and analytical thinking) vs concrete (detailed and specific thinking) rumination and found that concrete rumination led to less OGM (Watkins and Teasdale, 2004).

Another one of the key findings regarding OGM and depression is that depression was found to be associated with negative or positive overgeneral bias. This negative bias occurs when individuals with depression retrieve negative personal memories more easily than positive memories (Gotlib and Joormann, 2010), and a positive bias occurs when the opposite happens. Because of how the AMT is formatted (with positive and negative cue words), this valence effect was noted by Hitchcock et al. (2016), and Wessel et al. (2001) observed results indicating a

positive bias. However, Takano et al. (2017) found results that conflicted with this idea and did not find the factor to be of importance in their research (Rawal and Rice, 2012). Therefore, further research is needed to determine if this effect greatly affects the subjects' responses and the results.

A few limitations included in the articles that the authors expressed include too broad or too specific samples, differing versions of AMT, and differing levels of depression within the subjects. Takano et al. (2017) gathered data suggesting that the cognitive decline due to age impacts subjects' performance on the AMT, therefore suggesting that age plays a role in autobiographical memory specificity (AMS). A plethora of studies only included one specific age group, and thus their findings cannot be generalized to a bigger population (Kong et al., 2015). In addition, Takano et al. (2017) also found that gender played a role in AMS, but a few of the research articles only conducted the experiment on one gender or had an unequal balance between them (Rawal and Rice, 2012). Another limitation listed by the researchers was the use of distinct versions of the AMT. Some studies used written AMTs while others used oral or modified versions with differing amounts of cue words (Beyderman and Young, 2016; Graham, Herlihy, and Brewin, 2014). In particular, Stange et al. (2013) used a new version of AMT (including three neutral words and subsequently three words, instead of five, for each valence) that had never been used in research before. Thus, it is unclear whether or not this new version impacts the results of the study. Likewise, Rimes and Watkins (2005) shared that self-reporting questionnaires must also be taken into account and suggested that future studies should also take non-self-reporting approaches. Moreover, the education/IQ and language of the participant play a role, particularly in the written AMT. Wessel et al. (2001) showed that education level predicts memory performance; consequently, the higher the individual's education, the more specific memories they have. Unfortunately, this measurement was not taken in various studies (Liu et al., 2016). Additionally, Phung and Bryant (2013) noted that their research was conducted in Hong Kong, where English was most likely the subject's second language. Accordingly, language plays a role in the AMT too (Graham, Herlihy, and Brewin, 2014). Finally, MDD severity has a role in the studies too, as Zhu et al. (2012) stated that because their subjects had mostly mild MDD, the findings cannot be generalized to all individuals with differing levels of MDD (Rawal and Rice, 2012).

Additionally, limitations to this specific review article include the databases and the range of the research articles. The articles were taken from ScienceDirect databases, but could have been expanded to many other databases (e.g., PubMed). Furthermore, the research articles were filtered from the years 2000-2025, but could have been filtered to even earlier years, such as 1990.

Further research can be conducted to conclude OGM's role in anxiety-related disorders, as well as other psychological disorders other than depression (e.g., PTSD, trauma). Rawal and Rice (2012) strongly stated that OGM predicts the development of depression but not of anxiety. Similarly, Wessel et al. (2001) also concluded this and even go on to say that past studies that have concluded a relationship between OGM and anxiety, the source may be co-morbid depression. On the other hand, Graham, Herlihy, and Brewin (2014) found that asylum seekers and refugees with PTSD and depression tend to retrieve less specific memories of their past, potentially suggesting an association between PTSD and OGM. Nevertheless, much more

research needs to be conducted in order to fully uncover the connection between OGM and the multitude of physiological disorders.

Conclusion

In conclusion, this review aimed to elucidate the association between OGM and depression. Based on the numerous research articles analysed, it is possible to conclude that OGM may be a predictor of depression. Understanding how our memory works is crucial for mental health, as the way we remember things can often affect our emotions and coping strategies. Vaguely recalling specific events can make it harder to solve problems, manage our emotions, and learn from our mistakes. By learning more about how memory and OGM work, therapists and individuals can work on improving memory, build coping skills, and potentially predict depression and therefore prevent it.

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Should Companies that Test on Animals Still Have a Heavy Reliance on that Method, When There Are More Accurate, and Cruelty Free Methods Available? By Priya Bisnath

Introduction

How do humans know how much pain is too much for an animal; why should humans get to decide that for animals? These questions stem from the fact that animals get mistreated every year even though they're considered "protected" under the Animal Welfare Act, (AWA) (Chen). The Animal Welfare Act was signed into law on August 24, 1966. It is the only federal law in the United States that regulates the treatment of animals in research, teaching, testing, exhibition, transport, and by dealers (National Agricultural Library). Animal testing has always been the dominant method for products, especially cosmetics. As a fast-moving society we try, and use new products every day. For instance, most women's everyday routines include the use of skincare and makeup. People use these items without giving a second thought about where they came from, if it's safe, or if the company the product is coming from performs in an ethical manner. Animal testing has always been a big problem and still is to this day. The Federal Drug and Food Administration (FDA) is in charge of ensuring that cosmetics and other medical products are safe to use and are properly labeled. However, the FDA does require companies that produce cosmetics to specifically use animals to test their products. Nevertheless, the FDA consistently advised cosmetic manufacturers to utilize whatever testing method is appropriate and most effective to sustain the safety of their products (FDA). Regardless of how many rules are put in place to reduce animal testing, it always finds a way to still happen. As a result of the increasing amount of controversy surrounding animal testing, companies should take a step back and refine their product-making process. Thus, product-based companies that still have a heavy reliance on animal testing should convert their methods due to the lack of efficiency of animal testing and new technological advancements like human tissue testing and in-vitro testing, which are more humane options.

Efficiency of animal testing

Tests performed on animals are not as accurate as they seem. As laboratory procedures and conditions greatly influence an animal's physiology and behaviors, those factors can also impact research outcomes. A variety of conditions like windowless rooms, artificial lighting, human-produced noises, and restricted housing environments in the laboratory cause changes in the neurochemistry, genetic expression, and nerve regeneration of an animal being tested (Akhtar). The author, Akhtar, an American neurologist, public health specialist, and animal ethicist who is also the co-founder, CEO, and President of the Center for Contemporary Sciences, stated, as an example in one study, "...mice were genetically altered to develop aortic defects. Yet when the mice were housed in larger cages, those defects almost completely disappeared". Providing further examples, typical noise levels in laboratories can damage blood vessels in animals, and even the type of flooring on which animals are tested in spinal cord injury experiments can affect whether a drug shows a benefit (Akhtar). All of these slight factors can alter an animal's composition making it unfit for the experiment it is being used for. Not only having an unqualified animal to work with is bad for the experiment, but it's also detrimental to the safety of humans using the final product. Coinciding with the environment the animal was

raised in, the similarities between animal models and human diseases are not identical. According to the Humane Society International, “Independent scientific reviews demonstrate that research using animals correlates poorly to real human patients. The data show that animal studies fail to predict real human outcomes in 50 to 99.7 percent of cases” (Humane Society International). This comment made by the Humane Society International implies that animal testing is not always the safest option, because human traits and activities are so different from animals, especially rats and birds, which are mainly used in animal testing models. Similarly, as mentioned in the Library of Medicine, “Human diseases are typically artificially induced in animals, but the enormous difficulty of reproducing anything approaching the complexity of human diseases in animal models limits their usefulness” (Akhtar). As animal models cannot effectively predict the evolution of the disease or provide essential feedback for treatments, they have been seen as inaccurate and they fail to be of use to human users/patients.

In the article, “Predator-induced fear causes PTSD-like changes in the brains and behavior of wild animals”, the authors explain how exposure to predators by animals has resulted in animals displaying PTSD symptoms. As stated in the text, “Wild, free-living adult chickadees of both sexes were live-captured during the non-breeding season and housed in flocks outdoors for 1 week before experimental trials. To experimentally test if predator-induced fear has enduring effects, individuals were housed solitarily in acoustic isolation chambers and exposed for 2 days to audio playbacks of the vocalization of either predator,” (Zanette). Not only were the wild animals taken from their home, but they were also used for an experiment that purposely tortured them. The chickadee's reaction to the predators had negative lasting effects, including not eating for long periods because they were scared to go out and a decrease in fecundity (Zanette). This article is from the scientific report journal and has direct research from experiments demonstrated in the article. This information highlights the fact that animal testing is unethical and can have lasting effects on the animal. This just puts a glimpse of what's happening in labs into perspective. Although this is not for consumer use, this is controversial because these situations can commonly happen in the wild, however, humans should not be able to decide to put animals in danger and even worse, cause animals to develop PTSD effects on purpose. For example, during the experiment, the scientists put animals in simulated environments with their predators, with no way out, and studied their reactions to said predators. In a similar fashion to Akhtar and her explanation that the environment has a negative influence on the effectiveness of the product, Zanette describes the artificial situation and environment the animals are put in. Using the information obtained by both Akhtar and the Humane Society International, it can be concluded that the factors expressed in the PTSD experiment can change the course and results of the intended experiment.

Alternative testing methods

“The “3Rs alternatives” refer to the replacement, reduction, and refinement of animals used in research, teaching, testing, and exhibition. According to Drs. William Russell, MD in physical medicine, and Rex Burch, a humane scientist, first described the 3Rs in 1959 in their book, “The Principles of Humane Experimental Technique”. Russell and Burch advocated for new scientific approaches that would minimize pain and distress of research animals while maintaining scientific integrity (National Agricultural Library). Although animal testing models

have been used for many decades and have helped test both cosmetic and medical products, animal testing needs to be put to a halt because there are new and improved testing methods available now. For instance, stand-alone methods have been demonstrated to be helpful for some specific toxicological predictions with some limitations. However, new strategies for the application of New Approach Methods, and solving complex toxicological endpoints are addressed by Integrated Approaches for Testing and Assessment (IATA) (Caloni). Increasingly, machine learning Artificial Intelligence, AI, has landed itself to integrate evidence streams (Caloni). Similarly, as AI was positively described by Caloni, the article, "LAB TO ALGORITHM: AI's ROLE IN MINIMISING ANIMAL TESTING" mentioned using Vivitrosi, which is integrating AI with new technologies like organ-on-a-chip and in vitro models that have shown positive and promising results for replacing animal testing in the future (Marques). This revolutionary system replicated the function and structures of human organs and tissues. This ultimately provides scientists with a more physiologically relevant environment for testing the substance because it is a replica of human DNA. This proves that animal testing is not the only option anymore, they're new and improved technology that provides scientists with this easier luxury that abstains from harming animals. Nevertheless, companies still choose animal testing as their main method. Why is that?

Counterargument

Unlike consumers, companies might ask themselves why they should change their entire testing method if they're not doing anything illegal or wrong. All companies should debate which methods will work best for them considering the circumstances. Only recently has Sephora converted fully to cruelty-free in 2020 and that's fairly new (Conscious Bunny). Brands like Sephora might not want to switch to other method options because it could be costly, and that is completely logical. Additionally, companies test on animals to provide data that they can use to defend themselves when they are sued by injured consumers, and some courts have ruled that the FDA has failed to show that the results of animal tests can be extrapolated to humans. The unreliability of animal tests allows companies to put virtually any product on the market (PETA). This might be seen negatively, but in the eyes of a company that just wants to make money that is why companies gravitate to this method. Although many product-based companies find animal testing to be cheaper and easier, the book "Animal Experimentation: Working Towards a Paradigm Change" disagrees with these claims. The authors of this writing present the argument that people don't know how valuable existing animal-based methods are, as none have ever been formally validated in the manner required for potential replacements (Herrmann). The authors Kathy Archibald, Robert Coleman, and Tamara Drake, who are the Director of Safer Medicines Trust, Consultant to Safer Medicines Trust, and Director of Research and Regulatory Policy, at the Center for Responsible Science, claimed "One reason for this is that the formal process of test-method validation is so slow, expensive, and demanding, in its current format, that it represents an effective block to testing existing accepted methods and a significant barrier to testing new methods" (Archibald). This is held back for companies and animals. The slow process of approving a new method can be seen as unattractive and unsustainable for the company. This is why companies don't want to switch to full human testing.

According to the article, “Moral Courage and Intelligent Disobedience,” Ted Thomas, Director of the Department of Command and Leadership in the U.S. Army, and Ira Chaleff, president of Executive Coaching & Consulting Associates in Washington, DC, defined two different terms. The first one is Moral Courage which means doing the right thing even if it puts someone or a group at personal risk, controversy, or other negative consequences. This is demonstrated by Sephora changing its testing policy to cruelty-free, even though this was costly for them and was a big change. The second term is Intelligent Disobedience which means deciding what is the right thing to do even though higher figures are telling you what to do. Both these terms mainly represent doing the right thing even when other people are not and if it's not ideal to you but would be the overall ethical choice. This is a perfect example of companies switching out of animal testing because it is the majority choice and has its benefits. However, morally it's not the right thing and is harming both humans and animals.

Conclusion/Solution

Thus, product-based companies that still have a heavy reliance on animal testing should convert their methods due to new technological advancements that allow data to be more clear and precise to human models. As demonstrated in the argument, animal testing does not only have a horrible impact on animals but destroys humans when the data is not accurate or effective from the tests. Yes, the animals used might be very similar to humans, however in the case of seeing if a product is safe to use on humans, the better, more logical answer is to use human models instead of animal models. On top of switching testing methods, the AWA should tighten up their animal testing policy so companies do not favor it anymore, which will cause them to push towards alternative methods like using visitors and human tissue models. In conclusion, animal testing should be put to a stop because it will help improve humans, animals, and the earth's environment for the better.

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An Analysis of Bubble Tea Prices Across Northern Virginian Counties By Claire Bai Yang

Abstract

This study examines the relationship between bubble tea prices and socioeconomic factors in Northern Virginia, specifically in Loudoun, Arlington, Prince William, and Fairfax counties. Average prices and price ranges for original or black milk tea were collected from five bubble tea shops in each county and compared with population estimates, median household income, and poverty rates. The findings suggest that population size, competition among shops, and household income play important roles in determining bubble tea pricing. Counties with higher populations and greater shop density, such as Fairfax and Loudoun, exhibited narrower price ranges due to competition, though Fairfax maintained the highest average price consistent with its relatively high income levels. Contrastingly, Arlington and Prince William, with smaller markets or fewer shops, showed wider price ranges or unexpectedly higher averages despite lower median incomes. Overall, the results indicate that bubble tea prices are influenced by a combination of economic capacity, population size, and competitive density, reflecting how local socioeconomic conditions shape consumer markets for culturally significant products like bubble tea.

Introduction

Bubble Tea (also often called boba tea or just boba) originates from Taiwan in the 1980s. Through experimentation in tea shops, chewy tapioca pearls (boba) were added to iced milk tea alongside other toppings. Originally, sweetened milk tea was mixed with traditional Taiwanese desserts that included tapioca pearls or jellies, eventually leading to the drink that has spread globally: bubble tea. As the drink's popularity propelled, it spread across Taiwan and reached neighboring countries in East and Southeast Asia during the 1990s. Bubble tea was able to expand globally as Taiwanese immigrants and international bubble tea chains exposed North America, Europe and other areas to the drink, further bolstering the drink's popularity.

Since its expansion, bubble tea shops have branched out significantly and created countless variations of the tea-based drink. Cheese foam toppings, brown sugar toppings, and additional fruit jellies have become staples at bubble tea shops. Furthermore, customers are often able to adjust sweetness, ice levels, milk type, and add toppings of their choice to customize their drink to their liking. The extent of the customization that's possible for bubble tea appeals to a lot of customers and pulls them away from other drink competitors like Starbucks and Dunkin' Donuts.

Beyond the drink itself, bubble tea has become a pop culture symbol that represents Asian identity and youth culture as bubble tea shops are seen as popular social hangout areas. In addition, most bubble tea shops include aesthetic interior design and decoration that sets them apart from the typical cafe, further appealing to younger adults and teenagers. Bubble tea shops, however, are often well-known for a specific atmosphere or drink that propels customer loyalty

and differentiates them from other boba competitors. Thus, the bubble tea market throughout the globe has skyrocketed in value and bubble tea chains have arisen across cities worldwide.

Methodology

The purpose of this study is to determine if there is any connection between bubble tea prices, median household income, and poverty rates in Northern Virginia. In order to compare the bubble tea shop prices of the various counties in Northern Virginia, the four counties Loudoun County, Arlington County, Prince William County and Fairfax County were chosen. It's unclear as to which counties are definitively part of Northern Virginia; however, most literature generally considers these four as part of Northern Virginia ("About NVRC"). From each County, five bubble tea shops were selected as this was the total number of shops in some counties. For counties that had more than 5 shops, the first 5 shops that sold original or black Milk Tea were selected. The price of their original or black Milk Tea was used to calculate average price and price range. Data on population estimates, median household income, and poverty percentage was obtained from

Results and Discussions

All Topics	Fairfax County, Virginia	Prince William County, Virginia	Arlington County, Virginia	Loudoun County, Virginia
Population estimates, July 1, 2024, (V2024)	1,160,925	497,003	239,807	443,380
Income & Poverty				
Median households income (in 2023 dollars), 2019-2023	\$150,113	\$128,873	\$140,160	\$178,707
Per capita income in past 12 months (in 2023 dollars), 2019-2023	\$69,971	\$50,883	\$88,024	\$70,133
Persons in poverty, percent	6.1%	6.7%	7.1%	4.1%

Figure 1: table for comparison of the median household income, per capita income, and percentage of persons in poverty between four Northern Virginian counties

Loudoun County

Loudoun county has a population of 443,480, which is the second least amongst the 4 counties. Its median household income, however, is 178,707, which is the highest of the 4 counties. In addition, the county has the lowest percentage of persons in poverty with only 4.1% ("Explore Census Data."). Loudoun County has a substantial amount of bubble tea shops increasing competition and causing prices to have less range. Accordingly, Loudoun County has the lowest range of prices between the four counties. They also have the second lowest average price for bubble tea, which can be explained by the high competition. Cafes must keep prices low in order to attract customers amidst neighboring competitors.

Arlington County

Arlington county has the lowest population of the four counties, with only 239,807 people. Their median household income is the second least with a median household income of

\$140,160. In addition, Arlington County has the highest percentage of persons in poverty at 7.1% (“Explore Census Data.”). Naturally, Arlington County has the lowest average price and highest range amongst the four counties. Some bubble tea shops will lower prices to account for lower household income in the area, while others will keep prices high, contributing to the high price range. Moreover, Arlington County is the smallest of all the counties, decreasing the amount of locations bubble tea shops can occupy. As the shops are forced to be closer together, competition will increase and they will be incentivized to lower prices to attract more customers.

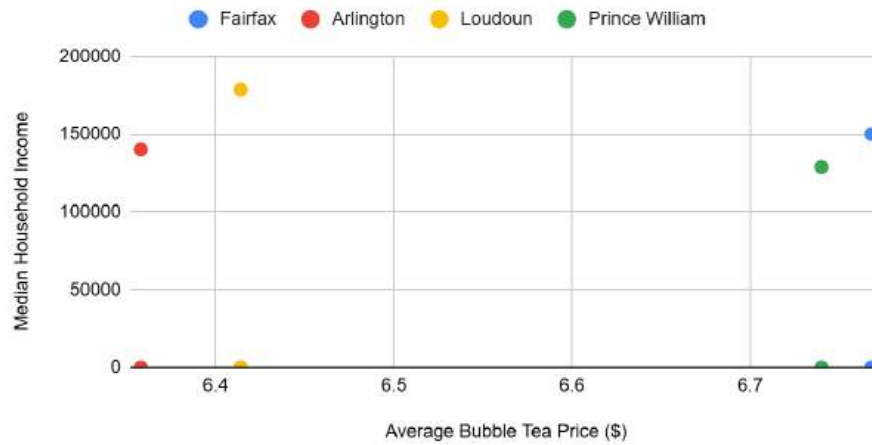
Prince William County

With the second highest population of 497,003, Prince William County’s median household income is the lowest amongst the four counties at \$128,873. Accordingly, its poverty percentage is the second highest and just below that of Arlington County at 6.7% (“Explore Census Data.”). The average price of Bubble Tea in Prince William County is the second highest of the four counties. However, its average price is just barely below that of Fairfax County, even though the median household income is the lowest. This can be explained by the low number of bubble tea shops in Prince William County, which decreases competition and allows bubble tea shops to price higher despite the lower household income and higher poverty rate.

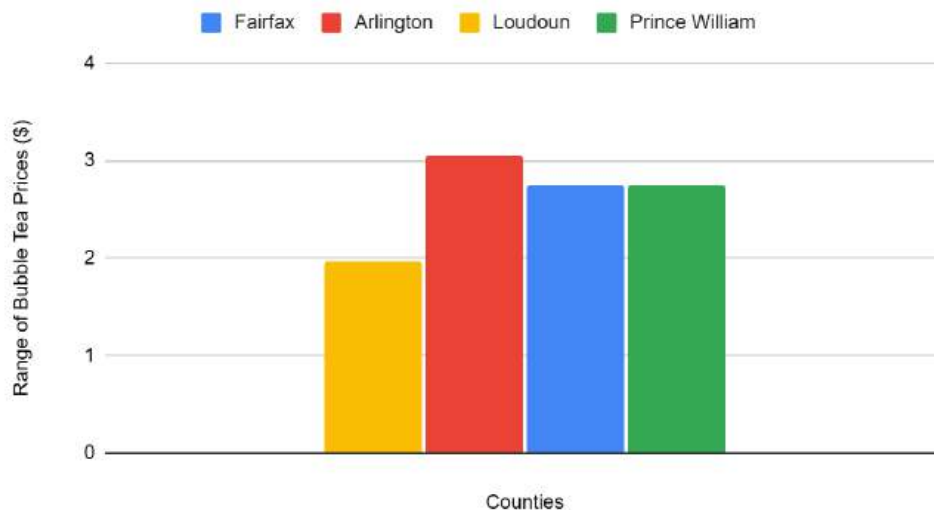
Fairfax County

Between the four counties of Northern Virginia, Fairfax County has the highest population at 1,160,925 people. Fairfax County's median household income is the second highest at \$150,113 while its poverty rate is the second lowest at 6.1% (“Explore Census Data.”). As it has the highest population of the four counties, Fairfax County also has a higher number of bubble tea shops throughout the region. Thus, the range of prices in Fairfax County is lower due to this increased competition. The average price of Bubble Tea, however, is the highest, which aligns with the high median household income.

Average Bubble Tea Prices and Median Household Income Based On County



Range of Bubble Tea Prices Based On County



Conclusion

As reflected in the prices of bubble tea, population count, number of competitors, median household income, and the size of the county all contribute to the decision-making of cafes. Population count generally allowed bubble tea shops to price higher as there are more customers available. Likewise, meeting household income had a positive relationship with the price of bubble tea because shops were able to maintain customer loyalty knowing that customers could afford their higher prices. The size of the county related to the number of competitors for bubble tea shops, and this forced stores to keep prices lower as competition grew. Ultimately, bubble tea shops and cafes were influenced by the region around them and the characteristics of the population.

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R2P's Justification in Libya Under the Just-War Theory By Olivia Hicks

In a time of crisis, Obama once said, “the Libyan people need our aid and support. It's our duty⁵⁰.” He was referring to the violence happening in Libya under the Gaddafi Regime. During this time of terror and violence in Libya, the UN made a crucial decision to launch a controversial intervention that, although it rid the country of its dictator, is blamed for sending Libya into a civil war⁵¹. Scholar Patrick CR Terry believes that the military invasion in Libya was neither lawful, justified, nor successful because of its eventual outcome of civil war and further human rights violations⁵². Today, it is critical that we discuss how to address humanitarian crises, as human rights should be a top global priority. I believe that the case study of Libya is an example of an operationally successful intervention that is justified in terms of the Responsibility to Protect (R2P) Just-War Theory. The short-term outcome of the intervention along with the actions taken to fulfill NATO's goals displays the principled nature of the intervention. I will explain how the criteria of the Just War Theory and the short-term operational success make the intervention justifiable. I will also refute opposing schools of thought that say this intervention was illegal, NATO had illegal support for Libyan rebels, and NATO failed to impose a government which led to long term instability. To end, I will discuss how to integrate the successes of this intervention with changes to create long term prosperity for a country.

Background Information

Before the war, Muammar al-Qaddafi had been in power for 42 years, bringing peace, opportunities, and tyranny to the nation. On September 1st, 1969, he seized control of the nation from King Idris I through a coup. He removed US and British bases from Libya and exiled Italian and Jewish people living there as well. He enforced strict Islamic principles, such as no alcohol or gambling, and nationalized all foreign-owned properties in the country. He deeply believed in Islamic socialism, as he wrote in his book *The Green Book*⁵³. Internationally, Gaddafi gained a reputation for being unpredictable and erratic, as he also funded many groups with revolutionary agendas, such as the Black Panthers, the Nation of Islam, and the Irish Republican Army⁵⁴. In 2011, peaceful anti-government protests broke out in Libya over the rule of Muammar al-Qaddafi, urging him to release political prisoners, such as Fathi Tirbil, a legal advocate for the families of victims of the 1996 Abu Slim prison massacre. Libyan protestors were attacked by the government with tanks, artillery, and warplanes; all while Gaddafi vowed, he would fight for the regime “to the last bullet”⁵⁵. Within only a few weeks, 500-700 people

⁵⁰ Obama, 2011.

⁵¹ Rowan, 2019.

⁵² Terry, 2015, 162.

⁵³ Editors of Encyclopedia Britannica.

⁵⁴ Rowan, 2019.

⁵⁵ Editors of Encyclopedia Britannica, 2025.

were dead, with many more injured⁵⁶. After the intervention, Qaddafi was killed by rebels and soldiers, but without a designated leader, the country fell into political uncertainty and civil war.

The UN decided to intervene to protect civilians and stop the horrific human rights violations. R2P was founded in 2005, as a section of the UN, to stop “mass atrocity crimes of genocide, war crimes, ethnic cleansing and crimes against humanity.”⁵⁷ R2P uses the Just War Theory, a doctrine that provides ethical guidelines for when it is morally acceptable to go to war. This criterion includes having just cause, being a last resort, being declared by a right authority, possessing right intention, having a reasonable chance of success, and proportional means used, to determine that it was ethical to intervene⁵⁸. These criteria are critical for R2P’s work because they are able to effectively decide when intervention and war is necessary and just.

Just War Criteria

The Just War Theory is an ethical criterion to evaluate if it is necessary to enter into war or combat. It is a majority Christian philosophy that originated with classical Greek and Roman philosophers like Plato and Cicero. The six criteria of this doctrine can make war seem like a good thing, but it is important to remember that this doctrine only makes war just and not permissible.⁵⁹ Each category is essential to understand the full picture and evaluate if war or military usage is justified and necessary.

A. Just Cause

The Just Cause criteria is the strongest and most well respected out of all the Just War theory since the cause of war is the basis of its moral justification. The intervention in Libya fulfilled the just cause criteria because of the brutality of the violence Gaddafi was inflicting on the people. The just cause criterion is concerned with the reason for the intervention. In this case, the cause of intervention was the horrific violence being inflicted on the Libyan people. The violence, which originally started because of protests against Gaddafi, was stopped by intervention, so the UN was supporting the will of the Libyan people. Under R2P's criteria for intervening in conflict, a state must fail in its duty to protect its civilians, and there must be imminent or ongoing "serious and irreparable harm" such as: large-scale loss of life or large-scale ethnic cleansing⁶⁰. In this case, the Libyan government was using its military to harm people with no mercy. Gaddafi only seemed as if he would escalate the situation more, by calling the protestors cockroaches and declaring that “any Libyan who takes arms against Libya will be executed.”⁶¹ Since there was immediate violence and threats to civilian safety and Gaddafi made verbal threats to continue the violence, R2P and the UN had a responsibility to protect the

⁵⁶ Global Centre for the Responsibility to Protect, 2022.

⁵⁷ Global Centre for the Responsibility to Protect.

⁵⁸ Moseley.

⁵⁹ BBC, 2014

⁶⁰ Global Centre for the Responsibility to Protect.

⁶¹ Editors of Encyclopedia Britannica.

people. Under these circumstances, just cause was fulfilled because, without an intervention, it seemed that Gaddafi would not stop until all the protesters were gone.

B. Right Intention

The Right Intention criteria is crucial to judge the sincerity and motives of the war, to make sure resources are not being wasted. The intention must be based on peace and justice, not conquest or economic gain. The intervention must be done under the intentions to protect the citizens without ulterior motives. With all the deaths happening, the primary goal of the UN was to provide humanitarian relief and stop the violence, but they were also thinking about preventing refugee outflows and securing oil supplies. Although both of those could be seen as ulterior motives, national interest does not invalidate the right intention criteria since the goal of the intervention was to save lives⁶². The US alone donated 80 million dollars on June 9, 2011, to those affected by the conflict⁶³. The donations made re-enforce the positive intentions that the UN had when invading, only wanting to save civilians. The UN and NATO fulfilled the right intention requirement because the objective was to stop the violence against the Libyan people protesting for regime change, so the intervention was only helping the Libyan people take back their country.

C. Right Authority

The Right Authority aims to make sure that only leaders are able to make decisions about war, not private groups. This is important to make sure that war is a choice of the people and is legal. Since NATO, the UN, and R2P commenced the intervention through Resolution 1973, the right authority was fulfilled. Resolution 1973, which gave legality to intervening in Libya, was created and decided on by the UN Security Council; specifically, the countries of Bosnia and Herzegovina, Colombia, France, Gabon, Lebanon, Nigeria, Portugal, South Africa, the United Kingdom, and the United States of America⁶⁴. This intervention was distinctly different from other interventions because it was the first time military force was allowed to be used to intervene in a country. For example, the Kosovo intervention led by NATO was not supported by the UN Security Council, even though other forms of humanitarian aid were approved. There is no doubt that when compared to past interventions, Libya was given legal permission from the right authority: the UN. Unlike Kosovo, NATO and R2P were approved to be used by the UN Security Council through Resolution 1973, making it legal for the intervention to occur.

D. Last Resort

Although Last Resort is one of the most important categories, making sure that violence is the last option, it leaves much up to interpretation. What is truly considered all the possible steps prior to violence is very situationally dependent. The intervention was the last resort taken,

⁶² Kriz and Fridrichova, 2015.

⁶³ Center for Preventive Action.

⁶⁴ United Nations Security Council, 2011.

as other precautions had been taken with no sign of de-escalation. Before any military force was used to stop Gaddafi's violence, the UN had imposed a no-fly zone and sanctions on Libya, freezing at least 30 billion dollars in assets from the United States alone. Even with these steps taken, the Gaddafi regime did not halt the violence. As British Prime Minister David Cameron said, "he continues to brutalize his own people, so the time for action has come. It needs to be urgent, we have to enforce the will of the United Nations, and we cannot allow the slaughter of civilians to continue."⁶⁵ He emphasizes the urgency and lack of viable alternatives due to the speed of escalation within the country. There seemed to be no other option, except a military intervention, that would enforce human rights in Libya and stop the Gaddafi regime.

E. Reasonable Prospects

Before entering a country, there must be reasonable prospects of being successful without causing more deaths than would have occurred. Although this category can be hard to measure before the war, it is equally important to make sure that lives and resources are not wasted. Before the intervention, there was a high chance of success because the Libyan army was in disarray, there were ongoing military, political, and diplomatic defections from the Gaddafi regime, and the weak air-defense system made enforcement of a no-fly zone viable⁶⁶. Already, within weeks in Libya, there had been 400-700 people killed from Gaddafi's attacks⁶⁷. Gaddafi's words and actions indicated that the violence would not stop any time soon, and NATO had the ability to make the intervention quick and effective, achieving its goal in only 6 months and killing only 70-400 people, fewer than the Gaddafi regime. Due to the starting and ending conditions, it is justified that the intervention under the reasonable prospects criteria because it seemed easy to defeat the regime and the intervention itself did not cause many civilian casualties. The intervention successfully reduced the level of violence and death compared to what would have occurred under the Gaddafi regime, and the circumstances leading up to it made it appear to be an easy win.

F. Proportionality

Lastly, the Libya intervention fulfills the Just War Theory's criteria of proportionality because the actions taken by the NATO soldiers successfully achieved their goals without immediate harm to the Libyan people. This cost benefit analysis is essential when deciding to go to war and only inflict the necessary violence and harm without extra civilian casualties. In an attempt to stop civilian casualties, NATO-led airstrikes against the regime's military bases, moving the violence away from the homes and populated civilian areas. NATO took no purposeful actions against the Libyan people and only went after Gaddafi's military bases to stop the violence against the Libyan people. There was controversy because during the airstrikes, NATO accidentally struck family homes, but these strikes were few and exaggerated in the news.

⁶⁵ Reuters.

⁶⁶ Sullivan, 2007, 135.

⁶⁷ Kelety.

AP News reports that even though The Post claims NATO killed tens of thousands of people, the experts said only 72-403 civilians were killed⁶⁸. Although every life lost is a travesty, these losses do not amount to what Gaddafi would have done if not stopped by NATO, as he showed no mercy towards anyone. The airstrikes are estimated to have only killed 400 people maximum in 6 months, much less than the hundreds Gaddafi's men killed in weeks⁶⁹. Additionally, the actions of the airstrikes were just focused on ending the regime and not imposing any outside agendas on the country. Similar to the reasonable prospects, since there were not many casualties and a singular focus on defeating Gaddafi. Therefore, NATO's intervention remained proportionate by focusing on military targets, minimizing harm to civilians, and aiming solely to stop Gaddafi's violence rather than impose foreign control or influence.

Operational Success

The intervention was operationally successful in achieving its immediate military and humanitarian goals. The military and humanitarian goals were to stop the violence on citizens caused by the Gaddafi regime, and on October 31st, NATO left Libya after assessing its success. NATO used airstrikes to target Gaddafi's military bases, to stop the regime from using it against civilians. Gaddafi himself was killed on October 20th, ending the regime. With the airstrikes, NATO destroyed 6,000 military targets and de-conflicted nearly 4,000 to make sure that aid from the UN, GNOs, and other organizations could reach the Libyan people⁷⁰. During the intervention, NATO was able to end the violence from the Gaddafi regime and give 84 million dollars in aid to the people⁷¹.

Additionally, the intervention was meant to stop the injustices happening in the moment, not secure long-term stability. According to R2P, the organization is meant to "ensure that the international community never again fails to halt the mass atrocity crimes of genocide, war crimes, ethnic cleansing and crimes against humanity." It is not their responsibility to ensure long-term stability. Gaddafi's actions can be categorized as crimes against humanity, so R2P had an obligation to stop him. R2P followed the ethical guidelines required to stop Gaddafi, leaving no other options to successfully save lives. This intervention, in the short term, fulfilled its goals and saved millions of lives, making it necessary and justified.

In contrast, the Rwandan Genocide is a consequence of what happens when the international community fails to intervene. The Rwandan Genocide, which occurred from April 1994 till July 1994, killed over a million people, and an estimated 250,000 women were raped⁷². Rwandan government soldiers, who were Hutu, mercilessly carried out ethnic cleansing against the Tutsi, killing the prime minister and peacekeepers in the country. There had been a history of bias and discrimination against Tutsis in Rwanda, but the slaughter caused by the Hutus was

⁶⁸ Kelety, 2022.

⁶⁹ Kelety, 2022.

⁷⁰ North Atlantic Treaty Organization.

⁷¹ North Atlantic Treaty Organization.

⁷² United Nations.

unimaginable⁷³. All while this terror was happening, the UN watched and did nothing. This tragedy is today regarded as a “stain on the reputation of UN Peacekeeping”⁷⁴. In Libya, luckily, we will never know what would have happened if no intervention had been made, and it should be an example of the impact that an intervention can make. Libya, although not perfect, showed that there is no tolerance towards human rights violations. As a global community, it is our responsibility to protect other people, as the consequences of ignorance are shown in Rwanda. When the international community fails to intervene, death and destruction occur. It is a much more admirable cause to fight for peace in an intervention than to let people die defending themselves. This contrast between Rwanda’s inaction and Libya’s intervention displays why, when assessed based on the principles of R2P and Just War Theory, action in Libya was morally justified and operationally necessary.

Legality

Many scholars argue that Resolution 1973 violated Article 2(7) UN Charter and made the intervention illegal. They argue there was no reason for intervention and the UN security council was only after a regime change not helping the Libyan people⁷⁵. The UN Charter is the foundational treaty that the United Nations is built off of, while resolutions are “formal expressions of the opinion or will have United Nations organs”⁷⁶. The 2(7) UN Charter says that “nothing contained in the present Charter shall authorize the United Nations to intervene in matters which are essentially within the domestic jurisdiction of any state”⁷⁷. In contrast, Resolution 1973, which was created by the United Nations Security Council, gave a legality to an intervention into Libya by “Author[izing] Member States...to protect civilians and civilian populated areas under threat of attack in Libyan Arab Jamahiriya.”⁷⁸ The UN Security Council has the authority to create this resolution, even though it overrules 2(7). Additionally, the scholar Feisal Al-Istrabad, agrees that the Libya intervention was legal since Resolution 1973 was created by the UN Security Council⁷⁹. Jean-Baptiste Jeangene Vilmer also agrees that the wording of “all necessary measures...to protect civilians” made the military intervention legal⁸⁰. Even though the 2(7) Charter was broken, ethical guidelines were still followed to ensure that the intervention was creating justice and saving lives.

Within a constantly changing world, international law is also ever evolving, so there is nothing wrong with resolution 1973 going against something previously written. A prior example of an evolving law is the Nuclear Non-Proliferation Treaty (NPT) was created in 1970 to prevent the spread of nuclear weapons⁸¹. Then, in 2008, the U.S.-India Civil Nuclear Agreement

⁷³ University of Minnesota.

⁷⁴ United Nations.

⁷⁵ Terry, 2015, 164.

⁷⁶ United Nations Security Council, 2011.

⁷⁷ United Nations.

⁷⁸ United Nations Security Council, 2011.

⁷⁹ Al-Istrabadi, 2014, 124-129.

⁸⁰ Vilmer, 2026, 28.

⁸¹ United Nations.

was created, where the US and India would trade nuclear weapons despite the US being a part of the NPT⁸². Even though there was a prior law forbidding the trade of nuclear weapons, the new law was completely legal. This is just one example that international law can change over time, and resolutions and treaties can be made that contradict prior agreements.

In his paper, CR Terry argues that the intervention was an operational failure because NATO did not establish a stable post-conflict environment and government. He argues that since NATO's actions did not lead to a stable post-intervention, it discredited the R2P doctrine. R2P prides itself on creating peace and stability in the world, so in his opinion, by not creating a stable post war government, R2P contradicted their mission⁸³. Within the goals for the intervention, there was never any mention of establishing a stable post-conflict environment, only getting rid of the current leader who was causing genocide across his country. In fact, not helping Libya post-intervention, NATO and the UN were not taking away Libya's sovereignty and choosing to pick a new government. Additionally, since the central government had been overthrown, there was no clear recognized authority in Libya that could approve a new leader to represent the country. As stated in Article 1(2) of the UN Charter, every country has the right to "self-determination" of its government⁸⁴. Implementing a government in Libya would be to take away that right and therefore violate Article 1(2).

Moreover, outside countries that have helped create new governments post-intervention have historically violated that country's covenant, such as the new government after the Iraq intervention. In 2003, after US forces took down Saddam Hussein's regime, it aimed to help the Iraqi people build a new, democratic government, but this failed in many ways. The US did this without Iraqi consent, limiting the autonomy of the Iraqi people within their own government⁸⁵. The number of internally displaced people (IDP) grew from zero in 2003 to 2.6 million in 2007 and the number of refugees was 2.3 million in 2007⁸⁶. President Obama eventually withdrew US forces from Iraq in 2011 because of the worsening relations with the government they put in place. Overall, building this government cost the US about 2 trillion dollars and the lives of 4,600 US soldiers and around 200,000 Iraqi citizens⁸⁷. The government building after the intervention only caused sovereignty to be taken from the Iraqi people, and resources to be taken out of the US. To this day, Iraq is still considered an unstable state and has an amount of IDP and refugees, displaying the lack of positive effect the government building had on Iraq⁸⁸. NATO does not have the responsibility to establish a post intervention because of Article 1(2) of the UN Charter and the historical example of Iraq shows the lack of success outer organizations and countries have at establishing governments.

⁸² U.S. Department of State

⁸³ Terry, 2015, 162.

⁸⁴ United Nations.

⁸⁵ Chambers.

⁸⁶ Duggal, 2023.

⁸⁷ Haass.

⁸⁸ Center for Preventive Action.

Long-Term Instability

Long term instability is often blamed on the NATO intervention and the rise of Islamic extremist groups, but these groups had been on the rise for years and the civil war was worsened by neighboring countries. Right after the NATO soldiers left Libya in 2012, the General National Congress (GNC) took control of the country. The GNC faced the spread of the Islamic State, leading to General Khalida Haftar's military campaign Operation Dignity, led by the Libyan National Army (LNA), which targeted these Islamic extremist groups⁸⁹. These groups retaliated, especially Ansar al-Sharia, which formed a counter-coalition known as Libya Dawn. This group gained control of Tripoli and much of western Libya, causing retaliation by the LNA and the Libyan Civil War (2014-2020)⁹⁰.

The intervention is blamed for the spread and violence caused by these groups, but this is not entirely accurate. Although they were suppressed under Gaddafi's rule, these extremist groups were not completely eradicated because, in the 1990s and 2000s, there was a notable spread of jihadist ideology through Eastern Libya, even under the Gaddafi regime. For example, in the 1990s Libyan Islamic Fighting Group (LIFG) was formed from veterans of the Afghan jihad, with a focus on overthrowing Gaddafi. Even though originally a minority of this group were aligned with al-Qaeda, this Libyan-based group officially merged with al-Qaeda in 2007, displaying the spread and popularity of these ideas⁹¹. The roots of Libya's long-term instability are to blame on the rise of Islamic Extremist groups, which had been expanding even during the Gaddafi regime, and not solely the intervention.

The conflict after the intervention was also worsened by neighboring countries, such as Egypt, Turkey, Qatar, and the United Arab Emirates (UAE), as the Libyan civil war became a proxy war for regional struggles. During this time, 900,000 people became in need of humanitarian aid, and 345,000 became IDP⁹². Egypt and the UAE backed General Khalifa Haftar as he rose to power, eager to stop the conflict and violence in Libya. In comparison, Turkey and Qatar supported the Government of National Accord (GNA), which aligned with their agendas⁹³. The support of these countries through weapons and resources prolonged the civil war and contributed to the violence and instability in Libya. Instead of helping Libya rebuild its government, neighboring countries purposefully made creating a government more difficult by fueling conflict for their own gain. Even though the NATO intervention caused a stable regime to fall, it did not contribute to the instability after, which was caused by already growing Islamic extremist groups and neighboring countries who wanted to use this war to their benefit.

Even though the instability can be blamed on other factors, Terry claims that since NATO and the UN did not create order post intervention, it discredits R2P and their doctrine. The purpose of R2P is to stop human rights violations and protect civilians, and if their actions are

⁸⁹ BBC, 2011.

⁹⁰ Center for Preventive Action.

⁹¹ United Nations.

⁹² Al Jazeera, 2020.

⁹³ Italian Institute for International Political Studies, 2022.

directly causing the opposite of that, they are invalidating their purpose⁹⁴. The intervention, although to protect the people, did end a mostly peaceful 40 years for the Libyan people, and R2P did nothing to help rebuild the country. Although this could seem like a violation of their doctrine, many times helping rebuild a country has limited the sovereignty for that country. Implementing a government is a direct violation of the UN Charter 1(2) that says every country has the right to self-determination⁹⁵. That said, this does not take all responsibility away from R2P, in order to make sure the outcome of the intervention is successful, there should be additions to the R2P doctrine. R2P and the UN should facilitate a peaceful transition of power within the country, without implementing a new government. This would allow for the success of the military intervention to have long term benefits for the country. By not having a section about the long-term stability of the country, it does not discredit R2P's mission, but should be added to strengthen the positive outcomes of military interventions.

NATO Bias

CR Terry also claims that NATO unfairly favored the rebels and did not protect the citizens who were fighting for Gaddafi, which would invalidate the intervention. He claims that NATO helped the rebel forces, which would violate the intended neutrality protection of resolution 1973. He believes that this bias was harmful to civilians and caused more deaths and violence throughout the intervention⁹⁶. Although it is true that the NATO helped anti-government forces, it does not change the legality or ethics of the intervention. NATO intervened with the intention of stopping Gaddafi and giving the country back to the people, so it is no surprise that they sided with citizens and rebel groups from Libya. Together, NATO and opposition forces were able to overthrow the capital and kill Gaddafi loyalists, a big step in taking back the country. NATO teaming up with Libyans shows that this intervention did not take away their sovereignty, but only solidified that this intervention was meant to liberate the people. Gaddafi was distinctly against the people, opening fire on protestors and saying that this uprising was caused by hallucinogenic drugs⁹⁷. NATO's favoring the rebels does not invalidate anything about the intervention; in fact, it shows the intentions to help the Libyan people and give them sovereignty over their country.

Relevance and Future Application

Although the Libya intervention happened over a decade ago, it still holds relevance today. It demonstrates that military interventions, even if not successful long term, can be operationally successful when measured against ethical criteria such as the Just War Theory. Libya and Rwanda display how R2P and the UN have a moral obligation to step in and aid a country using military force if necessary to protect civilians in a humanitarian crisis. Future military interventions should be decided based on the Just War Theory or other ethical criteria

⁹⁴ Responsibility to Protect.

⁹⁵ Terry, 2015, 162.

⁹⁶ Berti, 2013, 21.

⁹⁷ University of Minnesota.

because of its fair and accurate assessment. This said, NATO and the UN should take more initiative to prevent long term instability, not through creating a new government, but by halting the involvement of neighboring countries, stopping terrorist groups, and letting a country led by the people flourish. This should be overseen by the UN and not led by one specific country so that there are not ulterior motives during the rebuild of a country. The UN should not be able to choose a government for the country, but they should be able to enforce no corruption or meddling in that country. The Libyan intervention remains an example of what taking a stand looks like, as well as a cautionary tale about how to approach future conflicts in a way that minimizes controversy. Ultimately, Libya shows us that military interventions can be necessary and justified when decided upon from an ethical framework, but the UN has an additional responsibility to facilitate a peaceful and freedom filled political transition.

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Construction of a Transgenic Mouse for Astrocyte-Specific tdTomato Red Fluorescent Protein Expression By Vivika Kapoor, Adrienne Wai, Mary Ramirez, Levi Bar-Cohen, & Dr. Michael Jakowec

Abstract

The objective of this study was to create a double transgenic mouse line that enables astrocyte-specific expression of the red fluorescent protein tdTomato by crossing Aldh1l1-CreERT2 mice with tdTomato-flox reporter mice. Parkinson's Disease (PD) is characterized by the loss of dopaminergic neurons and synaptic connections, leading to motor and cognitive impairments. Astrocytes are crucial in maintaining synaptic integrity through lactate production, which supports neurons and activates pathways that increase brain-derived neurotrophic factor (BDNF). BDNF promotes synaptic plasticity and motor function recovery. However, current approaches to visualize and manipulate astrocytes in vivo are limited.

Using PCR-based genotyping and gel electrophoresis, the presence of both transgenes was detected in a subset of offspring. The double transgenic mice allowed for astrocyte-specific fluorescent labeling, facilitating the precise study of astrocytes in PD models. This model will support future studies into how exercise-induced lactate production regulates astrocyte-driven BDNF expression, potentially leading to the discovery of new treatments that target astrocytes and lactate pathways to slow down PD and help the brain repair itself.

Introduction

Parkinson's Disease (PD) is a progressive neurodegenerative disorder characterized by the degeneration of dopaminergic neurons and the breakdown of synaptic connections, which leads to impairments in both motor and cognitive functions. While neurons have been the main focus of research, increasing evidence suggests that astrocytes, supportive glial cells found throughout the brain, play a vital role in maintaining neuronal survival and synaptic plasticity.

Astrocytes produce lactate, a metabolic byproduct of glucose, that serves as a neuronal energy source while also activating signaling pathways that elevate BDNF expression. BDNF promotes neuronal growth, synaptic repair, and motor recovery. In the context of PD, where neuronal death disrupts critical brain circuits, this astrocyte-lactate-BDNF pathway becomes essential for potential recovery (see Figure 1).

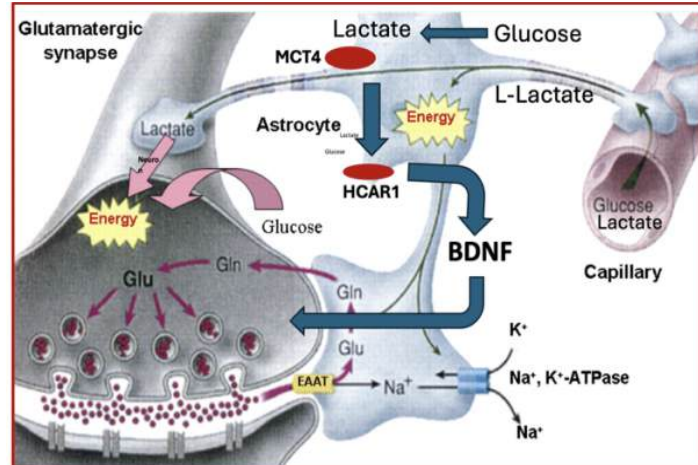


Figure 1: Central model of astrocyte-BDNF expression: L-lactate is transported through astrocytes from blood vessels, is released through MCT4, and interacts with HCAR1 signaling to elevate the expression of BDNF to maintain synapse integrity or promote synaptic plasticity.

Despite their significance, methods to selectively visualize and manipulate astrocytes *in vivo* remain scarce. To overcome this challenge, a double transgenic mouse line was utilized, in which astrocytes specifically express tdTomato, a red fluorescent protein. This genetic model allows for selective visualization of astrocytes, providing a platform to study their role in PD and their contribution to brain repair.

Methods

To generate astrocyte-specific tdTomato expression, two genetically engineered mouse lines were crossed. The first line, Aldh1l1-CreERT2 mice, expressed Cre recombinase selectively in astrocytes. The second line, tdTomato-flox mice, carried a tdTomato gene activated by Cre recombination. Upon tamoxifen induction, tdTomato was expressed exclusively in astrocytes, enabling them to be visualized under fluorescence microscopy (See Figure 2)

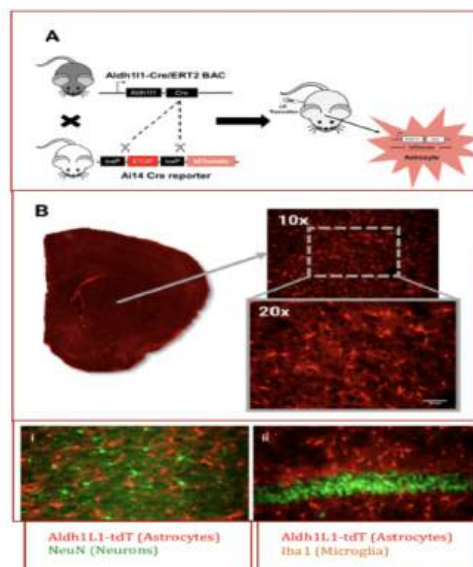


Figure 2: Construction and validation of ACT mouse expressing tdTomato red fluorescence exclusively in astrocytes.

Genotyping was performed to confirm the presence of both transgenes. Genomic DNA was extracted from ear and tail tissue samples using a lysis buffer and proteinase K digestion, followed by DNA resuspension. PCR reactions were carried out using primer sets specific for Cre recombinase, tdTomato, and beta-actin as a control. Negative DNA controls and mastermix-only controls were included to ensure accuracy. Each PCR product was resolved on a 2% agarose gel alongside a DNA ladder. A standard curve was used to estimate the band sizes according to the equation $Distance = -41.7 \times \log(bp) + 157$ (See Figure 3).

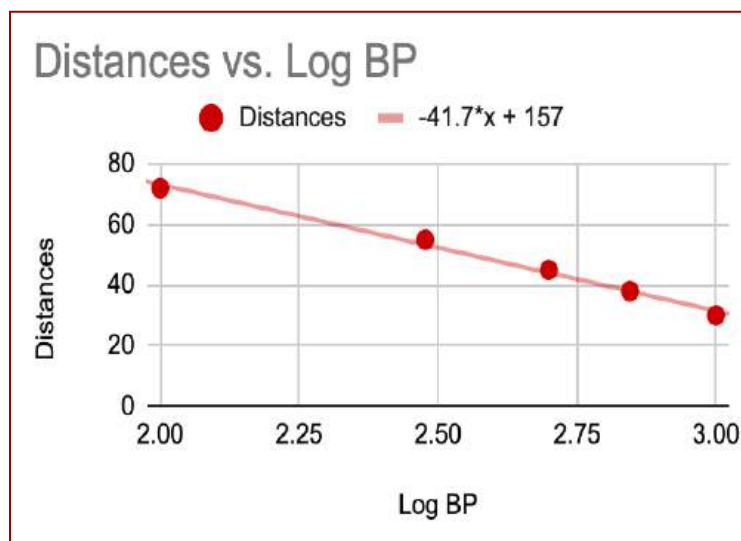


Figure 3: Standard curve plotting band distance versus log(bp).

The expected band sizes were ~200 bp for tdTomato, ~198 bp for Cre, and ~1000 bp for beta-actin. The PCR products were visualized under UV light, and the resulting bands were compared to a DNA ladder to determine the presence of the transgene.

Results

PCR genotyping confirmed the presence of the desired transgenes in the offspring. Mouse 1 displayed both a ~200 bp band corresponding to tdTomato and a ~198 bp band for Cre recombinase, confirming its genotype as double transgenic (Cre⁺/TDT⁺). Mouse 3 displayed only the ~200 bp tdTomato band, classifying it as single transgenic (TDT⁺ only). Negative controls showed no amplification, validating clean PCR conditions, while beta-actin (~1000 bp) was consistently present across samples, confirming DNA integrity and PCR success. These findings validated the generation of an astrocyte-specific tdTomato transgenic model (see Figure 4).

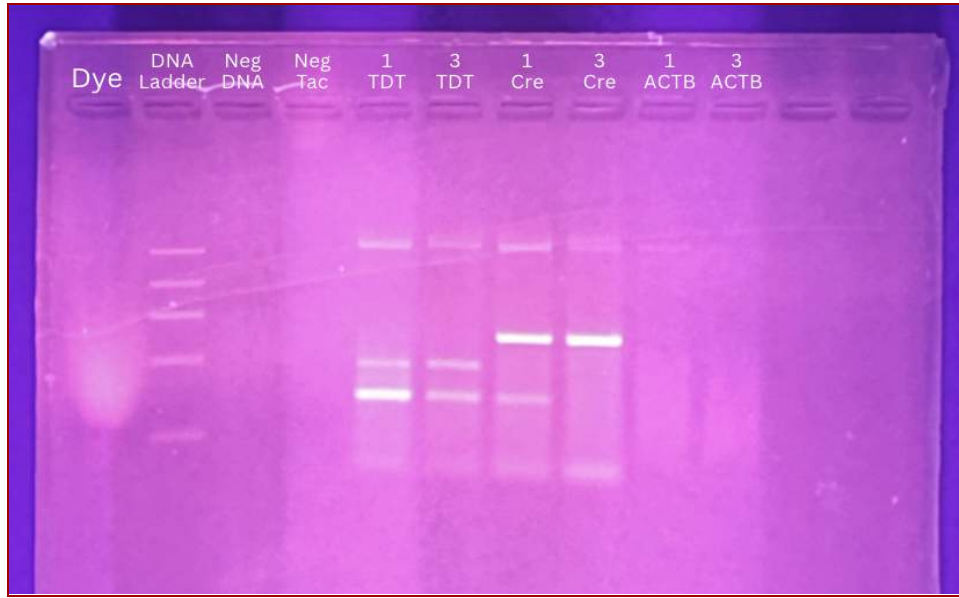


Figure 4: PCR gel electrophoresis confirming double transgenic genotype.

Fluorescence microscopy provided further confirmation of astrocyte-specific tdTomato expression. Red fluorescent labeling was observed exclusively in astrocytes, which were clearly distinguishable from neighboring neurons and microglia (see Figure 2). This demonstrated the successful restriction of tdTomato expression to astrocytes and confirmed the functional utility of the genetic cross.

Discussion

The successful generation of an astrocyte-specific tdTomato mouse line provides a robust model for investigating astrocytic contributions to neurodegenerative disease. By allowing selective visualization of astrocytes *in vivo*, this model provides new opportunities to study their role in maintaining synaptic function, particularly through the astrocyte-lactate-BDNF signaling pathway. Given that BDNF is essential for synaptic repair and motor function recovery, this tool is well-suited to advance understanding of astrocytic mechanisms in PD.

Moreover, this model allows for the exploration of how lifestyle interventions, such as exercise, impact astrocytic activity. This model has important implications for developing therapeutic strategies targeting astrocytes to slow disease progression and promote brain repair.

Future Directions

To further examine astrocytic involvement in PD, two treadmill-based exercise protocols will be applied. The first is an acute protocol involving a single 60-minute treadmill session with progressive speed increases every 5 minutes. The second is a chronic protocol, consisting of 10 consecutive days of treadmill exercise, also with progressively increasing intensity. Following these interventions, lactate concentration and BDNF expression in astrocytes will be measured using this model.

By comparing acute and chronic conditions, this approach will clarify how varying durations and intensities of exercise affect the astrocyte-lactate-BDNF pathway. Ultimately, these studies may guide the development of therapies to mitigate PD symptoms and promote neuronal recovery.

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Affiliations

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Art Without an Artist: Why AI's Lack of Intrinsic Humanity Makes it Incapable of Creating Authentic Art By Ariel Ting

Since the 1960s, computers have played a role in art-making, but today's digital landscape has transformed this interaction entirely—images can now be created solely through artificial means (Paul). Over 2,000 AI image-generation programs are currently in use, collectively serving millions of users (Shalwa, 2024). These programs work by analyzing massive datasets of existing human artworks, learning their brushstrokes, compositions, and color palettes, and eventually producing images that are, in essence, collages of this source material (Clarke, 2022). As such, AI-generated images can be characterized as derivative syntheses of pre-existing human creativity. When an AI-generated image won an art contest in 2022, it sparked public outcry and a wave of anxiety over the encroachment of artificial intelligence into creative domains once thought to be exclusively human (Roose). Why, then, are so many people now generating images using AI? In *Wired*, author Kevin Kelly offers a simple explanation: “the same reason that humans have always made most art: because the images are pretty and we want to look at them” (Kelly, 2022).

Yet this rationalization reduces art to superficial visual pleasure, overlooking what I believe to be its true purpose—a uniquely human form of emotional and intellectual expression. To understand why AI-generated images don't meet the criteria necessary to be classified as true art, we must consider the role of the artist. Through that lens, it becomes clear that while AI may produce visual artifacts, it lacks intention, consciousness, and emotional depth—qualities essential to authentic artistic creation.

Art, at its core, is a form of personal and cultural communication. The most moving works do more than please the eye—they invite introspection, challenge perceptions, and stir the soul. Vessel, Starr, and Rubin found that profound aesthetic experiences activate frontal and subcortical brain regions associated with “inward contemplation” and self-reflection (2012). Konecni postulates that such art encourages viewers to assess their place in society and their responsibilities to others, demonstrating its tangible influence on social awareness (2007). Historically marginalized groups, such as Black Americans during the Harlem Renaissance, used art as a vehicle for visibility, resistance, and cultural affirmation. Artistic expression often emerges from personal and societal struggle, giving it distinctive depth, authenticity, and even urgency. It is not merely decoration—it is declaration—which is often powerful enough to inspire change. For instance, Francisco Goya's trailblazing depiction of the atrocities inflicted on ordinary people during war in his painting *The Third of May 1808*, shifted the public's romanticized notions of war and promoted anti-war sentiment.

AI, by contrast, cannot engage in this kind of reflective creation. It does not observe the world, form opinions, or process emotion. It cannot suffer or celebrate; it can only simulate. As a tool without sentience, AI lacks the self-awareness necessary to interpret or respond to the human condition. Hume, in his *Treatise*, argued that art is a representation of human activity and therefore its creators and observers must possess human sentiment, morality, and cultural context

(Stanford, 2020). The act of making and experiencing art is a social-epistemic process—one that AI, which merely mimics human behavior without true comprehension or intent, cannot authentically participate in (Kaliouby, 2020).

Evgeny Morozov characterizes AI as fundamentally “pattern-matching” machinery, a legacy of its military origins (2023). This distinction between mechanical knowledge and human understanding is critical; while AI can synthesize data, it cannot form opinions or create meaning. Drawing on Ignacio Blanco’s theory of bi-logic, Morozov contends that AI lacks a sense of the “past, the present, and the future; of history, injury, or nostalgia,” —and thus lacks the capacity for judgment or imagination (2023). Without these qualities, AI cannot create art that speaks to the full range of human experience.

Art is not created in isolation; it is a social practice, rooted in shared norms, cultural values, and individual voice. Sherman describes art as a “human cooperative activity,” one that reflects and shapes communal meaning (2017). This is why original artworks are so highly valued. They are seen as not merely aesthetic objects, but as “physical extensions of their creators.....imbued with the person’s soul/essence.” In contrast, AI lacks a personal style, a distinct voice, or perspective derived from lived experience. Clarke notes that AI programs merely “[lays] down pixels...that resemble the dataset closely enough” (2022). The result is image without essence and expression without an expressor.

The emotional impact of an artwork directly affects its perceived value. Some argue that AI-generated images can be appreciated for their ornamental value or that AI can serve as a neutral tool in the hands of a human artist. Yet, under further scrutiny, both claims fall apart. We instinctively equate artistic merit with emotional labor and moral intention—qualities that AI does not possess. Messer argues that though a human artist may have a clear artistic vision, even partial use of AI in executing it, diminishes perceived creative control and introduces a “perception of inauthenticity” (2024). Employing the effort heuristic theory, he shows that artworks involving AI are often seen as requiring less effort, passion, and inspiration, and consequently, are deemed less authentic and worthy of esteem (Messer, 2024). Similarly, Chamberlain et al. explain that visual isotropy—a signifier of meticulous human workmanship—adds to an artwork’s “temporal or monetary value” (2018). With its absence of human effort and authorship, AI art simply cannot claim comparable status.

Audience perception further reinforces this distinction. Bellaiche demonstrates that attaching artworks with a “human label” triggers stronger emotional engagement and suggests the presence of narrative depth (2023). Participants in his study consistently viewed human artists as capable of creating works imbued with cognitive and emotional complexity and AI as limited to producing only “surface-level reflections of creative thinking” (Bellaiche, 2023). Granulo corroborates this perspective contending that people overwhelmingly prefer human authorship in symbolic contexts like that of art, where a sense of empathy, intention, individuality, and shared experience, is paramount (2021).

Ultimately, because AI is incapable of functioning without human input, its output should be recognized for what it is: the byproduct of collective human labor, or, in many cases,

unacknowledged appropriation and potential copyright infringement. Epstein et al. use the case of Edmond de Belamy—a \$432,500 AI-generated work created by a web of human coders and artists—to demonstrate that authorship remains inseparable from human agency (2020). McCormack argues that software developers and users who guided the output are the true creators, since AI systems are not generally accepted as authors in either artistic or public domains (2019). Hertzmann further supports this notion using computer animation as an example. He points out that despite advances in animation technology, its value derives from the incredible amount of painstaking human labor and skill it still requires, which makes them the true authors (2018, p. 18).

This human dependence is further highlighted in recent legal cases. In August 2024, a federal court in California ruled that AI companies like MidJourney and DeviantArt violated copyright by training their models using artists' works without their consent. These programs, far from being autonomous creators, are better understood as engines of digital plagiarism—replicating and repackaging existing human creative expression and ideas at the whim of other humans.

To be fair, human artists have always created artwork that is derivative. This type of appropriation, however, is arguably an inevitable and vital process of artistic evolution wherein creators reinterpret, challenge, and build upon existing works to reflect shifting cultural values, aesthetic sensibilities, and philosophical ideas. AI-generated art, by contrast, relies on algorithmic synthesis of existing works without intentionality, context, and the ability to offer deliberate commentary, homage, or criticism.

In the end, art is the product of consciousness and emotion—of memory, desire, grief, joy, and struggle—in other words, of the human experience. It is the story of being human, whether rendered in image, sound, movement, or word. As such, I posit that only those with conscious selfhood can claim authorship of it. AI cannot cry, laugh, sulk, dream, love—or, for that matter—make art.

And yet, perhaps AI's increasing popularity offers us a hidden gift: a challenge to human artists. If machines can mimic our creative expression, then, as a result, artists may be forced to reach even deeper—for more honesty, more emotion, more soul—and create art that is more human than ever before.

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Pose Estimation and Machine Learning for Sprinter Form Comparisons By Bryan Zhao

Abstract

Our study aims to discover what factors play the most important role in developing faster sprinters. Using data from high schoolers and professional athletes, differences were compared in each athlete's top speed position at their MVP stance, which is the maximal height of vertical projection as defined by the ALTIS Kinogram Method. With TensorFlow's MoveNet Thunder pose estimation model, each athlete's leg and arm limb angles were investigated. Alongside these angle key points, the ground-to-air ratios (number of frames with foot on the ground divided by number of frames with foot in the air) of each athlete at their top speed were measured. Comparing the angles, it was discovered that professional athletes tend to have a more constricted range of movement at their maximal height projection. In comparison, school athletes tended to swing wider in the same position. With speed data of the high school athletes, it was also found that a shorter ground-to-air ratio also meant a typically faster time. Paired with this data, models also determined that the front hip and elbows determine athletes' speed. However, while these findings may serve as benchmarks for success, performance will vary among athletes, so individualized training will most benefit a sprinter.

Introduction

Sprinting performance is governed by a complex interplay of biomechanical factors, including limb kinematics, ground contact dynamics, and force application. Previous research has identified critical components of sprinting mechanics that contribute to overall performance. An overview of sprinting emphasizes force and power during acceleration and consistent technique during constant speed (Mero et al., 1992). A 1985 study on a 200-meter dash provided insight on the fundamentals of biomechanical skill, stating in their study that “the critical body kinematics variables related to success included upper leg angle at takeoff (indirect), upper leg velocity during support (direct), lower leg velocity at touchdown (direct), foot to body touchdown distance (indirect), and relative foot velocity at touchdown” (Mann & Herman, 1985, para. 1). Another study conducted research on twenty-eight male athletes, collecting video and ground reaction data to study the reliability of different sprinting variables in assessing runners. Their study found that “the reliability of a single score differed widely among variables. Variables describing horizontal velocity were the most reliable, whereas variables based on [the body’s center of mass (COM)] vertical displacement or braking [ground reaction force (GRF)] were the least reliable” (Hunter et al., 2004, p. 8-9). A paper investigated step frequency and contact time, concluding “both the greater top speeds of faster vs. slower level runners and those attained during declined vs. inclined running were achieved by the application of greater support forces to the ground while the legs were repositioned in nearly the same minimum time” (Weyand et al., 2000, p. 6). Another study investigated sprinters during 40-meter sprints, determining that the effectiveness and ability to produce horizontal forces decrease linearly as sprinters accelerate (Rabita et al., 2015). However, prior studies have emphasized the importance

of body positions (Kugler & Janshen, 2010) and leg angles (Milanese et al., 2014) during acceleration, but fewer have investigated these variables at maximal velocity and rather focus on force application, where elite sprinters exhibit distinct mechanical adaptations. An example study investigated lower leg joint angles at max velocity, highlighting that the knee-ankle joint is a highly consistent and crucial factor in top speed (Gittoes & Wilson, 2010).

One can adapt their techniques to achieve greatness or follow in the footsteps of greats before them. In sprinting, the prototypical runners that have consistently won track accolades and broken world records are Usain Bolt, Yohan Blake, Asafa Powell, Tyson Gay, and many more ("100 Metres – men", 2025). This study aims to explore what biomechanical attributes these athletes share. Though several studies have unearthed the mechanical attributes that yield optimal sprinting efficiency, the interplay between limb angles, ground-to-air ratios, and sprinting speeds remains understudied, particularly across skill levels.

To bridge this gap, this study leverages pose estimation—a validated tool for biomechanical analysis (Cheng et al., 2025)—to compare sprint mechanics between high school and elite athletes. Previous studies have analyzed the effects of different knee angles in the starting position of sprinting, identifying differences between fast and slow acceleration (Milanese et al., 2014). By analyzing joint angles (e.g., hip, knee) and ground-to-air contact ratios at the maximal vertical projection (MVP) phase (McMillan, 2018), we identify biomechanical trends distinguishing fast and slow sprinters at top speed. This work builds on foundational sprint mechanics research while providing actionable insights for training. By quantifying elite athletes' techniques, we offer a framework for coaches to refine sprint mechanics in developing runners.

Methods

Data collection and analysis took a straightforward approach: collecting data from videos, splicing and editing the videos into images manually, running the images through code, and analyzing the results. The most crucial part of understanding the biomechanics of a sprinter through image analysis was finding footage to supplement data analysis. This footage ranged from videos on the internet to training data from my high school's track and field team's workouts. These videos were then downloaded and uploaded into a video-to-image converter, with each frame numbered, which was a minor but crucial detail for later analysis. Each frame was then analyzed to check whether the athlete's position matched those in the ALTIS Kinogram method, specifically the MVP, which is "the maximal height of vertical projection, as defined by the position where both feet are parallel to the ground" (McMillan, 2018, Our Protocol). These images were then cropped and painted over manually using digital software for the pose estimation model to analyze body positions better. TensorFlow's MoveNet Thunder ("MoveNet", n.d.) pose estimation model was used to analyze images as it is a relatively quick, accurate, and easy-to-set-up model, and previous work has identified it as a reliable model (Vadlamuru, 2024). With TensorFlow, multiple body angles deemed essential in sprinting were captured, including the pull of the back leg, the knee-rise at max velocity, and the forward-lean overall. Along with

capturing body angles, it was determined that a crucial part of sprinting is ground contact time, as the time spent between the ground and air plays a significant role in how power is effectively applied during running in general (Hayes & Caplan, 2012). For example, a jogger spends much of their time running with their feet on the ground as they are not focused on applying excessive power to the floor, and a person walking spends the entire time with at least one foot on the ground. Conversely, in sprinting, athletes are encouraged to apply vertical force into the ground, propelling themselves forward and upwards. A more extreme example would even be jumping, as one would hope that most of the time spent by an athlete participating in the long jump would be in the air. This study aimed to locate trends in faster sprinters by using ground-to-air contact time ratios and the body angles captured during the ALTIS Kinogram phases. The process of data collection and table of analyzed joints (Table 1) are listed below.

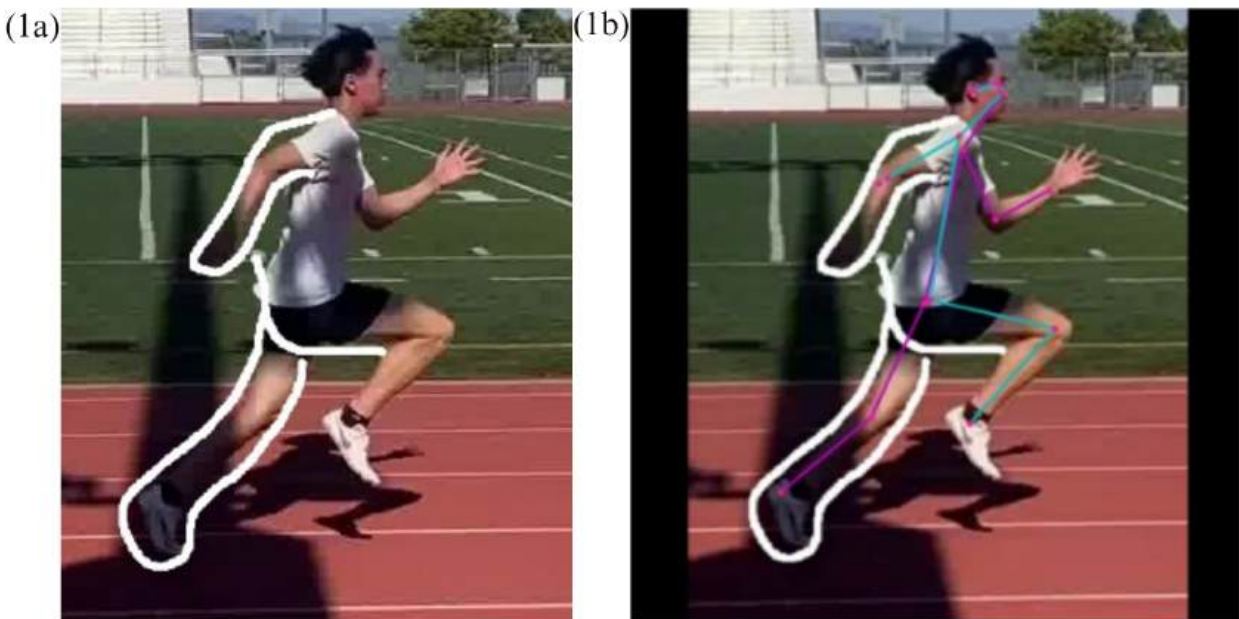


Fig 1: Annotated figures of steps 3 (1a) and 4 (1b) of the data collection process.

1. Video footage was collected and spliced into individual frames.
2. Frames were sorted and selected individually for analysis while recording frame counts.
3. Frames were cropped and obstructions were removed to improve joint identification (Fig 1).
4. The model analyzed each image to capture body angles and calculate ground-to-air ratios (Fig 1).
5. Data were entered and organized in a spreadsheet for analysis.

Table 1 Metrics at MVP analyzed with TensorFlow MoveNet

Metric	Knee	Hip	Shoulder	Elbow
Description	Knee angle measured from hip to knee to heel	Hip angle measured from shoulder to hip to knee	Shoulder angle measured from elbow to shoulder to hip	Elbow angle measured from wrist to elbow to shoulder

After data was collected and organized, amateur and professional athlete graphs were constructed using Python.

Results

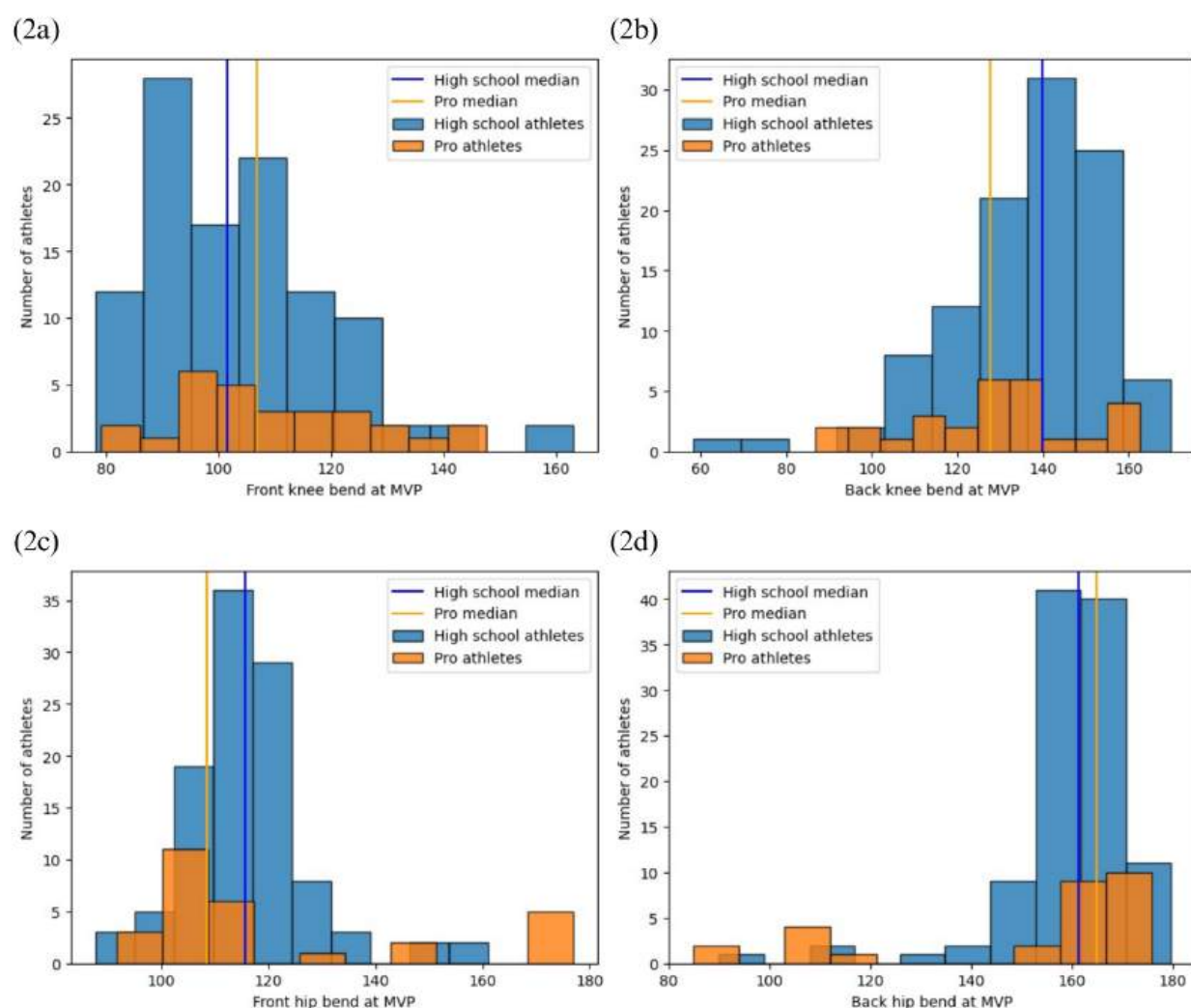


Fig 2: Histograms displaying the distribution of front and back hip and knee bends at MVP position. Data compiled from various online video analyses. (2a) Front knee bend (2b) Back knee bend (2c) Front hip bend (2d) Back hip bend.

When comparing the angles of the front knee bend (Fig 2a) at the top sprinting position between the professional athletes (orange) and amateur athletes (blue), it was discovered that amateur athletes would exhibit a wider variety of angles compared to the professional athletes. While professional athletes still showed a wide range of angles, the identified range was slightly shorter and converged near 100 degrees, even with a low sample size. On the other hand, the angles of the amateur athletes centered around 90 degrees and 110 degrees, showing inconsistency in the athletes. Some notable outliers exist in all graphs due to a discrepancy in TensorFlow's MoveNet model, which sometimes may mix up the left and right sides of the body due to an unclear image. Ignoring the values to the right, which are determined to be discrepancies with the model's code, there is an even clearer difference in terms of the front hip bend (Fig 2c) between high school level and professional athletes, with pro athletes exhibiting a much lower bend in general, which can likely be explained with the fact that professional athletes will tend to be able to lift their leg higher at their top position, exhibiting a lower hip angle. Even when observing the angles of the back knees and hips (Fig 2b and Fig 2d) (ignoring the discrepancies), professional athletes, at the very least, tend to have a lower average back knee and a higher average back hip angle.

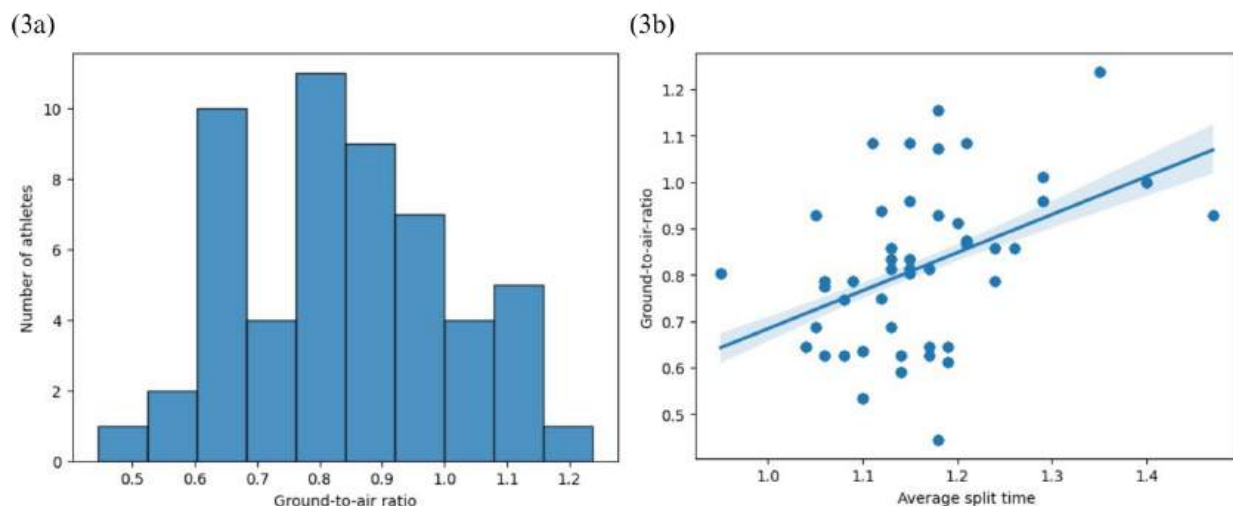


Fig 3: (3a) Histogram of distribution of ground-to-air ratios of high school sprinters accompanied with (3b) linear regression plot of average split times to ground-to-air ratios of high schoolers.

Observing the ground-to-air ratios of high school athletes (Fig 3), a wide range of values exists, ranging from 0.5 to 1.2 but ultimately centering around 0.8, which is the typical ratio for a high school sprinter. When comparing the split times of a 10-meter fly during the workout in which the ground-to-air ratio samples were also taken for each recorded athlete (Fig 3b), there is a positive linear correlation between ground-to-air ratios and split times. The lower the split time, the generally lower the ground-to-air ratio, and this logic would follow sprint mechanics scientifically as it has been proven that less time spent on the ground equates to faster speed in general through various studies—a study in 2021 observing the “swing-pull” technique of sprinting acknowledges that shorter ground contact times led to longer stride-lengths, which in

turn led to higher speeds (Mattes et al., 2021), and another study on optimal training for greater sprinting fitness observed that improving leg stiffness, faster times reacting off the ground, will be beneficial to a sprinter (Haugen et al., 2019). There will be discrepancies as power and form play a prominent role in determining speed, but generally quicker people with better form are more likely to spend less time on the ground as a study on ground reaction forces correlates faster sprinters to step frequency based on getting off the ground faster and a more optimal way to apply ground forces (Morin et al., 2012).

Modeling was the last and most crucial step in determining what defines a good sprinter. For the test-train split, a 25:75 ratio better fits our needs for an evaluation model. The sample size of our data is relatively small, containing about 50 key points, and the 25:75 split is a standard and flexible ratio to test with. The dependent variable was the average split time for each athlete, and the independent variables were all the angles associated with each split time that was unique to each athlete.

Regarding running models, three models were chosen, each with relatively similar accuracies. The first model was multiple linear regression, which compared all the key points in a low-dimensional analysis. It was most straightforward to understand and compare, and it seemed most logical given the assumption that there were likely direct relationships between faster times and specific angles that needed to be exhibited—such as a higher knee lift—when sprinting. The second model was the random forest regressor, a learning method that builds multiple decision trees and combines their outputs. To account for the still possible non-linearity of data between split times and angles, the random forest regressor was used as it is resistant to overfitting and effective against high dimensionality (Biau, 2012), which is also a problem that could have been encountered: there are many angles to reference from, the front hip, the front shoulder, the front knee, etc. The random forest model would be much better at narrowing down helpful factors in determining sprinting. The last model was an XGBoost regressor, which uses gradient-boosting to predict highly non-linear relationships. This was most effective for our dataset as our data contained many features and points that had to be compared. Overall, it is a great model in terms of flexibility and accuracy. However, when comparing all the mean absolute and mean squared errors (Table 2), the XGBoost regressor surprisingly did the worst, albeit only slightly. All three models fell within roughly the identical scores, each having an absolute error of approximately 0.055 and a squared error of 0.0045, with the XGBoost regressor model being an exception with a squared error of around 0.0057.

Table 2 Error comparisons of multiple linear, random forest, and XGBoost regression models

Model	MAE	MSE
Multiple Linear Regression	0.05765267356793944	0.004356423303205583
Random Forest Regression	0.054649999999999994	0.00448632333333333466
XGBoost Regression	0.055812061627705876	0.0057454938633964905

Discussion

Observing the histograms from the exploratory data analysis (Fig 1), professional athletes, from the front of the body during MVP positioning, tend to do a much better job at pushing vertical forces down through the knee with a 90° angle, and they also can keep the leg high with a lower hip angle. Regarding backside mechanics, professional athletes do a much better job at positioning themselves to cycle the leg, keeping a low knee bend and higher hip bend to bring the leg forward quicker. Using the median angles of both high school and professional athletes as a reference, when visualized, professional athletes tend to maintain a tighter, constricted form at maximal height projection, which is an emphasized quality of good sprinters. A study comparing the effectiveness of training stride length versus stride frequency identified that stride frequency plays a crucial role in developing faster sprinters. However, it should be noted that stride length plays an equal if not more important role in creating the balance for optimal sprint training (Sobarna et al., 2023). Maintaining tighter angles means that faster turnover occurs, increasing the stride frequency and consequently increasing the speed of an athlete.

Using the scatterplot of the ground-to-air ratios versus average split times (Fig 2), we observe a trend that is emphasized by sprinting coaches and researchers. As mentioned, lower time spent on the ground—a lower ground-to-air ratio—means that times will also be lower. This occurs because the faster a sprinter can apply vertical force into the ground, the faster they will be able to run.

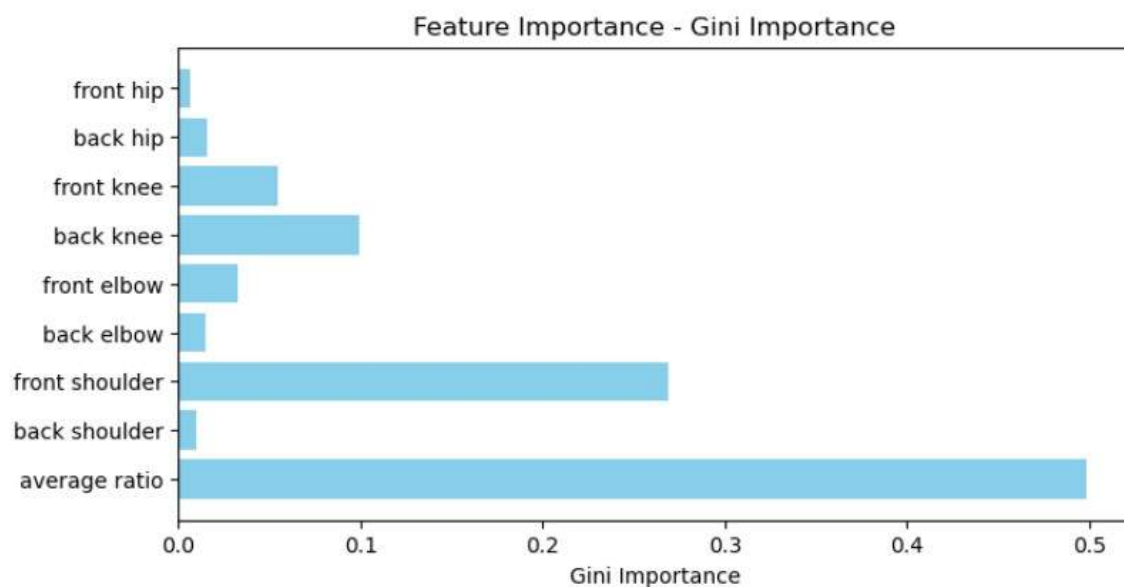


Fig 4: Feature importance lists of angle and ratio metrics versus average split times for Random Forest model

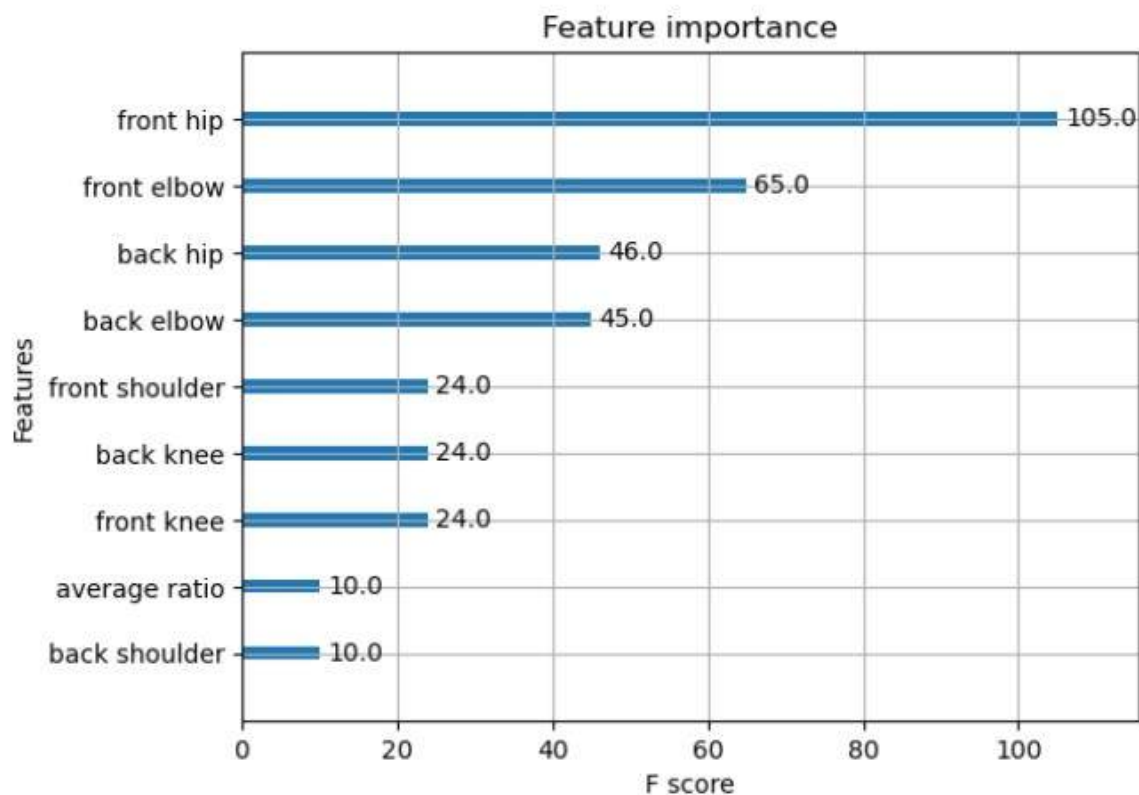


Fig 5: Feature importance lists of angle and ratio metrics versus average split times for XGBoost model

The feature importance lists between the random forest regressor (Fig 4) and the XGBoost regressor (Fig 5) differed significantly in the emphasis on what aspects of sprinting they used. While the random forest model favored the average ground-to-air ratio and front shoulder metrics the most, the XGBoost regressor preferred using the front hip and front elbow as its top metrics. The algorithmic difference between each model accounts for their differences in higher-scoring metrics. The random forest model favors the broader metric, the average ratio, likely because it has a more linear relationship with the average split times of runners. Referencing the previous linear regression plot of the average ratios and divided times, a linear correlation can be seen, and this is likely also what the model recognized. The XGBoost model determines that the front hips and elbows are more critical in deciding sprinting speed. The emphasis on these front angles can also be because the front hip angles generally are more constricted to about a 90° angle when sprinting. Most sprinters will bend their hips around this range, and this explanation can also account for how the front elbow functions, as its angles and movements reflect the leg movements and are also somewhat constricted. The knee angles, however, did not score very highly in either model. A likely cause of this is that knee extension when sprinting can vary from athlete to athlete. Unlike the hips, there can be a more extensive

range of extension, such as over-striding or not bending the knee enough, which can lead to various angles.

We ultimately concluded that many factors play into an athlete's success in sprinting. Still, most importantly, the factors most emphasized in coaching, the hips, remain the most important in making an athlete faster. Certain angles, like a 110° bend at the front hip, are also more typically exhibited, serving as a benchmark for athletes to display. A previous study investigating the strength and bend angle at hip flexion and extension strongly positively correlated hip flexor strength and speed (Watanabe et al., 2000). However, working solely on the hips will not make an athlete faster. Every joint plays a crucial role in developing vertical force, ground-to-air times, and overall speed. A study investigating the exertion of joints while sprinting showed that "the whole leg should be considered as one functional unit in which one or more of the joints may dominate generation of propulsive joint work" (Simonsen et al., 2023, p. 8). Many surprising results came from this project, and there could have been more accurate predictions given more data points and evidence, especially professional split times and videos. These 50 points serve as a simple baseline, emphasizing the importance of certain features of sprinting but also emphasizing that there will always be variance among athletes. While it may be helpful, it is unnecessary to constantly focus on hitting the most common angles or reaching the fastest ground-to-air times. This project aimed to show what was most exhibited and emphasized to help the fastest be the fastest, but these tendencies will not be displayed in everybody. Coaches will always emphasize on race day to get out there and go as fast as possible. The fastest, truest sprinters will step up to their race, take a deep breath, and run.

This study contained a small dataset, which, with more points, could provide more accurate results. More concrete results can be produced by either searching the internet for clear racing footage or recording data of athletes by oneself. In terms of video footage, slow-motion recordings would be more useful in both determining the MVP position as described and calculating more accurate ground-to-air time ratios. Most of the data collection process was manual, and automating the process of splicing footage and identifying the MVP position would greatly improve the convenience in continuing this study. By addressing these limitations, future research can provide deeper insights into sprint mechanics and pave the way for more effective training methodologies.

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