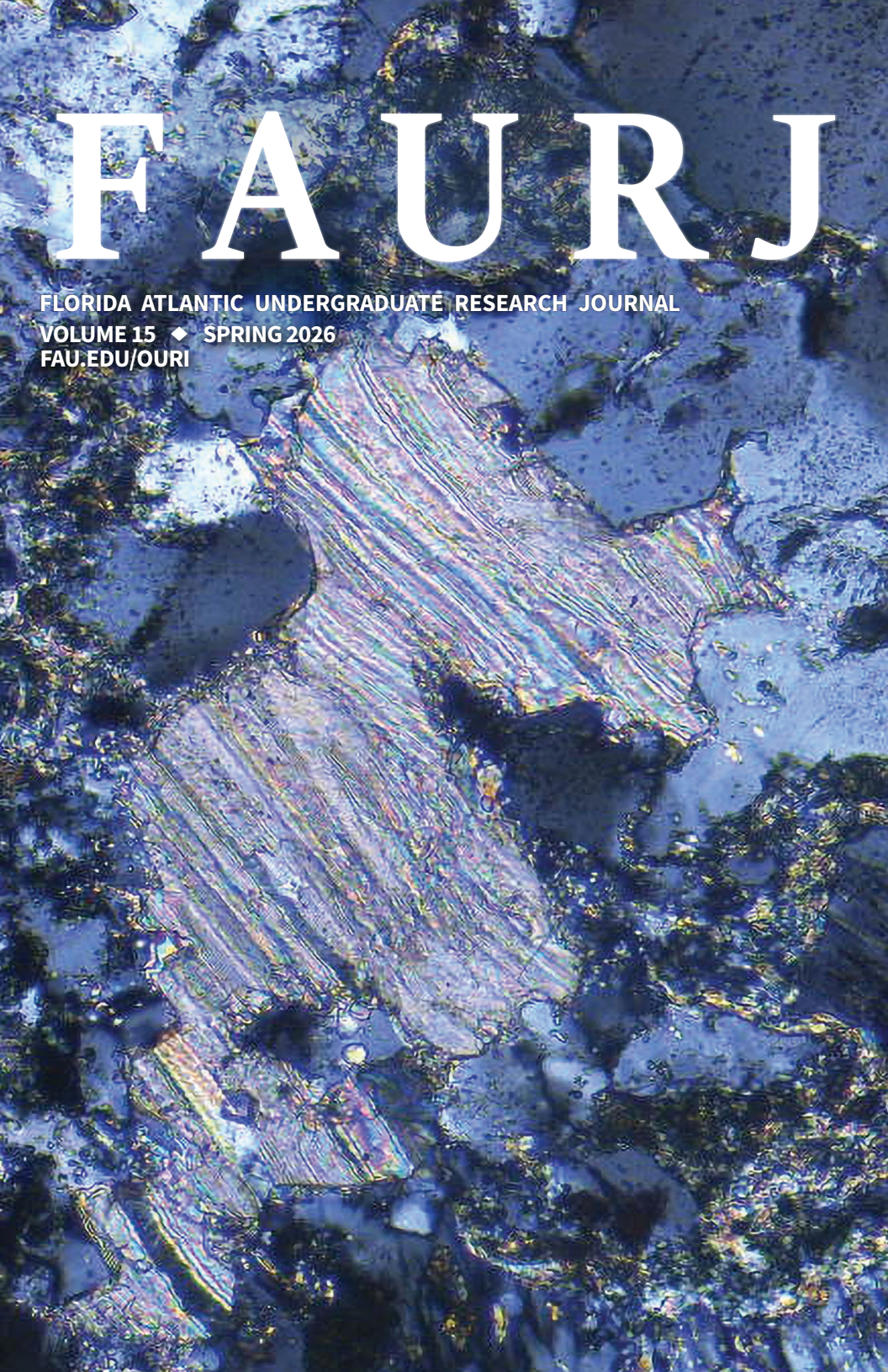

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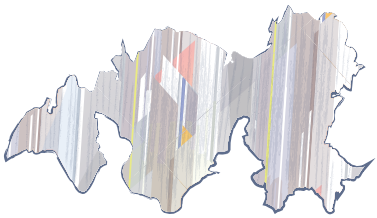

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The *Florida Atlantic Undergraduate Research Journal* is published online and in print by OURI and stored digitally through FAU's Digital Library. Its missions are to showcase high-quality undergraduate research in all fields, supply students with an idea of the standard of research and promote inquiry-based activities at FAU. For submission guidelines please visit the *FAURJ* website.

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*Faculty Advisor

Letter from the Editor

It is with my utmost pleasure that I present the fifteenth edition of the Florida Atlantic Undergraduate Research Journal. This year's edition showcases a wide array of compelling topics produced by Florida Atlantic's talented undergraduate researchers and their dedicated mentors. Within these pages, readers will find work spanning disciplines from history and languages to behavior and artificial intelligence. We hope that each reader discovers something that inspires curiosity and excitement.

I would like to extend my sincere gratitude to the students who submitted manuscripts for this edition and worked diligently to produce the finalized research presented here. Their commitment to scholarship and revision made this publication possible. I would also like to thank the faculty mentors who guided these undergraduate researchers, offering invaluable support and expertise throughout the research and writing process.

Additionally, I would like to acknowledge the faculty members who generously contributed their time and insight during the rigorous peer-review process. Their thoughtful feedback and academic rigor helped ensure the quality and integrity of this journal.

It has been a privilege to help share this work, and I hope readers enjoy engaging with the research as much as we did preparing it.

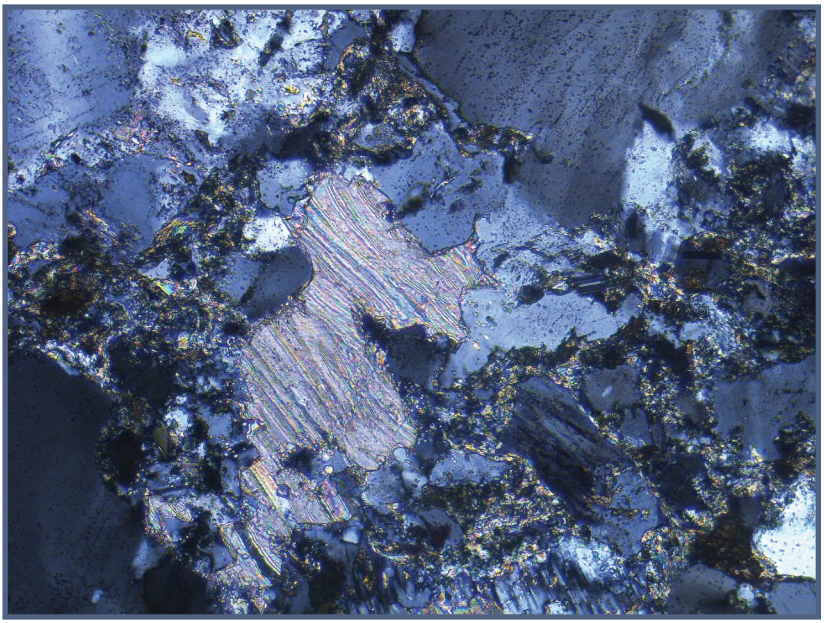
Sincerely,
Ana Tyulmenkova

Cover Design Artist Statement

"Beauty in the Dust"

"My photo *Beauty in the Dust* reminds us to look for the beauty in the most unexpected places, especially in the most mundane parts of nature. From the laminated beds in gargantuan boulders to the tiniest grains in a small granite pebble, oftentimes the most beautiful mosaics are hidden among the dust."

— Zarina Mason
Undergraduate Student
Charles. E. Schmidt College of Science
Faculty Mentor: Matthew Edwards



The Roles of Shame in Ex-Christians' Personal Experiences and Deconversion Journeys

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Anaya Bruno, Dr. Robin Vallacher (Faculty Advisor)

Abstract

Although the benefits of religion on individuals' mental wellbeing have been well-studied, research exploring aspects of religion that may prove harmful to mental wellbeing is limited. This study explores the roles of shame in the experiences of ex-Christians that led to their deconversion. The study's results have implications for understanding the experiences of religious trauma, considering that chronic shame has been linked to the development of trauma. Respondents, recruited via Reddit, answered survey questions about the ways in which they perceived shame to influence their religious experiences, personal experiences, and religious deconversion. Inductive thematic analysis was utilized to derive themes from the responses. The themes include the centrality and persistence of shame, the shameful nature of purity ideals, social ostracism and judgement, doubts of self-worth, and dissatisfaction with religious community and logic. The findings of this study may be indicative of the ways in which shameful aspects of religion may potentially prove traumatic to individuals. This way, the findings of this study will be able to contribute to the development of effective therapeutic interventions against religion-oriented mental ailment, and may guide the development of healthier religious practices.

Introduction

Overview of Study. Religious trauma is a very under-researched condition. There has been a plethora of research that has explored the potential benefits of religious belief and practices, and that has framed religion as a method of coping during difficult life circumstances. However, research framing religion as a contributor to mental ailment—as opposed to being a healing tool for it—is minimal. To expand upon previous research that has established a significant relationship between chronic shame and trauma, and has suggested that shame is a significant part of some interpretations of Christianity, this research explores the roles of shame in ex-Christians' personal experiences, religious experiences, and deconversion journeys (Arel, 2019, pp. 45–70; Downie, 2022). Considering the aforementioned research findings, the ways in which shame influences ex-Christians' religious experiences, personal experiences, and religious deconversion may be indicative

of the ways in which certain religious practices may potentially prove traumatic to some individuals. This study also expands upon previous research that has derived discontentment as a theme in the motives behind religious deconversion (Pérez et al., 2019). This was done by inquiring about the ways in which discontentment in faith contributed to respondents' religious deconversion. Finally, this study expands upon previous research that has established a connection between shame and the issues of sociality, normativity, and morality (Neckel, 2020). This is done by exploring how the respondents' desire to behave "righteously" or in a socially acceptable manner, according to their previous faith, contributes to feelings of shame.

Effects of Religion on Mental Well-Being. There is variability in the mental health outcomes of religious individuals. Receiving compassionate religious care following traumatic experiences has been shown to have a positive relationship with post-traumatic growth; however, experiencing judgment and shame following those same traumatic experiences has been shown to be related to negative post-traumatic symptoms (Harris et al., 2008). Despite its potential to cause mental harm, religion may prove helpful in protecting against depression and stressors related to anxiety (Dein et al., 2012). The diverse nature of religion's potential effects on individuals' mental health must be acknowledged in order to avoid drawing absolute—and possibly misleading—conclusions on how religion affects people's mental well-being. However, although both perspectives are important to consider, the potentially positive effects of religion on people's mental well-being have already been well established. Religion has been observed as a tool that is often utilized in providing comfort and security during life's challenges (Koenig, 2020, p. 206). Less research has explored the notion that religion may prove harmful to people's mental well-being. Findings that do explore this notion include the fact that the prohibition of certain emotions in authoritarian religions has adverse effects on certain psychological functions, contributing to the development of depression, anxiety, and obsessive-compulsive tendencies. This encouragement of rigid and legalistic thinking also poses adverse effects on people's intellectual abilities (Stone, 2013). The disruption of such mental functions may prove detrimental to people's long-term mental wellbeing. Forcing people to witness life through polar extremes discourages them from engaging in mental processes which would allow them to develop necessary critical thinking skills. Such thinking also deprives people of the knowledge needed to make accurate judgements, which may contribute to the aforementioned adverse long-term outcomes (Panchuk, 2020).

Religious Trauma. The term "religious trauma syndrome" was coined by Dr. Marlene Winell and is described as ". . . the condition experienced by people who are struggling with leaving an authoritarian, dogmatic religion and coping with the damage of indoctrination" (Winell, 2011, p. 17). Stone (2013) elaborates on Winell's coined term by describing religious trauma as "pervasive psychological damage resulting from religious messages, beliefs, and experiences" (p. 324). In a medically reviewed article, the clinical features of this syndrome have been noted, including diminished critical thinking abilities, difficulty in decision-making, diminished sense of self-worth, difficulty in building strong relationships, unfamiliarity with mainstream culture, struggles with belonging, sleeping issues, eating issues, sexual dysfunction, anxiety, grief, guilt, fear, and loneliness (Powell, 2023). Despite not currently receiving recognition in the DSM-5, religious trauma may be present in more individuals than scholars are currently aware of. It is possible that up to 1 in 5 U.S. adults struggle with religious trauma symptoms (RTS) (Slade et al., 2023). These statistics highlight the surprising prevalence of such an under-researched condition.

Shame. Shame arises in response to a conflict between an individual's self-concept and their perception of ideal. Neckel elaborated on this point by claiming that shame is connected with sociality, normativity, and morality (Neckel, 2020). This idea suggests that those who place high importance on blending in socially or acting morally may be more likely to feel shame when falling short of such expectations. Considering that feelings of belongingness in religious spheres are typically attributed to spiritual morality and divine acceptance, as opposed to in secular spheres, compliance and shame in connection to religious sociality may feel particularly high stakes. There comes a point where, as opposed to merely being a temporary emotion, shame becomes a *habitus* (harmful cycle) that is expressed through perception, interpretation, and repetitive behaviors (Arel, 2016, p. 10). "Chronic shame" is a potential factor in the development of religious trauma. This makes people who practice interpretations of Christian faith that emphasize fundamentalistic values particularly susceptible to developing religious trauma due to the tendency of these sects to utilize shame in demanding obedience (Downie, 2022). Leaving fundamentalist religions with authoritarian leadership may lead to difficulties in emotion and adjustment abilities (Hartz & Everett, 1989). Hartz and Everett described a fundamentalist mindset as one that is intolerant of ambiguity and uncertainty. Thus, in theory, the shameful and dogmatic nature of certain interpretations of Christianity may increase people's risk of developing symptoms associated with religious trauma. Shame has been linked to trauma (Arel, 2019, p. 45–70). This current study aims to understand the implications of shame in ex-Christians' religious experiences, personal experiences, and deconversion journeys, as this data may be representative of those suffering with religious trauma symptoms. Albeit this, one must acknowledge that not every aspect

of Christianity may prove harmful to people's mental wellbeing. Although some Christians tend to behave prejudicially towards mental illness, others honor aspects of their faith that encourage empathy and compassion for those who struggle (Lehmann, 2021). This point further demonstrates the diversity of interpretations and execution of Christianity, something that must constantly be remembered to avoid drawing absolute conclusions.

Deconversion. Popular conversations around religious disengagement bring up both deconversion and deconstruction. To make a distinction between the two concepts, deconversion is defined as the exiting of a religious movement, a process of transformative learning and change from an inherited belief, while deconstruction—in a religious context—generally refers to "a process of shifting one's beliefs" (Beaudoin & Hornbeck, 2014; Cole, 2025, p. 1; Skonovd, 1981). Definitions of religious deconstruction have emerged largely from popular culture, including social media networks and self-help texts (The Deconstruction Network, 2020). Leaving high-cost faiths—those that require significant personal sacrifice—may prove harmful to people's emotional and mental wellbeing by causing them to live in extreme fear and guilt, to experience grief over the loss of their faith, and to feel worthless as a person; however it may also prove beneficial by allowing people to rebuild their sense of self and to experience the freedom of leaving a restrictive faith (Björkmark et al., 2021). Three main themes were drawn from a qualitative study on the factors that go into deconversion: reason and inquiry, criticism and discontent, and personal development (Pérez et al., 2019). This current study aims to further explore the theme of discontentment, inquiring about how discontentment in faith contributed to ex-Christians' decisions to and/or journeys of leaving Christianity, and why so.

Methodology

Institutional Review Board approval was acquired prior to data collection. A link to the survey was distributed via the "r/Exvangelical" and "r/Deconstruction" subreddits. The recruitment post explained the purpose, process, risks, and benefits of participating in the study. Twelve responses were collected and utilized in data analysis. The only demographic question asked was acquiring the gender identity of the respondents (five cis-gendered females, five cis-gendered males, one transgender woman, one gender nonconfirming/nonbinary individual). Many religions promote gendered roles and behavior expectations in faith practice, hence the significance of gender identity in the experiences of ex-Christians (Goldscheider et al., 2014). The questions that the respondents were asked are listed in Figure 1, in the results section.

Following their completion of the survey, the respondents were provided with a list of resources to utilize if necessary. Thematic analysis was completed by the primary researcher in order to derive major themes from the responses (Braun & Clarke, 2006). An inductive approach, as opposed to a deductive approach, was utilized in order to gain new insights from the data, rather than fitting the data into previously established categories. This process consisted of noting recurrent concepts—also known as codes—that were relevant to the questions being asked. The codes were then grouped into themes based on similarities and patterns. The responses were anonymized for confidentiality reasons.

Results

The following tables consist of the codes that recurred throughout the data, along with an example quote for each code. The six overarching themes in the data were: "shame is inherent and central to religious teachings and experiences," "shame persists even after religious deconversion," "the condemning nature of purity ideals contributes greatly to sexuality-related shame," "social estrangement and/or judgement," "doubting of one's morality and/or worth," and "dissatisfaction with the logic, factual accuracy, and morality of religious practices and/or communities." When asked about how much of a role shame played in their deconversion, two individuals responded, "not a lot" and "not very much at all."

Figure 1a
Thematic Codes Per Question and Accompanying Example Excerpts

How much of a role has shame played in your deconversion journey/decision? **How have the tenets of your previous faith influenced this shame?**	**Themes/Codes**	*Examples of excerpts from each code*
	• Shame was central/ inherent to religious experiences	" Christianity is a closed loop circuit that only prevents the inherent shame..."
	• Shame persists, following religious deconversion	" I had to dig deeper into my psyche and I am still doing the work of removing programmed shame."
	• Condemnation of sexuality influenced shame	" I felt wrong for experiencing natural feelings of sexual desire. I was told that it was sinful and wrong to want to have sex."
	• Shame was ingrained in religious doctrine	" [shame] introduced... a total disconnection with my inner being due to the toxic theology inherent to christianity."
	• Shame was not a big motivator in deconversion	" None. It was not shame but hypocrisy and the fact they don't exist in reality."

Figure 1b
Thematic Codes Per Question and Accompanying Example Excerpts

	Themes/Codes	*Examples of excerpts from each code*
How have you perceived shame to affect non-religious aspects of your life such as in your relationships, productivity, and pursuit of self-pleasure?	• Lack of trust in oneself & feelings of inadequacy	" Being taught that there was nothing good in me except 'christ' made me completely incapable of trusting my thoughts, my emotions and my desires"
What were the functions of this shame both before your deconstruction journey and after (if applicable)?	• Shame from engaging in activities condemned by previous faith	" Many things that have brought me pleasure or joy as an adult that go against the religion I was raised in (drinking, recreational drugs, casual or monogamous sex, etc.) have been surrounded by shame"
	• Shame from purity culture both before deconversion and after	" When I'll have a sexual encounter with another person I'll still feel some shame even though there is no reason to."
	• Social estrangement/ judgement	" Not being a Christian in my area and my former circles is not an option"
	• Shame did not impact non-religious aspects of life	" Almost zero"; "No"

Figure 1c
Thematic Codes Per Question and Accompanying Example Excerpts

How did the desire to behave morally righteous and socially acceptable according to your faith relate to the shame that you felt?	**Themes/Codes**	*Examples of excerpts from each code*
	• Obsessive checking of one's morality due to shame	" To escape this shame I had OCD behavior of making sure I never missed my devos, prayer (pray without ceasing), constantly checking my own motivations."
	• Shame from past religious involvement, rather than from not meeting religious standards	" I felt ashamed later on for being so judgemental when I was Christian."
	• Feeling as if morality determines one's value as a person	" ...there was a message that you had no value without being morally righteous so it was a big source of shame to have my inner feelings reflect anything that didn't align"
	• Fear of judgement from community	" As I deconstructed, I worried what my mom would think"
	• Shame was not the predominant motivator of pursuing righteousness	" None. It was not shame but hypocrisy...."
	• Shame from one's identity not matching up with one's faith	" This gulf between what I was supposed to want and want I actually did want was such an enormous source of shame that I had to stop attending church altogether..."

Figure 1d
Thematic Codes Per Question and Accompanying Example Excerpts

Did feelings of discontentment in your faith play a role in your religious deconversion journey? If so, in what way(s)?	**Themes/Codes**	*Examples of excerpts from each code*
	• Discomfort from oppressive origins of faith	" Christianity as a whole has been dragged kicking and screaming into the modern world and then turns around and claims to have believed in the ideologies it fought against from the start. Aka, slavery, colonization, women's rights, civil rights, wealth disparity, etc"
	• Logical inconsistencies and/ or discouragement from asking difficult questions about faith	" I also began to see faults in them, the ways they'd let me down, the hypocrisies, and intellectual inconsistencies"
	• Dissatisfaction with the true moral state of the church	" The absolute hypocrisy of the church in saying they love everyone while also condemning those who don't believe or behave the way they want to hell, is absolutely disgusting."

Discussion

Theme 1. Phrases describing the centrality of shame in ex-Christians' religious and personal experiences were recurrent, hence the creation of this theme. Such phrases include:

> " Shame was my birthright when I was born into a christian family that ingrained Original Sin and later on Total Depravity."

> " I have had to unlearn shame as a 'motivator,' internal voice, and view of my own unworthiness."

When asked how much of a role shame played in deconversion:
" A lot."; "A large amount."

While some respondents described shame as a major influence in their religious decision-making, others described shame as inherent to the theology that they were taught and the behaviors that they executed. This relates to Downie's research that has proposed shame as a tool for asserting control and demanding obedience in Christian faiths (2022). Overall, for many respondents, shame was perceived as inherent and/or central to religious experiences.

Theme 2. Respondents shared that, despite having been separated from their religious origins for a substantial amount of time, shame persists following religious deconversion. Phrases describing such persistence of shame include:

> " I am still doing the work of removing programmed shame."

> " I think shame and guilt was central to my experience in the church, as I was in the process of leaving, and now 10 years on."

> " I still experience so much shame around so many things."

For example, feelings of shame surrounding behaving righteously pre-deconversion have been said to persist as feelings of shame surrounding secular matters post-deconversion, such as doing one's work perfectly. Many respondents explained that they are still actively and constantly deconstructing the subconscious influences of religious shame in their day-to-day lives. Research has highlighted how religion influences identity exploration and formation through providing ideological, social, and spiritual contexts in which to function (King, 2003). Being core to people's identity, aspects of religion may prove difficult to abandon, especially if one was raised in religion from an early age.

Theme 3. A recurrent concept throughout the data was that the purity ideals of one's previous faith contribute greatly to sexuality-related shame, even after deconversion. Phrases describing such experiences include:

> " When I'll have a sexual encounter with another person I'll still feel some shame even though there is no reason to."

> " Women aren't supposed to be high libido. Like I had as a teen, I felt shamed for possessing a sex drive."

> " Before I deconstructed my faith I felt a great deal of shame for wanting to pursue sexual relationships as well as self pleasure."

The basic message of purity teachings is that one's worth is tied to one's sexual purity and abstinence. Many respondents shared that they felt shame while engaging in sexual acts that are condemned by their previous faiths, such as non-heterosexual relations and sex outside of marriage. This supports previous research that has defined the relationship between purity culture and sexual shame (Benton, 2022). This trend was particularly pronounced in cis-gendered women. This demonstrates how shame in a specific domain of religiosity impacts religious deconverts in the long-term.

Theme 4. Respondents reported feeling estranged or judged by their previous communities, whether it be church communities or familial relationships. Phrases describing such experiences include:

> " Even though there would be no 'actual' punishments for behaving outside of the rules, if the chuck community knew then it felt like you would be judged, people would pray for you to change, and people would talk about you."

> " As I deconstructed, I worried what my mom would think."

> " Not being a Christian in my area and my former circles is not an option."

The transgender woman shared that she experienced judgement from her youth group, contributing to the shame that ultimately ended in her leaving her church. Her experience of shame is particularly significant because it highlights how her experiences with transphobia and church judgement foster a unique experience of shame in her church community. Respondents reported feeling unsupported and as if they needed to hide the sides of themselves that was contradicting the faith of their community. This expands upon the idea that shame is connected to social normativity and

acceptance (Neckel, 2020). Shame occurs in social contexts related to faith, contributing to feelings of estrangement and judgement in religious deconverts.

Theme 5. Respondents described themselves as doubting their own righteousness and/or worth as a result of religious shame. Phrases describing such feelings include:

> " I was not content to be constantly made to feel like I was worthless, and hearing that discontent echoed by a youth pastor (not my own, a guest at a conference) was what enabled me to view that as a fact in the world and not just another flaw inside my brain"

> " The gospel as presented by evangelicals harps on a person being unworthy."

> " It was very connected, there was a message that you had no value without being morally righteous so it was a big source of shame to have my inner feelings reflect anything that didn't align"

They reported feeling as if their value as a person came from behaving "righteously" according to their faith, contributing to diminished feelings of worthiness following religious deconversion. By building their self-concept on the foundation of religion, the respondents' self-esteem was shaken by the deconstruction of that foundation. This connects to how central religious virtue and belief are to one's identity.

Theme 6. Some respondents reported feeling dissatisfied with the logic, factual accuracy, and/or morality of religious practices/communities. Phrases describing such feelings include:

> " I also felt like the church was being hypocritical in the fact that it wasn't doing the work to support the community that I felt like it's beliefs required it to do."

> " The discontentment started when I began to question the goodness of God if he saw me as an unworthy sinner."

> " Yes, the main trigger of my discontent in my faith was conservative politics mixed into the Sunday service. Everyone else bought it hook, line and sinker. The other trigger was the misogyny being taught. These factors made me angry and defiant, the definitive push out the Church door."

It was reported that the oppressive origins of Christianity caused discomfort that contributed to the skepticism of the morality of Christian faiths. Respondents also described instances in their deconversion journeys where they were met with existential questions and dilemmas, which remained unanswered due to the tendency of Christian faiths to condemn questioning. Ultimately, these respondents viewed belief in their faith as less important than the discontentment that they felt, contributing to their deconversion.

Future Directions. These results contribute to the understanding of ways in which certain aspects of religiosity may prove harmful to mental wellbeing. However, the study has some limitations: 1) the sample size was fairly small (n = 12) and the respondents were recruited from only one website; 2) the subjective nature of qualitative analysis introduces the possibility that researcher perspectives can inform the interpretation of the data, so replication of this study from various perspectives is encouraged; 3) this research focuses on Christian faith, so it cannot be generalized to all types of religion; and 4) only the demographic of gender identity was collected, so the results cannot be generalized to all social demographics. The results of this study may be used in developing quantitative studies to determine the expressions of religious shame relevant to specific demographic groups and specific sects of Christianity. Additional qualitative and quantitative research methods may also be utilized to understand the roles of shame in other kinds of religious experiences. The results will also be able to inform the development of therapeutic interventions against religion-oriented mental ailment.

Closing Statement

Google's AI Overview was used in a limited capacity to assist with identifying article summaries and supporting citation formatting. All sources were independently reviewed and verified by the authors. No generative AI tools were used for data analysis, interpretation, or substantive content development.

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Learning About Gujarati: Cultural Identity and Family Language

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Abstract

Language loss is a prevalent problem that is occurring in immigrant families in the United States. Since regional languages such as Gujarati are not used outside of households and community gatherings, it is not given much importance to learn. In order to combat this problem, community centers hold Gujarati classes for students of all ages to help preserve the language, but the lack of motivation to learn the language still remains. This is because a student needs to have a connection to the language to be motivated to learn it, which can be made through active learning. This study examines the engaging features of a Gujarati class by identifying characteristics of active learning. Data sources include class observations, journaling and photo elicitation.

Introduction

Language is an integral part of culture and identity, making the protection of heritage languages critical. Due to the increased amount of global migration, there has been an increase in cultural diversity in countries around the world (Alshihry, 2024). This global migration has allowed some children to have multiple cultural identities, through which they can learn about their different customs and languages.

Gujarati is an Indian language spoken by the people of Gujarat, an Indian state on the western side of India. There are over 65 million Gujarati speakers in the world (Patil et al., 2023). According to the U.S. Census (2019), in the United States, there are around 525,030 Gujarati-speaking people. Even those who speak Gujarati in India are turning to more commonly spoken languages such as Hindi and English to use at home to help their children perform better at school (Bureau, 2022; Kaushik, 2006). In the United States, families are beginning to find learning Gujarati challenging as it is not commonly spoken (Kidlol, 2023).

For multilingual families, knowing the family language in addition to English is a skill that can be used in a school or career setting in the United States because language is an integral aspect of Gujarati culture. Speaking Gujarati not only builds a community and family connection but also establishes a sense of cultural pride (Peng & Patterson, 2021). Younger second-generation immigrants

find it difficult to preserve their family language, which means that languages may slowly be lost if Gujaratis are not able to learn the language (Shen & Jiang, 2021). To address this problem, many Hindu temples around the world hold weekly Gujarati classes for students of all ages to preserve the language and to better help them communicate with their community, including understanding religious scriptures written in Gujarati (BAPS Swaminarayan Sanstha, 2025). However, these classes are not structured as a public-school setting since they are community-based offerings and are held by volunteers, making the learning experiences different and at times challenging. While there is a set curriculum for the instructors to follow, it can be difficult for younger students to find motivation to learn the language in an informal setting and limited hours because of the limited time spent in class. Scholars have pointed out that in order for a child to find a sense of interest in the language they are learning, there must be a connection between the child and the language (Benderev, 2020; Fielding & Harbon, 2013).

Despite the existence of research on language learning in a school-based setting, there is a deficiency in empirical literature about language learning in a community-based setting in the United States (Clifford & Reisinger, 2019). Therefore, the purpose of this study was to examine the delivery of a family language class in a community-based setting including teacher-student interactions and student engagement in a Gujarati class. The research question in the study asks, "What are the characteristics of an engaging Gujarati class in a community-based setting?"

Review of Literature

Cultural identity and motivation to learn a language, are key factors to encourage students to learn a language (Peng & Patterson, 2021). When examining previous empirical sources, the search criteria included: sources published between 2013 and 2023, and key words such as cultural identity, motivation to learn, language learning, early childhood, and immigrant families. The search was conducted using the Florida Atlantic University Libraries' OneSearch tool and Google Scholar. The search criteria included the following words: cultural identity, motivation, language learning, early childhood, immigrant families. The articles were collected and organized in Zotero, which is an online tool that facilitates the selection of articles and exclusion of articles based on our search criteria.

This review discusses empirical studies on cultural identity, motivation to learn, and active learning.

Cultural Identity & Importance of Family Language. Cultural identity and language learning have close ties due to the presence of language in all cultures. The relationship between cultural identity and family language has been described as complex, with researchers even considering them as one (Peng & Patterson, 2021).

Grosjean (2010) defines bicultural people as people who are involved in two or more cultures, modifying aspects of one of their cultures to better mix with the other culture or cultures involved in their lives. Certain attitudes and beliefs, or behaviors, can originate from a specific culture, or can be a combination of these cultures. Specific characteristics of a person can originate from one specific culture, and others could be a blend of the cultures a person is involved in (Fielding & Harbon, 2013). It is also important to establish that there are multiple core values from these cultures that can be involved, and some may be more important to a person than others (Smolicz, 1981). In Gujarati culture, there are core values of family connection (Singh & Sebastian, 2018), which were observed in Gujarati classes.

The conception that students have about the language has a relation to the speakers' belief about the language (Gursoy & Ozcan, 2018). Florez Gonzalez (2018) reported that students felt more interested and motivated to know about their history from the interviews and the stories told by the senior people. When children connect with elders, whether or not they are family members, they understand their history better, hence giving them a positive attitude about their language. When children associate their family language with a positive attitude, it allows them to understand why it is important for them to learn.

Motivation to Learn a Family Language. Motivation is defined as an individual's need to fulfill a goal through an unmet need (Pincus, 2022). Motivation is an integral factor in language learning and learning in general. Factors that exhibit motivation include investment, which is a term that describes both a student's motivation to learn a new language and the community's motivation to assist the student to develop the language (Norton, 2011). Other ways to examine the amount of motivation a student has is to examine students' attitudes toward and beliefs about their use of more than one language, and their attitude toward and affiliation with more than one cultural group or community. This can be an example of a motive as mentioned in Figure 1. The connection that the student has to a language can also factor into their overall motivation. Connections can be created or instilled through upbringing, and they can also provide learning benefits, as there is research supporting that learning a language at an early age allows speakers to acquire an (native-like) accent (Flege & Fletcher, 1992; Patkowski, 1990). In terms of created connections, one motivating factor is the age at which the language

is being learned. It is also important to note that when students hold negative perceptions about their ability to learn a new language, this negative perception will hinder their progress (Zhang & Hu, 2008). Possessing or learning to produce an accent similar to that of native speakers can allow a student to feel less of an outsider to the language. Making connections with friends and teachers and having parental support while learning a language are also motivating factors that can be seen in Figure 1, which is a table found in Entwistle's motivation paper (Entwistle, 1987), modified to fit the themes of this study.

Figure 1
Motivation to Learn Conceptualizations

• Motives
• Peer friendship
• Parental support
• Identification with teachers

Note. Modified version adapted from Entwistle (1987).

Active Learning. Active learning is defined as a pedagogical approach that includes advanced thinking through comprehension that fosters engagement and participation (Doolittle et al., 2023). Active language learners are identified as learners who embrace language-learning experiences and opportunities (Foushee et al., 2023). In this study, active learning is especially important because the students are not receiving school credit to learn Gujarati, hence this does not have a foreseeable effect on their academic futures. Though they are receiving grades from their teachers, the grades do not technically have any effect on a grade point average. Figure 2 displays a checklist based on a modified version of Active/Passive Motivation Scale (APMS).

In this study, we attempted to uncover factors that make a language class more engaging and provide more authentic learning experiences for students. The researchers examine cultural identity, which is defined as a personal awareness of culture and the ability to recognize which group one belongs to (Peng & Patterson, 2021); but specifically the bicultural identity of students as they partake in learning the language of their culture while living in the United States with both an American and Indian identity.

Methods

Research Design. The present study used a case study methodology to record observational data at the community center where the observations occurred. A case study is defined as an "analysis of an event, situation, organization, or social unit" (Yin, 2018, p. 15). A case in particular is defined as an occurrence with context to the real-life situation (Yin, 2018). In the context of the study, the case is a community center in South Florida that offers different community activities. The phenomenon in this case was learning a family language within a community setting. In the center, Gujarati classes are offered once a week on Sundays. There are seven levels that students progress through, requiring students to start at the first level in order to move on to the following. Classes are divided by gender in order to be aligned with the community center's guidelines. Since the researcher was female, she was only able to collect data in the Gujarati classes for females.

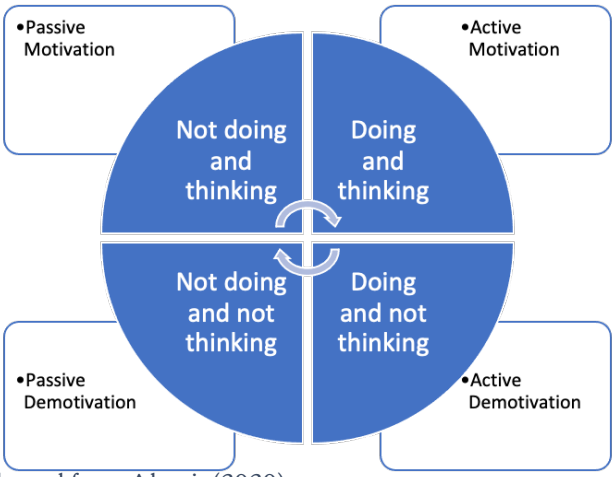
Participants. The sample of this study was a non-random group of 21 female students ages 5 through 13 years old and three female teachers. Though there were other students present in the classroom, only the students who were given permission to be included in the study were observed. Since this was an observational study, no direct information was taken from the students or their parents, so the ages of the students in each specific level can only be assumed. This project received Institutional Review Board (IRB) approval and required parents to read and sign a Google Form granting permission. The forms were distributed through WhatsApp group chats that existed for communication between the teachers and parents. Teachers also received forms asking for their consent to be included in the study. Only the students that had permission from their parents were reported on. All the participants in this study are exposed to Gujarati at home and come to these Gujarati classes to learn to read, write and speak in a cohesive manner.

Data Collection Methods. There were two forms of data collected throughout the study. To address the question that asked for the engaging characteristics of a community-based language learning center, the researchers used two data sources. First, data were collected using an observation form for the field observations. During the three observations, the first author's role was an etic observation since she did not interject with students or teachers. The observation form was a modified version of the Active/Passive Motivation Scale (Alami, 2020). The second data source was the first author's pictures from her Gujarati lessons and personal language learning experiences. Photo elicitation was used to select and discuss the meaning of the pictures (Doolan & Liebenberg, 2019).

Procedures. In terms of field observations, data collection occurred at three of the six levels offered at the center. First, permission was gained from the community center to conduct data collection at their Gujarati classes. Then, IRB approval was obtained to conduct research involving human minors. Next, consent was collected from the parents/guardians of the minors in the study. A data collection form was created using the active learning conceptual framework. There were three one-hour observations that occurred over a period of three weeks. On average, an hour was spent in each level observed. Figure 3a and 3b are an observation form that was created based on Figure 2, the Active/Passive Motivation Scale. The observation form guided the researcher on different behaviors in the classroom.

Data Analysis. The unit of analysis in this current study was the classroom as a whole. The researchers used data from the observations and the pictures. Data were analyzed using 15 codes and three themes derived from the active learning conceptual framework. Through mind mapping, the researcher created codes related to the themes and analyzed the notes that were taken during site observations (Davies, 2011). Mind mapping is a tool that is used to link and arrange ideas around a topic. Starting with the idea of "Learning Gujarati" the mind map was broken up into subtopics of cultural identity, importance of family language, motivation to learn family language, and active learning (Palaniappan, 2023). In terms of photo elicitation, photos were used from the researcher's personal language learning experiences, which were analyzed using the Active Learning Conceptual framework as a second source of data.

Figure 2
Checklist Based on Modified Version of the Active/Passive Motivation Scale (APMS)



Note. Adapted from Alami, (2020).

Figure 3a
Checklist Used During Site Observations

Date:

Observation Form

Level

0 1 2 3 4 5 6

Number of participants: _____

Seating arrangement:

- ☐ Rows
- ☐ Semicircle
- ☐ Circle
- ☐ Other:

Teacher postitioning:

- ☐ Standing
- ☐ Moving around
- ☐ Sitting in one spot
- ☐ Other:

Communication:

Directions and procedures:

- ☐ Clear
- ☐ Understandable
- ☐ Other:

Oral Language

- ☐ Simple langauge
- ☐ Complex language
- ☐ Other:

Written language

- ☐ Clearly written
- ☐ Understandable
- ☐ Other:

Engagement:

Between teacher and student

_____

_____

_____

Among Students

_____

_____

_____

When not using Gujarati

_____

_____

_____

Questions

_____

_____

_____

Participation

_____

_____

_____

Figure 3b
Checklist Used During Site Observations

Feedback:

To students:

- Amount:
- Quality:

To teacher

- Amount:
- Quality:

Clarity:

- ☐ Of objectives
- ☐ Of material
- ☐ Other:

_____
_____
_____

Use of tools:

_____
_____
_____

Presentation skills:

- ☐ Clear speech
- ☐ Loud enough
- ☐ Shows enthusiasm about material
- ☐ Other notes

_____
_____
_____

Student reaction:

- ☐ Clear speech
- ☐ Enthusiasm
- ☐ Other

_____
_____

Results

This section discusses the themes that emerged from the observations and how they connect with the discussed framework. There were three themes: cultural identity, family language, and active learning. The observations yielded numerous occurrences for each theme, as shown in Table 1.

Cultural Identity & Family Language. These two themes were found to be interconnected; thus, we discuss them together. One of the ways that engaging characteristics of a Gujarati class can be categorized is through cultural identity. The themes relating to cultural identity in this study were language, events, and connection to family. During the time of data collection, the community center was celebrating the Hindu holiday, Diwali, so the classrooms and hallways were decorated with posters and other festive decorations (Editors of Encyclopaedia Britannica, 2025; Kaur, 2024). The decorations around the classroom in which the classes occurred, whether placed there deliberately or not, helped the student feel a sense of cultural identity while learning their family language (Gouda-Vossos et al., 2020).

Based on the data, the researcher observed multiple instances of social interactions and familiarity among the students and teachers as evidenced by 23 codes in Table 1. Social interactions and familiarity among the students deepened their cultural identity as their peers in the classroom came from the same background as them (Wang et al., 2024). Many of these students had friends that were other students in their class with them, and students who did not seem to have as many friends were not as engaged with the material. For example, when students interacted with others in the class, they smiled and laughed with each other and engaged themselves in the material together. The students who did not interact with their peers did not seem to interact with their material, and often looked around the classroom, distracted.

Students exhibited the importance of family language when they chose to speak in Gujarati instead of choosing to speak in English because it shows how connected they are to their language. The younger students tended to prefer to speak in Gujarati more than the older students, who answered in English, which can be because the younger students might not have been exposed to cultures outside of their home for as long as the older students. It was observed that attending these classes creates community connections as students become familiar with the people in their community. This can include teachers, other peers, and older students who may switch back and forth between the classrooms.

Active Learning. The data of this study yielded descriptions of activities that can be considered motivating and demotivating. In the case of motivating occurrences, students were more engaged with their material when they received positive reinforcement from their teachers, as they seemed happier to complete tasks after receiving compliments such as "good job" in English. The classrooms that did not use positive reinforcement showed less enthusiasm as those classrooms had less codes of active motivation. Enthusiasm was operationally defined as emotional experiences of joy and pleasure during instruction and learning (Song, 2022), as students showed interest in the learning activity and teachers and students were engaged. Based on the observation, there were 26 different codes that emerged that were categorized as active learning as shown in Table 1. This was an indication that students were engaged in class. When tools were used, active learning was facilitated as students were not uncomfortable. However, due to the timing of the study (during a religious holiday), there were no desks, whiteboards, or other tools available, making it difficult for students to stay engaged when they did not have the appropriate tools to help them learn (demotivating activities). Two teachers who were more enthusiastic had more enthusiastic responses from their students, and the one teacher who was less enthusiastic had less positive feedback from students, such as a lack of participation. Some students complained when they were asked to do repetitive tasks such as tracing, but it is a necessary element in learning a new language with a different alphabet (James et al., 2012). During this time, students also talked about their personal experiences at school, highlighting the differences between the community-based setting and the school. At school, students claimed to use more technology; however, due to the nature of a community setting, the same resources that are available at a school are not available at the center.

Table 1
Codes and Themes from Qualitative Data

3 Themes	N of Codes	Codes
Active Learning (AL)	26	Active Motivation
		Active Demotivation
		Tools
		Students
		Teacher
		Setting
		Parents
		Positive Reinforcement
		Communication
Importance of Family Language (PS)	20	Family Connection
		Identification with the Teacher
		Community Connection
Cultural Identity	3	Language
		Events
		Connection to Family
Total	49	

Grammar drilling was found to be demotivating as well. Figure 4 shows an example of a grammar drill completed by the researcher when they were in Gujarati class. The image in Figure 4 shows examples of active demotivation. Active demotivation refers to when a student is doing and not actively thinking. Due to the repetitiveness of the drill, the student is not required to think, but they are still practicing their Gujarati handwriting; hence, they are doing the drill but not thinking about it. Nevertheless, the teachers chose to use grammar drills as an instructional activity as drills are considered to reinforce reading, writing, and grammar skills.

Figure 4
A Grammar Drill Used in a Non-School-Based Class Using Active Demotivation

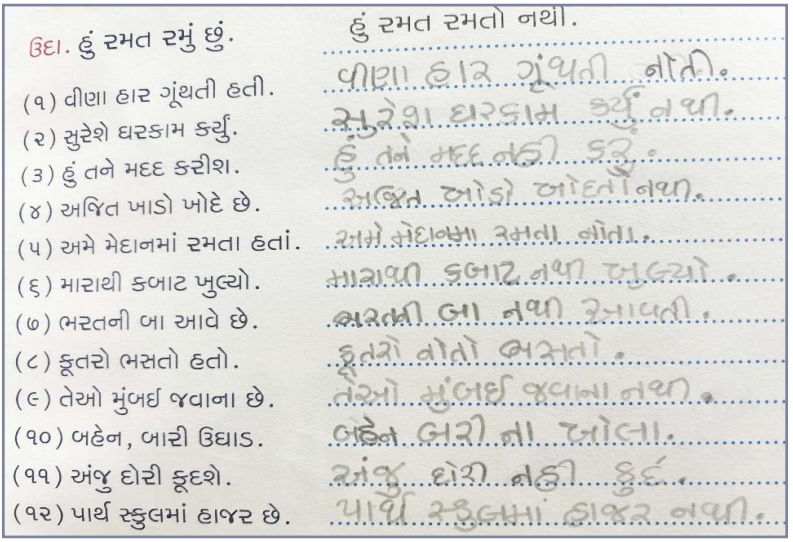
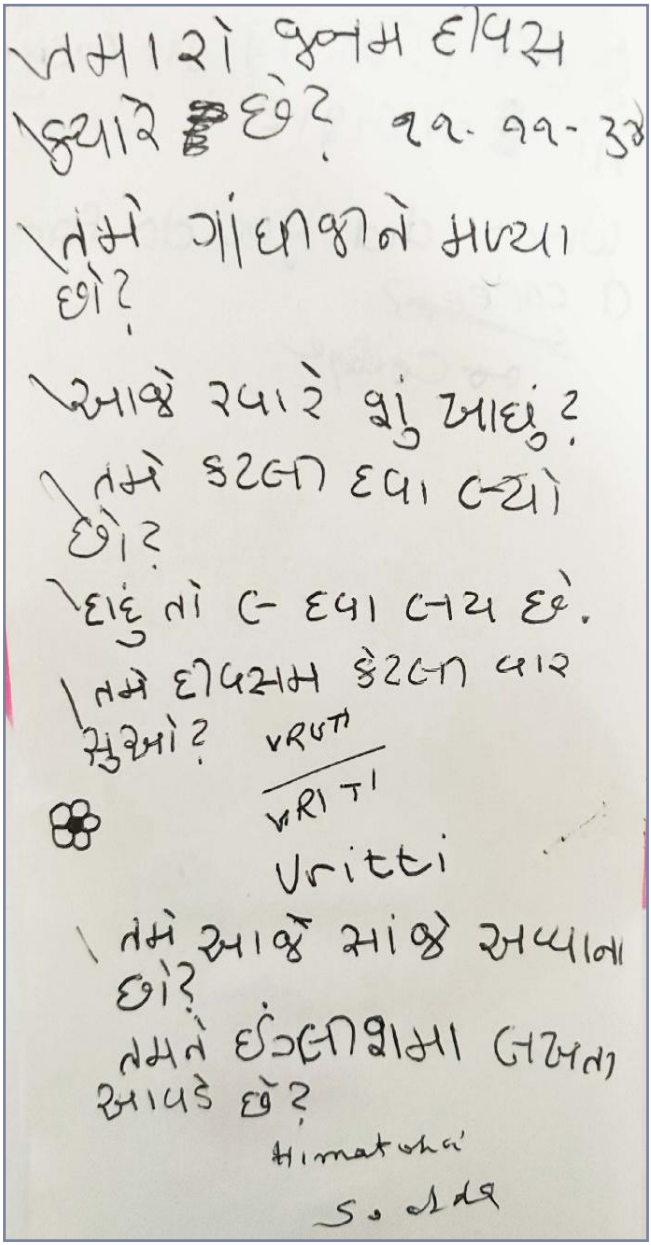


Figure 5 is a written interaction between the researcher's Gujarati speaking family member in India. Since the researcher acquired the skills of reading and writing in Gujarati class, the researcher was able to communicate with this deaf family member through writing. If the researcher had not known their family language, they would not have been able to connect with this family member in the way they did. In conclusion, data shows that based on the findings of this study, the characteristics of an engaging Gujarati class have a class infused by enthusiasm from teachers and students, learning tools are used to engage students, a strong sense of cultural identity, and active motivation through doing and thinking about language learning tasks given.

Figure 5
Gujarati-Speaking Family Member–Student Interaction Showing Active Motivation



Discussion

The overall findings of the study revealed themes that were aligned to the current literature of learning a family language. Student and teacher enthusiasm was evident in the classroom as they seemed engaged in the learning process and smiled at each other when interacting. Their enthusiasm translated into improved motivation, as students began asking questions and showed interest in the content. Most notably, students exhibited their interest in using learning tools such as workbooks, whiteboards, and tracing worksheets to engage in class and a strong sense of cultural identity.

Based on the observations, students responded with positive feedback when teachers were more enthusiastic about the students' accomplishments in the class. For example, students were more likely to answer the questions that the teacher asked and participate when the teacher gave the students positive reinforcement. In one classroom, students were only allowed to speak when called on, and were given little to no positive reinforcement, causing students to be less engaged with the material, as they were not open to expressing their thoughts. In another classroom, there was more open conversation, and students were encouraged to work together and interact freely, making the class more appealing. Students were laughing and smiling but also completing their worksheets that were handed to them. Classroom settings in which the teacher created a relaxed atmosphere where students were free to share ideas, opinions, and feelings had the best engagement rates, as evidenced by the smiles and laughs observed between teachers and students and the interests of students when engaging with teachers.

When there were learning tools such as worksheets, workbooks, desks and whiteboards used to help facilitate learning, students found it easier to engage in the material. Specifically, worksheets that involved repetitive activities and less engagement with the teacher were less engaging for the students. When teachers were involved in the work of the students, even if they were doing repetitive tasks, students were more engaged by the attention of the teacher. This indicates that, regardless of how repetitive the task is, students can still be engaged when the teacher is following along with the students.

When there was a strong sense of cultural identity, whether that be through peer friendship or the classroom setting itself, students were more engaged with their work when they had peers from the same background as them.

Instances of active motivation, when students are doing and thinking, are the most engaging for students. When students are actively participating in class, they are "doing and thinking" because they are thinking about the answer to the question that was asked of them and giving a response while others can utilize this data to make their classes more appealing to students through more positive reinforcement and a more casual classroom environment, increasing

overall participation in students of all ages. Students are "doing and thinking" when they actively participate in class. For example, when a student is asked a question, they are thinking about an answer to that question, and are actively giving a response, while receiving positive reinforcement from their teacher. Others can utilize this data to make their classes more appealing to students through more positive reinforcement and a casual classroom environment to increase student participation. Families can use this research to build stronger cultural connections with their children to create a connection to language.

Study Limitations

This study has some limitations. First, while scheduling was difficult because the temple had events that utilized the classrooms, this informed the multipurpose role of a community center to connect with their members to their family language. The fact that many of these students attended these events, contributing to another aspect of learning their cultural identity, further builds a connection that can motivate them to learn Gujarati. Second, researcher bias could have affected the observations since the researcher was a former student and teacher at this center; therefore, personal biases towards the teacher were present during the data collection and analysis of this study. To address this, the researchers kept a log of the observations and reviewed them constantly. Last, there were cases of missing data since some parents were not comfortable with consenting to their children being involved in this study, and the attendance of the students in the classes during the weeks of data collection. The teachers could have slightly altered their behaviors due to the knowledge of the researcher being present. However, the teachers could not have altered their lesson plans, as they were unaware of the weeks that were scheduled for data collection.

Future Research Recommendations

This study observed student-teacher learning engagement in Gujarati classes. The purpose of this study was to find ways to motivate students to learn their family language. Future research opportunities can explore the experiences of students learning their family language in formal and informal settings. A future research recommendation can include conducting a research study specifically to study the connection students have to their family language that motivates them to learn their language.

Another recommendation includes designing a study like the current study in a non-religious setting, considering that other language learning classes occur at different community centers that are not religious. The study could include teachers' perspectives. These perspectives can be helpful as classes are planned and scheduled to meet students' learning needs.

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Man, Cut the Crop: Effects of Cropectomies on Survival and Behavior in *Drosophila melanogaster*

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Abstract

The gut-brain axis mediates communication between the digestive and nervous systems to regulate physiology and behavior. Its dysfunction profoundly impacts human health and causes disease. Region-specific hormones and neurotransmitters in the digestive system respond to several processes to signal the brain, but the mechanisms of gut-brain signaling are not fully defined. *Drosophila melanogaster* is a powerful model for studying gut biology by showing remarkable similarity to mammalian digestive systems, as both regulate energy by distributing nutrients. We refined a minimally invasive surgical protocol to remove the crop from adult flies. We then utilized the Activity Recording CAFE (ARC) and *Drosophila* Activity Monitor (DAM) to quantify feeding and sleep in recovered flies. Cropless flies showed no change in total consumption but ate smaller, more frequent meals and exhibited altered sleep patterns. This model offers insights into how digestive system modifications, such as sleeve gastrectomies, may influence metabolism, behavior, and disease.

Introduction

The gut-brain axis (GBA) consists of the enteric system, immune responses, nerves such as cranial nerve X (Vagus), and the central nervous system (Appleton, 2018). The connection between the body's control center and the digestive system is important in the health and wellness of an organism. The stomach is a key organ that influences organismal behavior, such as sleeping and feeding. The gut microbiome within has been tagged as a promising target for therapies to treat gut and mental health. The gut microbiota within can be implicated in conditions such as anxiety disorders, chronic stress, and visceral hypersensitivity (Foster et al., 2017). This connection between gut and brain is aided by neurons innervating the crop that have Piezo1 proteins to control distention, and therefore satiety, which connects the brain and gut to control food intake (Wang et al., 2020), while neurotransmitters (such as serotonin and octopamine) and hormones controlled by the CNS control crop motility, satiety, and function (Ben-Menahem, 2021). The gut also sends

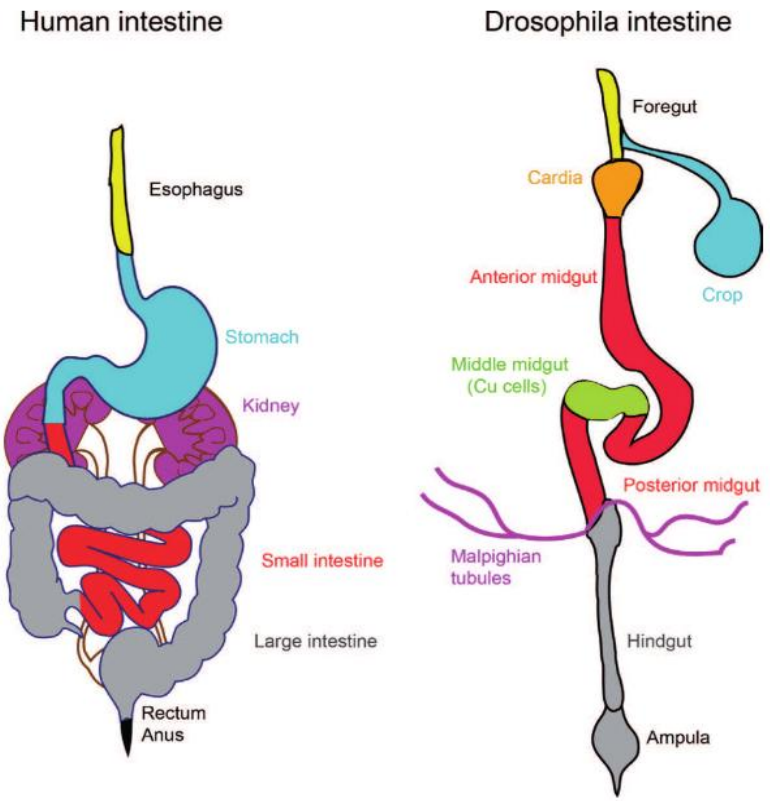
signals necessary for survival, such as nociception and satiation, modulates metabolism, and processes nutrients. Innervation of the gastrointestinal system by the stomatocentric nervous system and neurons that feed into the pars intercerebralis displays the connection between seemingly different systems that influence wellness (Wang et al., 2020). However, despite the immense influence of gut health on eudaemonia, how gut function influences behavior in response to a diverse microbiome is not entirely understood (Stoffolano, 2019). Understanding the connections between the brain and gastrointestinal tract in *Drosophila* can help identify the gap in knowledge and the need for improvement in care regimens.

With this implication of gut health on overall wellness, the long-term impacts of variations to the gastrointestinal system should be further studied (Azim & Kashyap, 2016). Identified variables that can impact gut health include physiological form, diet, activity levels, and pathologies of the gastrointestinal system.

Drosophila melanogaster, the fruit fly, is a key model organism for studying biological processes, including those that regulate feeding and sleep (Apidianakis & Rahme, 2011; Sadaqat, 2021). Fruit flies provide a reliable system to study neurological circuits and behavioral changes (Miguel-Aliaga et al., 2018). The morphology and function of the human and fruit fly digestive systems are similar. Whereas the *Drosophila* crop stores food and manages digestion, similar to the human stomach (Figure 1), the foregut is the first part exposed to the materials the fly ingests; it can process nutrients and subdue pathogens first entering the body (Zhu et al., 2024). The cardia (or proventriculus) works as a valve to permit food to pass through to the crop for storage and further movement through the gut. The anterior midgut maintains enzymes to begin the breakdown of food. The midgut is the site of copper and iron cell proliferation to secrete acid for digestion. The posterior midgut provides a site for further absorption, allowing waste to pass along to the Malpighian tubes, which work in conjunction with waste excretion to flush out products such as urine or toxins. (Miguel-Aliaga et al., 2018). These organs work together to orchestrate consumption, digestion, energy levels, and overall well-being.

Previous studies of the crop demonstrated the role of the organ in organisms in the same order as *Drosophila* (Diptera), such as blowflies and mosquitoes (Calkins et al., 2017). Cropectomies have been performed in Diptera organisms, but studies were performed in vitro as opposed to in vivo (Gelperin, 1966). These projects have focused on the crop as an expandable part of their anterior digestive system, which stores food and regulates the rate of nutrient release into the hemolymph, making it helpful for energy level control. The crop is vital to peristalsis and the proper and efficient digestion of food, as the rate of digestion can be controlled by the crop. When the fly is satiated, the crop is distended. In blowflies, the crop utilizes six pumps, five sphincters, and the osmotic pressure

Figure 1
Schematic of Human and Fly Digestive Systems



Notes. The human and *Drosophila* digestive systems share many similarities, as seen with the crop and stomach (teal). Reprinted from Sadaqat et al. (2021), Figure 1, *Comparison between human and Drosophila gut*, under the Creative Commons Attribution 3.0 License.

of the surrounding hemolymph to push food to the posterior gut (Stoffolano and Haselton, 2013). This feedback loop allows the proper rate of digestion to occur, depending on the energy needed and the amount of food ingested.

A cropectomy, or the surgical removal of the crop through an abdominal puncture in *Drosophila melanogaster*, may model sleeve gastrectomies in humans. Such procedures are mainly done for patients suffering from diabetes mellitus, stomach cancer, and obesity, which are prevalent chronic diseases globally, especially in the United States (Mayo Clinic, 2024). Vertical sleeve gastrectomies have been shown to improve metabolic processes for weight loss or removing sick tissue in the body, which can improve the quality of

life and other psychosomatic aspects such as self-esteem. Refining a treatment and understanding the effects of this procedure can allow further knowledge of the risks and advantages of sleeve gastrectomies. However, gut health and surgeries such as a sleeve gastrectomy can be difficult and unethical to study in humans. By performing these surgeries on *D. melanogaster,* we can scale the assays to study the effects on physiology, behavior, and survival rates with possible genetic variants. Improving the protocol and understanding the post-operative effects can improve the experience for patients recovering from the procedure and those who may benefit from a sleeve gastrectomy.

Due to the role that the crop plays in *D. melanogaster,* we hypothesize that the loss of this organ will impact feeding behaviors and sleeping patterns. Feeding and sleeping are interconnected behaviors influenced by neural and hormonal pathways (Kim et al., 2015). Therefore, disruptions in feeding, such as those possibly caused by a cropectomy, may alter sleep patterns. This research provides ways to study metabolic and sleep regulation, with implications for understanding and managing metabolic and sleep disorders in broader biological contexts.

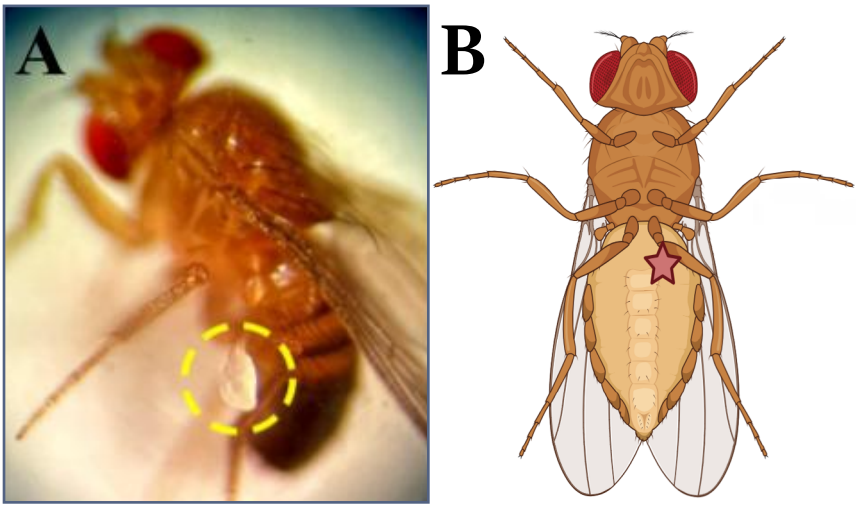
Results and Discussion

Development of the Cropectomy Procedure. Previously, a surgical cropectomy procedure was used to test whether the crop plays a role in bacterial colonization of the foregut (Dodge et al., 2023). We adapted this procedure in Dahomey and Canton-S genotypes in both sexes for our laboratory to determine the consequences of crop removal on physiology and behavior in wild-type flies.

The technique requires two pairs of forceps: a sharper pair in the right (or dominant hand) and the other in the left hand. The flies are sexed and transferred to new food vials no less than 24 hours before the procedure. The flies are anesthetized with CO_2 for approximately 30 seconds before the procedures begin. The left hand orients the fly, while the right pinches the abdominal cuticle (pink star, Figure 2b) and tears a small hole such that the hemolymph does not pour out from the puncture (Peraza, 2024). Then, the forceps are closed, enter the abdominal cavity via the hole, and open slightly to grab the crop (Figure 2d). Once the crop is identified and secured, it is pulled out of the body either with or without the crop duct. (Figure 2a, 2c). Although the procedure is performed somewhat blindly, with practice, the crop is excised most of the time.

The "mock" or sham surgery consists of the hole being made with forceps, but no further action is pursued after the initial insult. There is a ratio to the surgery order; approximately three cropectomies are performed for every one mock surgery. When more of the digestive system, such as the midgut, is pulled out during the procedure, the flies are set aside and not used in the subsequent assays. Sterilization

Figure 2a & 2b
Crop Morphology and Location

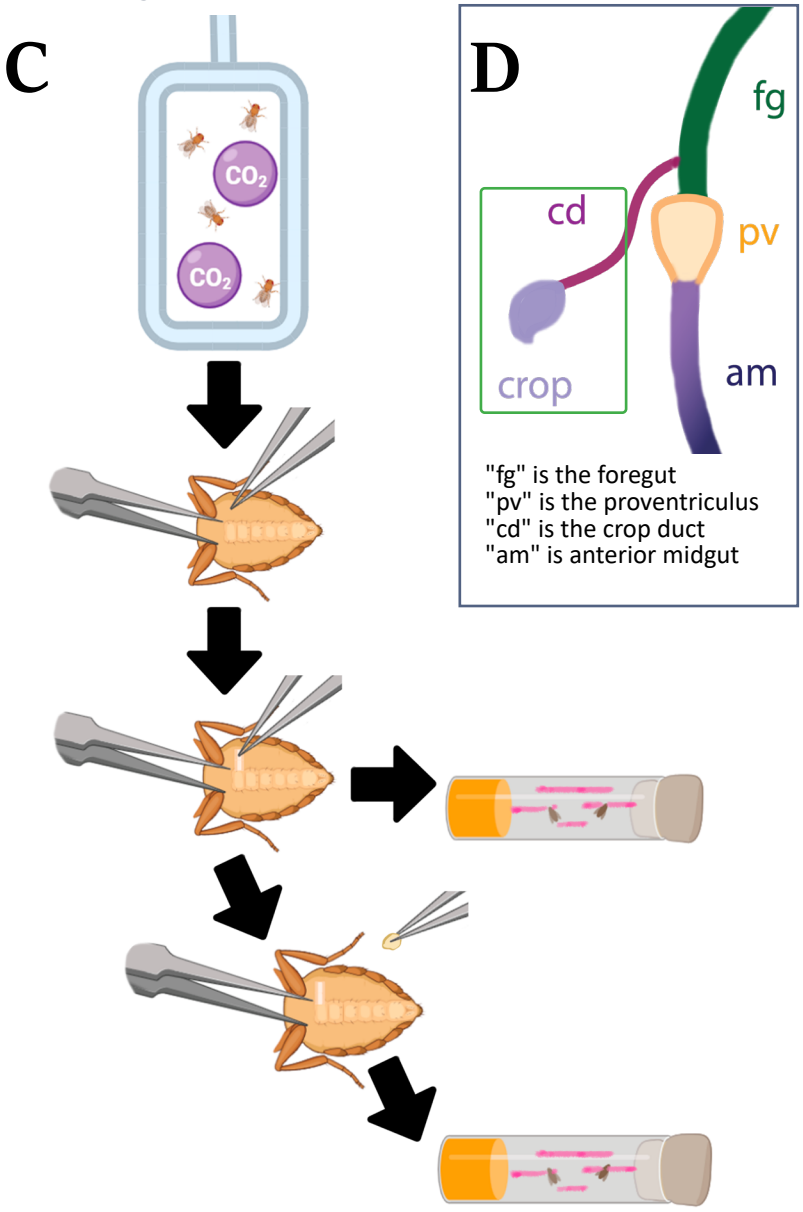


Notes. a) An image of the crop outside of the abdominal cavity is circled in yellow. b) The pink star denotes where in the abdomen the forceps will pinch and pull the crop out.

is described in the Methods section. The flies are then sorted into their respective labeled warmed vials, making sure not to leave them on the CO_2 for too long, then left to wake up while the vials are horizontal to mitigate the risk of them sticking to the food. After the flies have awoken, the vials are placed upright to recover for at least 24–48 hours for subsequent experiments. Flies that have died in recovery are discarded during vial transfers.

The procedure was optimized in the lab with a different area of entry—the original video showcased a more lateral hole on the abdominal cuticle, where, with months of trial-and-error and practice, a more medial hole had better rates of crop removal without further damage to the gastrointestinal tract. A smaller hole and quicker procedure time were achieved with practice, which allows for better survival by minimizing time on CO_2 and less injury to the body. This highlights a protocol for a homolog to human "sleeve gastrectomies," while encouraging further research on the gut-brain axis and gut function. The *Drosophila* crop is the region of interest for this study to focus on, both the sleeve gastrectomy protocol and possible treatments for pathologies of gut function due to its similarities to the human stomach.

Figure 2c & 2d
Crop Morphology and Location



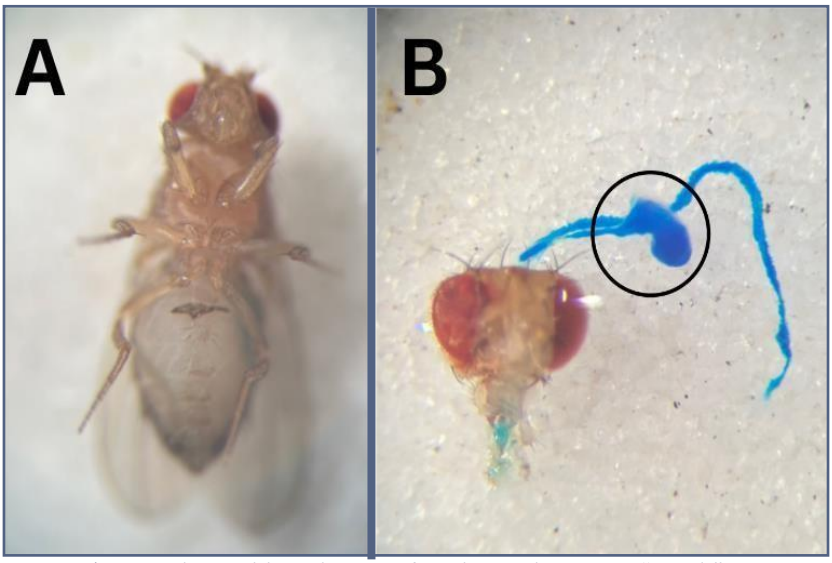
Notes. c) After anesthesia under CO_2, *Drosophila* are flipped on their dorsal side to pierce the upper abdominal cuticle. After the sham or cropectomy surgery, they are sorted into labeled vials. d) Graphic of the target area, including the diverticulated crop and the crop duct. Figures 2b, 2c & 2d created by author.

The Gut Remains Intact in Recovered Flies. In all age groups between both sexes of Dahomey and Canton-S flies, substantial scarring of the crop duct tissue has been identified internally and externally using imaging (Figures 3, 4). In both figures, external scarring on the abdominal cuticle was observed as early as 1-day post-surgery (Figure 3A).

The "smurf" assay employs a nontoxic blue dye, which is added to the diet to track the passage of food throughout the digestive system (Martins et al., 2018). The crop can be robustly visualized with the blue dye >24 hours after surgery (Figure 3b). The smurf assay, named for the fly's blue appearance if there is leakage, also revealed proper gut integrity when the crop is removed. No "smurf" phenotypes were observed 2 and 7 days post-surgery in both cropectomized and mock surgery groups.

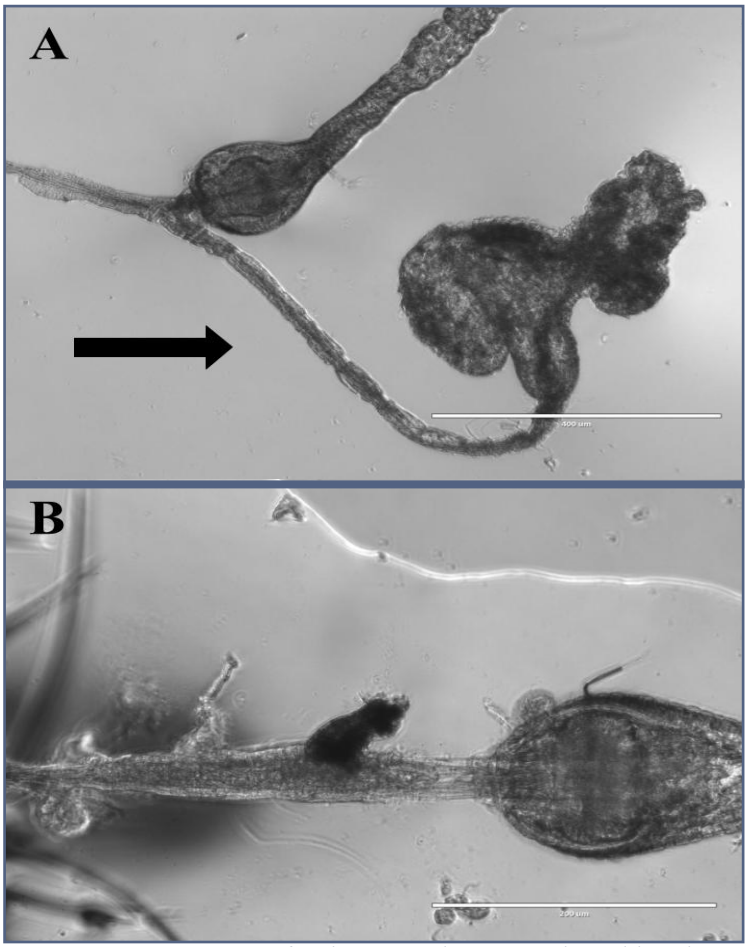
The duct that connects the crop organ to the anterior midgut (Figure 4a–b) created a prominent scar where the crop was torn off. The amount of scarring, either 1 or 4–5 days after the procedure, remains consistent for at least 4–5 days after the procedure. The scarring may be preventing leakage. Gastrointestinal perforations and "leaky gut syndrome" can impact the body negatively, as nutrients and food particles are loose in the individual. This trauma to the gut can lead to the inability to store nutrients, sepsis, peritonitis, abdominal pain, and other symptoms or conditions (Hafner et al., 2023).

Figure 3a & 3b
External Scarring and Dyed Digestive System



Notes. a) 5–7 days old Dahomey female, 1-day post "mock" surgery, presenting with external scarring at the location of the surgery with a medial tear. b) Blue dye showing the digestive system with the crop, circled in black, taken 1-day post "mock" surgery.

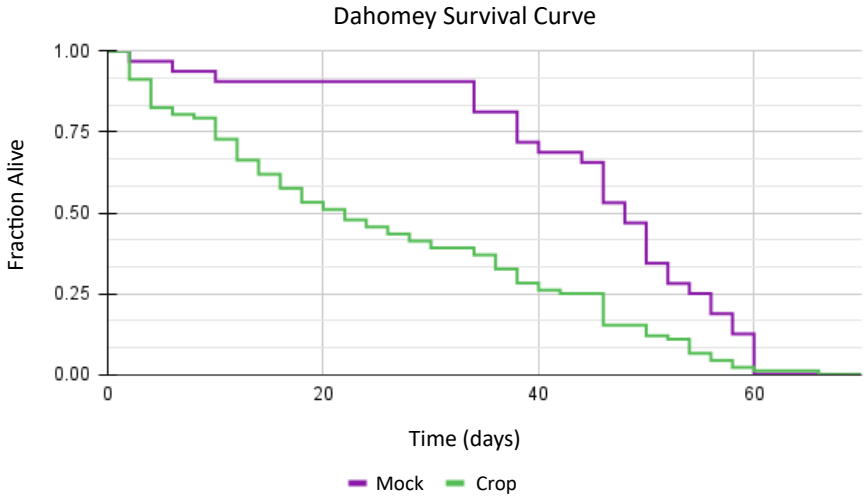
Figure 4a & 4b
Scarring and Organ Visualization



Notes. Representative images of Dahomey males, 10–12 days old, 1-day post-surgery. a) Mock surgery with crop and crop duct (denoted by arrow) still intact and attached. b) Cropectomized fly showing melanization and scarring of crop duct. Scale for 4a = 400µm. Scale for 4b = 200µm.

Crop Removal Shortens Fly Lifespan. Over the next 24 hours after surgery, approximately 80% of mock-treated flies survive, while survival of the cropectomized group is approximately 50% (from trials with a sample size, *n*, of >175 flies). For flies that survive treatments, maximum survival appears unaffected. Cropless Dahomey males show a similar maximum lifespan as mock-treated flies (Figure 5). Despite the similar maximum lifespan, cropectomized flies showed a decline 24 hours post-operatively in recovery, with a moderately shortened overall survival.

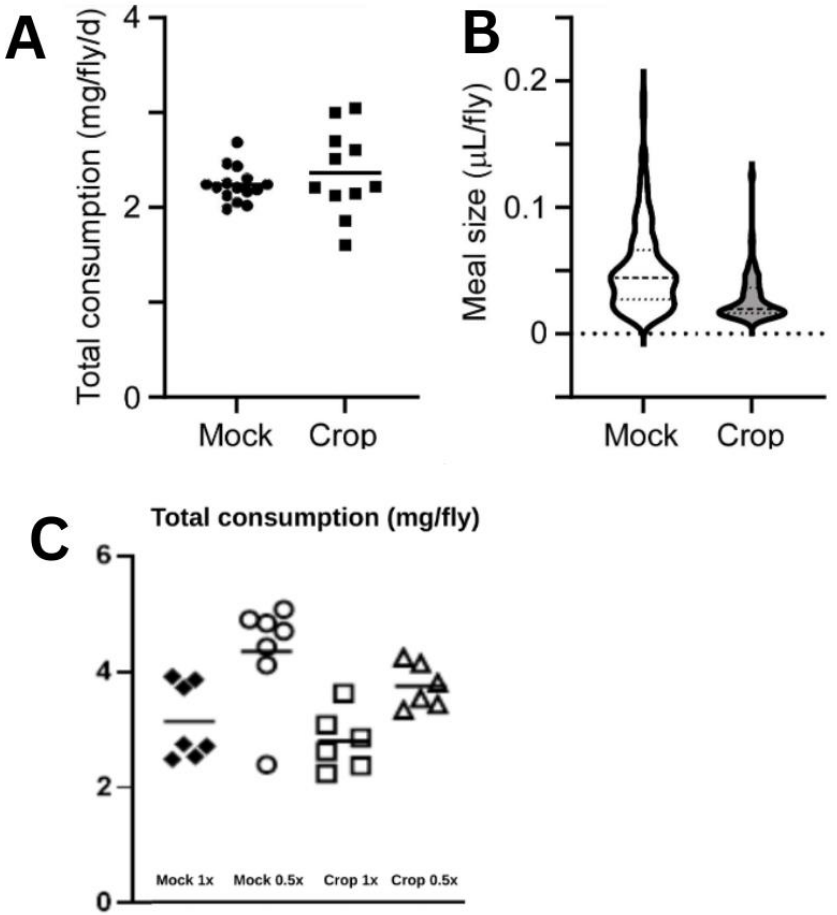
Figure 5
Survival Analysis of Dahomey Males



Notes. Cropectomies or mock surgeries were performed on Dahomey males aged 3–5 days old. Survival was then tracked for the remainder of life. The fraction of flies alive at each time point is plotted, with deaths within 48 hours post-surgery censored from the analysis. Flies survive up to 70 days in the cropectomized group (green). Mock, n = 32. Cropectomized, n = 92. Mantel-Cox test with significant differences between the treatment groups; Gehan-Breslow-Wilcoxon test with a p = .0225.

Crop Removal Alters Prandial Behavior Without Affecting Total Consumption. We next used the ARC (Murphy et al., 2016; Murphy et al., 2017) to quantify the effects of crop removal on feeding behavior. Although total daily consumption was unchanged, cropless flies had a decreased average meal size (Figure 6). Thus, cropectomized flies show a greater frequency of meal intake to achieve a similar total consumption to that of control flies. Consistent with the idea that cropectomized flies can still modify their feeding to maintain caloric intake targets, both control and cropless animals are capable of compensatory feeding on a yeast/sugar diet, where total food dilution induces a significant increase in total consumption (Figure 6c).

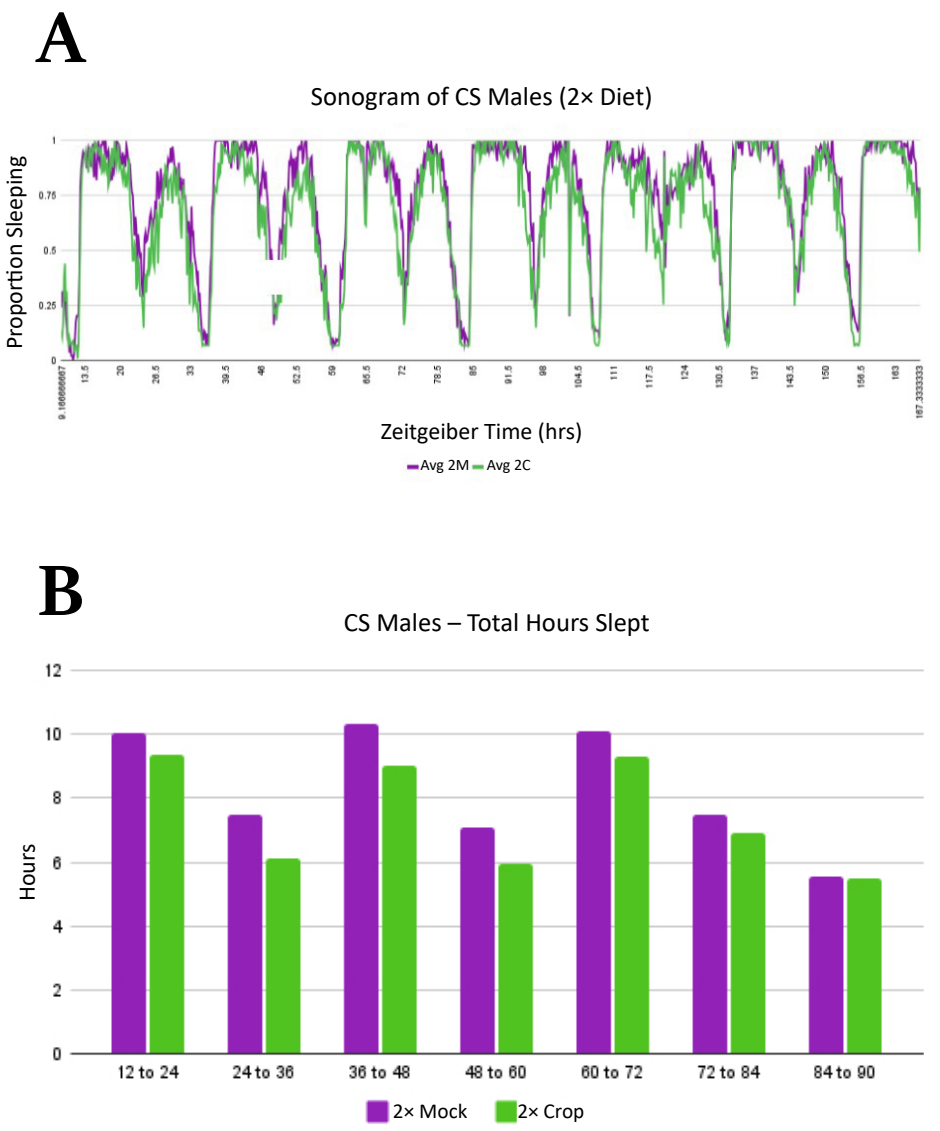
Figure 6
Cropless Flies Eat Smaller Meals



Notes. a) ARC assay was done 7 days status-post cropectomy to study postprandial sleep and meal size with CS males, 4–6 days old, showing similar total consumption. b) Cropectomized flies eat smaller meals compared to the mock surgery group. c) Dahomey male flies, 9–11 days old, were fed 32P-labeled diets (0.5× and 1×) to show that the flies attempted to compensate for the changing diets. The sample size was n = 60 flies.

Cropless Flies Show Normal Circadian Rhythms, But Overall Reduced Sleep. The results also showed changes in sleep with assays such as the Drosophila Activity Monitor (DAM) assay. The flies maintained a regular circadian rhythm that followed the 12/12 light/dark cycle (Figure 7A). However, the cropectomized flies slept less on average than the control group, where sleep is denoted by 5 minutes of quiescence.

Figure 7
Cropless Flies Show Abnormal Sleeping Behaviors



Notes. a) The sonogram shows regular circadian rhythms for both groups, with reduced hours of sleep shown by the cropectomized flies (green). b) After running the DAM for 7 days, the 2× diets between mock and cropectomized Dahomey male flies show a difference in the amount of sleep. The sample size was n = 44 mock, n = 46 cropectomized. Average hours of sleep for mock: 465.35 +/- 48.26 hrs. Average hours of sleep for cropectomized: 439.01 +/- 45.87 hrs.

Difficulties and Impediments with the Procedure Protocol. Impediments such as surgery stamina, reproducibility between surgeries, and the survival rate were encountered for this project. The surgery, on average, takes approximately 1 minute/fly for a skilled surgeon. With preparation time, sterilizing the forceps between every 4–5 surgeries, and recesses, a large sample size is necessary, and thus time-consuming. The first and last vials post-surgery seemed to have higher proportions of dead flies, which led to having larger initial amounts of flies to account for this loss, thus increasing the time spent at the microscope. Out of every 200 flies, approximately 15 flies will have their entire gut pulled out of the abdomen by accident, which required an increase in flies that were sexed and set aside beforehand. Due to the nature of the project, the reproducibility from each surgery to the next slightly varies; sometimes, the crop is pulled out, and the crop duct is still intact, or the duct is severed. The puncture location is slightly different in each fly, some more medial and some more lateral. These factors may contribute to the survival rate differences and the drastic drop in survival 24 hours after the procedure.

Due to the time commitment of each surgery and the failed surgeries in the duration of a sitting for consistent results, the sample sizes cannot be increased substantially without additional personnel.

Conclusion

The cropectomy procedure highlighted a consistent circadian rhythm, slightly reduced sleep, and overall shortened lifespan. Cropless flies consumed smaller meals more frequently and exhibited normal compensatory feeding behavior.

After refining this surgery protocol with a more than 50% survival rate and with baseline metabolic assays, the expansion of this project can be done with more surgeries on female flies. As previously mentioned, female flies were not used for the larger-scale trials due to their anatomy. It becomes more difficult to remove the crop, as the abdomen also includes ovaries and eggs near the crop. Further work may provide more insight or confirm a general effect of cropectomies on both sexes of flies (Figure 8).

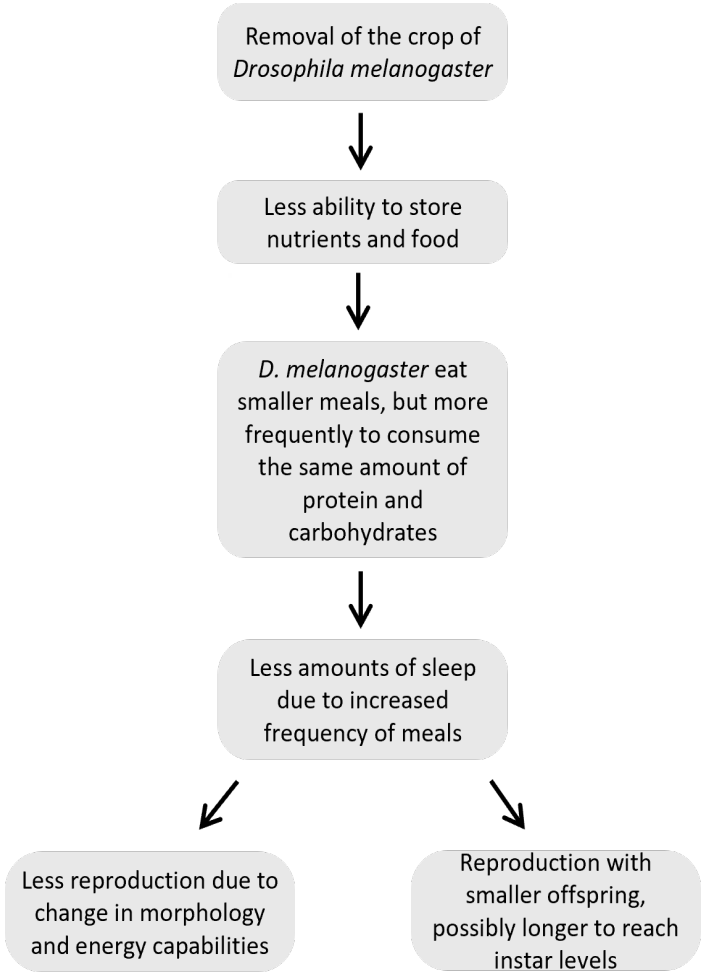
Elucidating the mechanisms, whether neural or hormonal, of food passage through the digestive system without the crop may show an augmented digestion rate, which can further the question of how the fly functions without the crop.

Hyperphagic flies that are genetically modified can be used in future studies to see how a drastic increase in meal size impacts the gastrointestinal system, with the loss of the storage organ, scarred lining of the tract, and change in neuronal projections to the gut. Using hyperphagic flies, a large increase in food is seen, permitting overeating, even when the crop is distended. The signaling back to the CNS is silenced, and communication to stop eating is unavailable.

Using tetanus toxin to silence genes in charge of eating, digestion, and organ function can expand the study into the role of the crop.

In humans, the post-operative instructions for sleeve gastrectomies include a liquid diet that aids in acclimation to the new anatomy and avoids irritants to the intestinal lining. An experiment in changing the diet from solid food to a softer compound may improve survival rates and provide more comparisons to humans in their postoperative state.

Figure 8
Changes to Reproduction Hypotheses



Note. The changes to feeding behaviors and meal sizes may impact reproduction, such as the ability to reproduce with the change in anatomy or the ability to store excess nutrients.

These findings support our hypothesis that the crop is vital for homeostatic behavior, such as feeding and sleeping. As stated previously, there are implications for improvement to enteric system procedures on humans with further research into this procedure using various assays, genetic manipulations, and arrays of approaches to the question of how cropectomies affect *Drosophila melanogaster*.

Materials and Methods

Fly Husbandry. Flies were maintained on a standard cornmeal, sucrose-yeast medium (3.1% active dry yeast, 0.7% agar, 5.8% cornmeal, 1.2% sucrose, 1% propionic acid, and 0.22% Tegosept in a light, temperature, and humidity-controlled incubator (12-/12-h light/dark cycle, 25˚C, 60% relative humidity), unless otherwise specified. Flies were collected at 2–4 days old for surgeries. Flies were transferred to fresh vials 24 hours before surgery and transferred to new vials after the procedure to ensure continuous access to fresh food was readily available to maintain a full crop.

Cropectomy. The complete procedure is described in the Results section, but the left hand holds down the fly on its dorsal side, while the right hand (with the finer forceps) tears a small incision, about 2 centimeters long. After this move, a second set of forceps goes into the hole to find the crop, which is a clear sac organ. The control group, named "mock", had the hole made, but nothing was pulled out. All the flies are then put into vials warmed to room temperature and then kept horizontal for several minutes before being put vertically.

Sterilization. Approximately every 4–5 surgeries, each forcep is wiped on a KimWipe soaked in a 70% ethanol mixture. However, this process is done immediately after a failed extraction of the crop, i.e., pulling out the gut entirely.

Fly Stocks. Flies are from Bloomington Drosophila Stock Center and were maintained by transferring to new food vials or bottles, made by the Herbert Wertheim UF Scripps Institute for Biomedical Innovation & Technology kitchen, every 1–3 days.

Imaging. All imaging was taken on the EVOS Digital Inverted microscope at 10–12-days old, 1-day post-surgery.

Drosophila Activity Monitor (DAM). Clean tubes and food capsules are prepared by soaking overnight in soapy water and boiling afterwards. Serial dilutions of 2×, 1×, and 0.5× food are performed to produce the three distinct diets for the assay. After marking which tubes and monitors have which conditions (mock versus crop), the monitors are hooked into an incubator with a 12/12 light/dark cycle for subsequent recording of behavior and analysis by Rtivity software. The tubes are bisected by an infrared light beam, which quantifies the number of times each fly in each chamber crosses the light to access food or otherwise be active. These beam crosses are recorded every minute and put into 5-minute moving average bins. Sleep is quantified by 5 minutes without activity. Analysis of results was performed in Excel.

Activity Recording CAFE (ARC). Automated capillary feeder assays were performed as described using the ARC apparatus to gauge consumption and feeding behaviors in the incubator and liquid food for the fly (Murphy et al., 2016; Murphy et al., 2017). Each ARC monitor had one fly in each chamber with an agar mixture of about 300 µl for a source of water at the bottom. The capillaries were aligned using lined cardstock, small plastic plugs were placed to hold the capillaries in place, and they were adhered to the chamber. Recording the position of each fly allowed software to graph the coordinates of the food as a function of time.

The software used to analyze the data is Noah15.12, which uses Python for data interpretation (Murphy et al., 2016; Murphy et al., 2017).

Lifespan Study. Flies kept in 25 ˚C incubators began at 2–4 days old and were transferred to new food in 25 ˚C vials every 2 days. Deaths were counted with transfers, with the tray being inserted into the incubator the opposite way each time to negate any adverse effects of the same exposure to light. Precautions were taken to ensure the trays weren't too close to the incubator lights.

Smurf Assay. For the assay, 1–2 drops of food dye were added to cover the surface of the short food vials, and left to dry for at least 24 hours before transferring to these vials. Blue powder dye was added to food for a robust coloring in later trials. Directly after surgery, flies were placed on the blue food vials and left for 48 hours. Every other day, the flies were placed on new food vials. On days 2 and 6 post-surgery, they were placed on the same blue food vials and scored 24 hours after the blue food transfer.

Acknowledgement

I would like to thank Dr. Ludington and Dr. Chenhui for allowing me to begin learning how to perform a cropectomy, as the introduction to the technique was modeled after a video shared from their lab. Thank you so much for answering my questions and for providing a foundation for this project.

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Unwilling Consent or Ravishment? Sexual Violence in Late Seventeenth-Century London

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Abstract

Between 1674 and 1700, there were 33 cases involving rape, also referred to as ravishment, processed at the Old Bailey in London. Over half of the trials involved girls between 5–10 years of age, and the rate of convictions in the trials with younger victims far exceeded the rate for teens and young women. This article shows that while the age of the victim is the main contributing factor, the economic ability to hire midwives or surgeons, the social status of the parties involved, as well as the politicized structure of the courts during Charles II's reign, also influenced the conviction rate of those indicted for rape or ravishment.

Introduction

In the years between 1674 and 1700, there were 33 cases involving rape, also referred to as ravishment, processed at the Old Bailey in London. At first glance, these numbers do not denote anything unusual or out of place. However, upon closer inspection, one would see that more than half of the cases involved girls between 5–10 years of age, and that the rate of convictions in the trials with younger victims far exceeds the rate for teens and young women. It is important to note that in the single instance where a defendant was found guilty of a lesser charge against an "older" female, the girl involved was 11 years of age. (see Table 1). The records indicate a significant difference in how rape perpetrated against minors was handled versus girls who were considered of age. This paper will look at the various causes of this phenomenon by taking into consideration the laws concerning rape and how they came into being, what defined consent, what evidence was needed to prove the allegation of rape, the underlying structure of patriarchy in society, the backdrop of political machinations, and, lastly, take a closer look at the trials to determine what might have led to the prevalence of convictions in the cases of girls under the age of 10 versus the very different results in the cases of the girls over the age of consent. While previous researchers have generally delved into these concepts, none have addressed the discrepancy in outcomes shown by these 33 records preserved in the Old Bailey archives from the last quarter of the seventeenth century.

Modern historians have presented several reasons to explain why so many men accused of rape in early modern England were acquitted. The most prevalent theory is that the courts were protecting the patriarchy. Barbara Baines cites many legal precedents concerning ravishment and its punishment in her work (1998). Yet, her premise portrays a pre-modern English society that did not understand the concept of consent. The flaw in her argument is that contemporary society did, indeed, have its own views on what constituted consent—they just differed from the modern definition. The contemporary legal jurisprudence shows how society's views on rape and consent changed through the preceding centuries and were still evolving in the late seventeenth century. Other historians, including Blessin Adams, perpetuate the idea of a male-centric society that only serves to oppress females (2023). She asserts that since men controlled both law and its implementation of it, male bias created a society in which women were kept subservient to men and thus vulnerable to sexual abuse.

Table 1
Indictments and Results of Rape or Ravishment Trials at the Old Bailey, 1674–1700

	10 years and younger	11 years and older
Total number of indictments	18	15
Number of acquittals	5	12
Number of "Guilty" verdicts, rape/ravishment	9	2
Number of "Guilty" verdicts, assault/trespass	4	1

Note. Data were compiled from Old Bailey Proceedings Online (www.oldbaileyonline.org, version 9.0). Trials in which age is not disclosed are counted as 11 years and older.

On the other hand, Garthine Walker, who has written extensively on sexual relations during the late seventeenth and early eighteenth centuries, debunks the simplistic idea that patriarchy is the sole cause of seemingly apathetic attitudes of the courts. She takes a new look at how rape was viewed by contemporary society, including what even constituted rape within the constraints of contemporary common law and how the law's interpretation reflected society's views (Walker, 2013a; Walker, 2013b). In other words, she argues that it is society's ever-changing stance on the concept of consent defines that the difference between what is considered rape and what is not. Yet, this small sampling of trial recordings from the Old Bailey during

the last quarter of the seventeenth century shows that in addition to the age of the victim, the economic ability to hire midwives or surgeons, the socio-standing of the parties involved, as well as the politicized structure of the courts during Charles II's reign, influenced the conviction rate of those indicted for rape or ravishment. The law concerning rape in the early modern period attested to the severe nature of the crime, and it was society's view on the concept of consent that created the leeway in how the law was administered.

Evolution of Consent and Ravishment in English Law

English law concerning rape and consent can be traced back to King Adelstan's reign during the Anglo-Saxon era. During medieval times, rape was considered a property dispute between men; the women themselves, even though they were the victims, were not the focus of the charges. The loss of property value, mainly the loss of virginity, was perceived as the central issue of the crime. In other words, the crime against a woman became a matter between men (Baines, 1998; *The lavves resolutions*, 1632). This meant that even though rape was considered a consequential crime and often a violent one, the female's consent was irrelevant; it could only be given by the father or husband. By the late seventeenth century, the idea of rape and consent had evolved; although the crime was still considered a capital offense, women were able to sue their attacker. However, the rules regarding the evidence pertaining to rape were stringent and almost impossible for victims to satisfy. To achieve a conviction of ravishment, the evidence submitted to the court needed to prove penetration and, for girls over the age of 10, lack of consent. As part of the proof of lack of consent, the law required the victim to present herself immediately after being raped, usually to a surgeon or midwife to preserve evidence, including torn clothing and bodily injury (*The lavves resolutions*, 1632). This was not always a feasible option, as young women might not know what to do after an attack, women employed as servants would not be allowed to leave the estate to accuse their master, and these victims would not have the means to pay for the services of a surgeon or midwife. Thus, men could defend themselves by claiming that the act was consensual, as the burden of proof fell on the victim (Adams, 2023; Walker, 2013b). While the law appeared to take rape and its punishment seriously, often the obstacles to proving lack of consent rendered its implementation to exact justice a failure for many women.

The passage of a 1575/6 statute that prohibited intercourse with girls under 10 years of age meant that young girls did not have the onus of proving their lack of consent (Luder et al., 1965b, p. 1). While this removed a considerable obstacle to prosecuting their attackers, their age precluded them from bearing witness at the trial. It thus made their cases reliant on medical examinations and witnesses with first-

hand accounts (Walker, 2013b). The only exceptions were when the child was deemed mature enough to understand the gravity of swearing an oath and could demonstrate knowledge of right from wrong, such as in the case of eight-year-old Elizabeth Hopkins and her witness, a nine-year-old girl, who were both able to give sworn testimony against Elizabeth's ravisher, Stephen Arrowsmith (Old Bailey, 1678e; Walker, 2013b). Additionally, girls aged 10 to 14 were also considered too young to give testimony, being below the age of discretion yet old enough to need to prove a lack of consent. The ambiguity comes from an earlier statute during Henry VI's reign claiming that females can consent to marriage at age 12 and at 14 "to bee *hors du guard*" [free from wardship] (*The lavves resolutions*, 1632). Additionally, adult witnesses for the prosecution could not convey testimony given to them by the victim; they could only testify to what they knew or saw firsthand (Walker, 2013b). Despite the difficulties for young girls to prove allegations of rape, the courts, at least the Old Bailey, tended towards an attitude of presumed guilt on the accused's part in that when there was insufficient evidence for a rape or ravishment verdict, a lesser misdemeanor charge of assault or trespass was sought (see Table 1).

Early modern legal historians attempted to clarify and update the ancient laws. In his manual for Justices of the Peace (JPs), William Lambard (1610), a member of parliament who also had been a JP, discussed the concepts of ravishment and consent put forth by The Statute of Westminster of 1285. He felt that the phrase 'Rauisheth with force' was unnecessarily redundant and over-explaining, pointing out that the word rape derives from the Latin *rapere*, which translates to take by force. However, the unnamed author of *The lavves resolutions of womens rights*, originally published in 1632, has a different opinion. He writes that "*STamford* leaueth it doubtfull, and to be learned what the difference is betwixt rauishment with force, and without force. M. *Lambard* thinketh the word to be but declaratorie, signifying all rauishment to bée forcible," and that rape should be split into two categories "because it maketh one more odious than the other." He disagrees with Lambert's assertion that the phrase "Rauishment with force" is declaratory. He felt there should be a distinction separating "rauisheth with force, though the woman forgiue h••, and cons••• to him," from the brutes that used excessive violence (*The lavves resolutions*, 1632). These arguments show that in the first half of the seventeenth century, men in early modern England strove to understand the concepts of rape and were beginning to look at what constitutes consent with a fresh perspective.

Scholars are often unclear about where—for contemporaries—the ordinary fellow ended, and "the monstrous brute began" (Walker, 2013a). Many men who were accused of rape were acquitted by insisting that any sexual relations had been consensual. This defense not only aligned with societal views of the act but also deflected

the stigma solely onto the victim, who, accordingly, was to remain chaste and pure. Alternatively, men whose assaults fell outside of what was considered a fulfillment of normal sexual appetites, such as against young girls (under 10) and older women, and with excessive violence and excessive partners, were considered monsters (Walker, 2013a). Thus, society was able to overlook some cases where men sated their sexual desires on a less-than-willing partner.

Convention, therefore, was molded by male patriarchy where certain instances of rape could be a normality of life, because male sexual needs were considered unavoidable. A societal attitude was created that allowed men to be controlled by their urges and lust, while at the same time, it expected females to remain pious and chaste. Blessin Adams (2023) examines cases where young female servants are ravished by their masters. In the case of Elizabeth Balleans, a young girl whose age was only described as "too old to live at home, yet too young to marry," Adams describes a common situation for young women (2023). In addition to Elizabeth's story, Adams relates several similar instances where maids became the victims of their employer's lust (2023). The men who perpetrated the abuse faced little to no consequences, yet the victims bear the stigma of shame and the judgment of their neighbors. Adams reasons this is due to limited resources, the girls' dire situations, and a sense of naivety due to their young age. This set the stage to normalize non-consensual intercourse as long as it was not excessively violent (Adams, 2023; Walker, 2013a).

Folktales and fairy tales were used to reinforce society's views on sexual relations. These stories were meant to teach children about society and their place in it. "Little Red Riding Hood", featured in Charles Perrault's *Histories, or tales of past times...with morals* is no different. Although first published in France in 1697, the tale, based on popular European folklore, was adapted to reflect society's views and that "unlike the old fables devised by the Ancients, they contain useful morals" (da Silva, 2016). It is a cautionary tale for young girls not only about the dangers of men but also about how they should comport themselves while out in society. The story's moral is that men are predatory, and girls must safeguard their virtue. The scene introducing the tale also depicts the wolf as having a male appetite as he looks hungrily upon Red Riding Hood in the bed. The story proceeds to portray Red undressing and willingly, albeit unknowingly, climbing into bed with the wolf to be devoured—to satiate his sexual desire (*Histories*, 1741). Thus, girls and women relied heavily on how well they protected themselves from the appetites of men. The irony was especially cruel to serving-class women, who were often forced to sleep on the floor in their master's bedchamber, making them easy prey (Adams, 2023).

After the restoration of Charles II as king, the country was still in upheaval, and parliament, overcompensating for the previous decades, gave him some of the prerogative powers he desired,

such as replacing judges and JPs with those who were loyal to the crown and wanted to reestablish the Great Chain of Being (Bucholz & Newton, 2009). In addition, juries were made up of male landowners (Briggs et al., 1996). As a result, court proceedings during this period sometimes catered to the wealthier party or were solely based on the character and reputation of both the accused and the accuser. This was especially true when little evidence was presented other than the word of each party. The best the justices could do when faced with a defendant who was deemed guilty, but the evidence for conviction of rape was lacking, was to reduce the charge to assault or attempted rape, a misdemeanor with more lenient punishment. Even so, this seemed to be a tactic used only in cases pertaining to underage girls.

Trial Records from the Old Bailey

Within the Old Bailey cases that concerned minor girls, two of the nine trials that elicited a guilty verdict were because the prisoner confessed to the crime. In the other seven trials, the evidence presented by midwives and chirurgions (surgeons) all pointed to the fact that these children had been badly used. William Harding was accused of luring young Sarah Southy down to a cellar with the promise of treats, where he had carnal knowledge of her. Her mother brought in chirurgions as witnesses who verified that Sarah was "so abused [in] her secret parts, that the distressed wretch remained in a most miserable condition" (Old Bailey, 1680). In addition to the victim's physical evidence, Harding's character was judged to be lacking as "a debauched fellow," and he showed signs of venereal disease. While the surgeon's testimony could have been sufficient, the additional circumstantial evidence assured a guilty verdict.

Similar details appear in the trials of George Hutton and John Raven, both of whom were horse-keepers. Hutton was accused of abusing "Elizabeth Marriot, a Virgin, under the Age of Ten Years," whose mother was the owner of the horses (Old Bailey, 1690). John Raven was also charged with ravishing a child under the age of 10 in a horse stall (Old Bailey, 1686b). Both mothers were also able to afford the services of midwives and chirurgeons. The guilty verdicts for ravishment committed against underage girls, while a little easier to prove because they only relied on the physical evidence of forceful penetration, attested to by a midwife or chirigeon, still only occurred in half of the cases. In these cases, it appears that age was the deciding factor, as the victims did not have to also prove a lack of consent. Yet, the socio-economic status of the mothers who could afford the services of a surgeon may have also influenced the trial's outcome. All three previously mentioned trials conveyed an employer/employee relationship, and class bias could have also held sway.

However, in contrast, only two cases for prisoners involving older girls received a guilty verdict. In 1689, Elizabeth Deer, 16, was enticed to go around with John Bargeer and Abigail Bargeer, his wife. John and Abigail took Elizabeth to a pub and "there made her Lie all Night with them in one Bed, and on the Morrow kept her all Day and all the next Night in another place" (Old Bailey, 1689a). Elizabeth's only evidence was her sworn testimony. The Bargeers, however, gave conflicting testimonies as part of their defense. John Bargeer was found guilty of rape, and Abigail Bargeer was found guilty of abetment. In the other case, 15-year-old Mary Petts was accosted by Richard Smith on the highway, robbed, and ravished in 1694. Upon reaching her home, she presented herself to her mother, who swore that her daughter's virginity had been taken. Even though Smith produced "gentlemen" to attest his character, "the matter was so foul at the bottom, and so ill resented that it would prove a dangerous Consequence to suffer such evil doings to go unpunished" (Old Bailey, 1694a). Both of these trials involved girls who, while considered adults in the eyes of the law, were still young and were referred to as virgins. Their age allowed their testimony to be heard, and in both cases, it persuaded the jury to come back with guilty verdicts.

It appears that the court was more likely to pursue a misdemeanor charge of assault or trespass against prisoners accused of violating the 1576 statute. During the last quarter of the seventeenth century, this occurred four times (Old Bailey, 1676; Old Bailey, 1678b; Old Bailey, 1678e, Old Bailey, 1689b). In these cases, the midwives could not verify that penetration had occurred, even if the child had contracted a venereal disease, and thus were not able to provide the crucial evidence needed to prove that any intercourse had transpired. It is also of note that the only case that did not fit this category was the 1675 case, in which the victim was 11 and thus fell into the murky area of being considered too young to swear an oath but old enough to consent to sexual acts. Here, the child's aunt testified that she heard the child cry out and found Edward Coker abusing the child; however, since the room was in darkness, she was not able to swear that she had witnessed penetration, only that the child had been ill-used. Since the law restrained the Court, Coker was charged with assault, a misdemeanor, so that he would not go "scot-free" (Old Bailey, 1675). In these trials, it seems that the victim's age is the common denominator that played a role in pursuing a lesser charge. Since most of these types of cases did not record any details about the evidence, it is hard to conjecture what made the Justice of the Peace or jury pursue a misdemeanor charge. Nonetheless, the sentiment gleaned from Coker's trial could indicate the prevailing disdain concerning even the idea of carnally knowing a child, as this fell outside what society considered acceptable sexual activity.

Only five prisoners were able to achieve an acquittal against their rape charges against girls under 10 years of age. In 1694,

Robert Selman was accused of committing rape upon the 5-year-old Margaret Durant (Old Bailey, 1694d). The evidence against him was weak as the mother could not swear that it was he who abused the child, and the surgeon could not swear that penetration had occurred, even though the child had contracted gonorrhea. Being found not guilty of rape, the court tried him for trespass, for which he was also acquitted. Likewise, William Webb was tried for carnal knowledge of his ward, Mary Sidercombe (10), in 1687 (Old Bailey, 1687a). According to the trial notes, the only evidence presented against him was that he was a single male and that the child had been violently abused. Socioeconomic status could have affected the outcome of this particular trial. The girl was allowed to swear an oath and present evidence for her case, but she had no one to advocate for her since she accused her guardian. She had no wealth or status. On the other hand, Webb had taken this child off the streets and provided for her. Thus, the court decided there was insufficient evidence, and he was acquitted.

Status and character also played a role in the trials of Samuel Eales, Walter Butcher, and William Row (Old Bailey, 1694b; Old Bailey, 1685b; Old Bailey, 1687b). All three brought in witnesses to either highlight their character or to disparage their accusers' motives as ploys to get money, as the centuries-old laws still demanded reparations for guilty verdicts. Eales defended himself with evidence that he was not at home when the crime was supposed to have happened, that the girl in question was of "evil repute," and that he, himself, was a "person of modest behavior, and a very ingenious man." Butcher also brought in witnesses to attest to his character, while Row instead focused on the reputation of his accuser. He presented evidence that the complaint was not made in a timely manner and that "the Parents were of no good Repute." The defendants all alleged that their accusers were after money. This was a widespread claim when the accused was wealthier and thus considered of a higher class than the victims.

The ratio of acquittals in trials that involved "adult" women, that is, females over the age of 10, shows that a stigma was attached to women accusing men of higher standing of rape. It was often dismissed as a scheme to make some money, especially when the victim waited too long to complain or only made an accusation once they realized they were pregnant. In a 1685 case, the accuser, Mary Chard, had been in Bridewell, a workhouse for poor vagrants, when she discovered that she was pregnant and was then urged to make an accusation. In several others, the timing of the accusations was questioned and, coupled with the discrepancy in wealth between the accused and accuser, was relegated to "a design to get Mony" (Old Bailey, 1685a; Old Bailey, 1686a; Old Bailey, 1679; Old Bailey, 1681).

Another popular defense was to attack the victim's character either by associating them with a bawdy house or accusing them of being women of loose morals. Elizabeth Wale, spinster, Mrs. Ruth Turner, and Mary Haynsword, age not disclosed but assumed to be over the age of majority, were all accused of working in or running a house of ill-repute. The accused would rely on the business's reputation to be acquitted (Old Bailey, 1685c; Old Bailey, 1689c; Old Bailey, 1695). Others would bring in "quality" witnesses who would compare the defendant's upright standing in the community to the disgraceful behavior of the victims (Old Bailey, 1674; Old Bailey, 1677; Old Bailey, 1678c; Old Bailey, 1693; Old Bailey, 1697). Society had taught women how to fear becoming a victim of the "wolf," and they were sometimes reluctant to come forward with accusations because, more often than not, it would ruin their reputation and prospects. This hesitancy could work against them as the defendants would question the delay in filing a complaint and argue it was a scheme to get money. Women who did not call out or fight against their attackers were considered to have given consent. It did not matter if the victim said no or resisted passively for fear of being hurt or killed. Often, this counted as a double strike against the victims as the law required proof of resistance, such as crying for help. Women who did not adhere to society's strict views on chastity and purity by having sex outside of marriage lost any character or status they may have once enjoyed.

In all of these cases, even though the law was followed strictly, justice could not always be satisfied due to the nature of the crime. The strict rules of evidence made it harder for girls to receive justice once they turned 11 and almost impossible after they turned 15, as seen in Table 1. The victim would need to produce evidence that they had been violated through midwife or surgeon testimony, as both penetration and ejaculation were required to be proven. Socio-economic status becomes a factor, as expert testimony from a midwife or surgeon needed to be paid for, and the victim would be required to present herself in a timely manner to preserve said evidence. In the cases where a servant was ravished by the master of the house, she would not have the liberty to go to the authorities, nor would she have the funds to pay for an examination. In addition, it was essential for victims to prove that they resisted their attacker by calling for help and physically defending themselves; even then, the characters of the victim, her witnesses, and the alleged attacker could come into play.

The patriarchal society of early modern England also perpetuated a framework that kept women in a disadvantaged setting—men made and enforced not only the law, but also societal norms. Most trial outcomes came down to the issue of consent. Queen Elizabeth I's statute declaring girls under the age of 10 incapable of giving consent became a significant factor in determining guilt or innocence in those cases involving minor children. The removal of the question

of consent left the juries to consider the physical evidence alone, creating the imbalance seen in Table 1. The struggle to reinstate the Great Chain of Being that emerged after the Interregnum and Charles' strategy of appointing Tory justices were also reflected in the trial outcomes—wealth, status, and reputation were presented as valid evidence. It was not just ordinary men who made and enforced the laws; it was wealthy landowning men. Thus, while the trials discussed mostly came down to age and whether or not the victim needed to prove lack of consent, other factors, including the economic ability of the victim to hire midwives or surgeons, the socio-standing of the parties involved, as well as the politicized structure of the courts during Charles II's reign, impacted the conviction rate of those indicted for rape or ravishment in London during the late seventeenth century.

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Exploring Gender Differences in Perceptions of AI's Impact on Social Media

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Abstract

Artificial Intelligence (AI) is increasingly shaping social media through content personalization and moderation, raising questions about its influence on public opinion and trust in digital news. Gender plays a key role in shaping perceptions of AI's impact, with men and women potentially viewing its applications differently. This study explored gender-based perspectives on AI's role in social media, focusing on its effects on information credibility and privacy. Data from 155 participants, collected via Amazon Mechanical Turk, were analyzed using IBM's SPSS. The first hypothesis proposed that women would be more skeptical than men about AI's use in news, citing greater concerns over misinformation. The second suggested that women would view AI as less problematic when applied to creative content. The results confirmed these hypotheses and were statistically significant at the 1% level ($p \leq .01$). Women were more likely than men (56.3% vs. 43.4%) to see AI as "somewhat beneficial" for creative content applications. However, they also expressed greater caution about AI-generated news, with 37.5% of women strongly agreeing that AI contributes to more believable fake news, compared to 18.4% of men. These results indicate that women perceive AI as more beneficial for creative purposes but harbor greater concerns about its role in spreading misinformation. Understanding these gender-based differences can guide the development of AI tools that better address diverse concerns, enhancing both trustworthiness and user satisfaction on social media platforms.

Introduction

Background. From personalized feeds to deepfake videos, Artificial Intelligence (AI) now shapes what billions of people see, share, and believe online. AI is transforming nearly all aspects of modern life, and this is especially seen in its deep influence on social media. AI-driven technologies such as personalized content feeds and AI-generated images and videos play a critical role in shaping users' experiences with digital platforms (Beer, 2017). Alongside these risks, AI also offers tangible benefits: automating moderation of harmful content,

improving accessibility through captioning and translation tools, and expanding creative possibilities through filters and generative design features. These advancements highlight that AI's impact on social media is both enabling and disruptive, depending on how users experience its outcomes.

Social media platforms depend heavily on AI-powered recommendation algorithms that tailor content to each user. Although personalization may seem favorable, engagement-optimized algorithms can amplify sensational or polarizing content, accelerating the spread of misinformation and eroding trust in both news and platforms (Beer, 2017; Germani et al., 2024; Pennycook & Rand, 2019; Tufekci, 2018; Wack et al., 2025). Personalization also raises significant privacy concerns: to tailor feeds and ads, platforms collect and analyze vast amounts of personal data—often without users' full knowledge or consent—contributing to disempowerment and diminished trust in online environments (Andrejevic, 2014; Saura et al., 2024; Teraiya & Krishnamurthy, 2025; Zuboff, 2019). Preserving privacy amid large-scale data personalization remains an open design challenge (Beyari & Hashem, 2025).

These tensions have prompted scholars to call for ethical frameworks that guide AI development. Floridi and Cowls (2019) argue that AI technologies must be governed by principles that promote fairness, accountability, and transparency. This argument is especially relevant to AI-generated media, where the boundaries between authentic and synthetic content are increasingly blurred. Public attitudes toward AI's creative capacities, as well as its potential risks, should therefore inform both platform policy and AI governance efforts.

Notably, public opinion regarding AI's role in social media is highly variable. Existing research shows that gender differences influence how people perceive and interact with AI technologies. Women tend to be more skeptical about AI and experience greater anxiety about its implications for society (Russo et al., 2025), whereas men often hold more positive opinions about AI-generated creative content and are less concerned about its potential to spread disinformation (Helberger, 2019). Understanding these disparities is crucial for developing AI technologies that are both ethical and trustworthy for diverse users.

Theoretical Framework and Research Aim. Recent scholarship has also emphasized that perceptions of emerging technologies are shaped by psychological and sociocultural factors, including gender. Studies show systematic gender differences in technology attitudes and adoption: women often weigh social and ethical risks and social influence more heavily, while men's usage decisions are more strongly tied to perceived usefulness (Gefen & Straub, 1997;

Venkatesh & Morris, 2000). These findings align with Risk Perception Theory, which holds that people evaluate technological benefits and harms through socially shaped judgments of trust, control, and affect (Slovic, 1999). The Technology Acceptance Model (Davis, 1989) provides a complementary lens, suggesting that perceived usefulness and perceived ease of use drive attitudes and behavioral intentions, dimensions that can vary by gender. Women's stronger emphasis on privacy and ethical implications may therefore shape more cautious attitudes toward AI's informational uses, whereas men may focus more on its efficiency and creative potential.

Despite growing literature on AI ethics and misinformation, few studies directly compare how men and women interpret AI's expanding role on social media, particularly in balancing its risks and benefits. To operationalize these constructs, the survey instrument included items mapped to four themes—AI integration, misinformation/credibility, creative use, and privacy—derived from the prior literature and the study's theoretical framework. This study addresses that gap through an empirical analysis of gender-based differences in attitudes toward AI's integration, credibility, and privacy implications. By identifying these demographic distinctions, the study aims to inform the development of more transparent, ethical, and user-centered AI-driven systems within the digital media landscape.

Methodology

To examine public perceptions of artificial intelligence (AI) in social media, I designed a 17-question survey and administered it through Amazon Mechanical Turk (MTurk). MTurk was selected for its ability to reach a diverse participant pool and to provide small monetary incentives that increase response reliability. The survey consisted of 11 topic-specific questions and 6 demographic questions, using a combination of Likert-scale and multiple-choice formats.

The 11 topic questions were developed based on themes identified in the literature review—AI integration, misinformation, creative use, and privacy concerns—each representing one core construct of public perception identified in prior studies (Beer, 2017; Floridi & Cowls, 2019; Pennycook & Rand, 2019; Russo et al., 2025). This ensured that the instrument directly measured attitudes relevant to both the theoretical framework and the study's research question.

The final sample included 156 respondents, all aged 18 years or older and residing in the United States. Of these, 76 participants (48.7%) identified as male and 80 (51.3%) as female. To ensure demographic balance, respondent weighting was adjusted in IBM SPSS (Statistical Package for the Social Sciences) according to national distributions reported by the U.S. Census Bureau (2020). SPSS was used to conduct descriptive analyses, cross-tabulations, and chi-square (χ^2) tests to assess associations between categorical

variables. The chi-square test was chosen because it is appropriate for detecting statistically significant relationships between gender (a nominal variable) and survey responses, which were measured on ordinal scales.

While this quantitative design enabled rigorous comparison across demographic groups, it relied entirely on structured, closed-ended questions. This choice allowed for standardized analysis but limited exploration of the reasons underlying participants' attitudes toward AI. Future research could include open-ended questions to capture the motivations and personal experiences that shape these perceptions.

This structured methodology successfully provided representative data on how U.S. adults perceive AI's influence on social media and revealed demographic-specific patterns that contribute to understanding public trust, misinformation sensitivity, and privacy concerns.

Results

Cross-tabulations and chi-square tests revealed statistically significant gender differences in perceptions of AI's role on social media, particularly regarding its ability to spread misinformation and overall attitudes toward AI integration. The chi-square test was selected because it allows comparison of categorical responses between independent groups making it appropriate for identifying associations between gender and survey responses measured on Likert-type scales.

Figure 1
Eleven Topic Questions

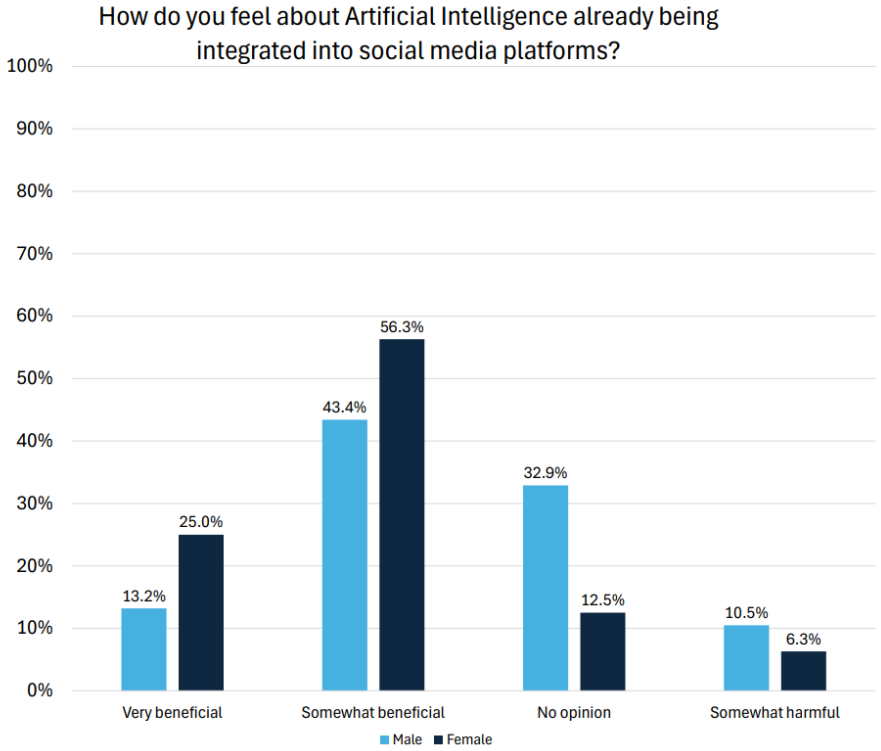
Eleven Topic-Related Questions
1. How often do you rely on social media sites such as Instagram and TikTok for news?
2. How often do you use Artificial Intelligence?
3. How do you feel about Artificial Intelligence already being integrated into social media platforms like Facebook and Instagram—do you find it beneficial or harmful to users?
4. How strongly do you agree or disagree with the following statement: "I feel the ability of Artificial Intelligence to create more believable fake news on social media outweighs the good Artificial Intelligence can do"?
5. How frequently do you encounter AI-generated content on social media platforms like Instagram and Facebook that you find misleading or fake?
6. To what extent do you agree or disagree with the following statement: "Social media companies are doing enough to protect users from harmful or inappropriate content"?
7. Do you believe that the amount of misinformation on social media has increased or decreased in recent years?
8. Has the increased presence of AI had a negative or positive impact on privacy in social media?
9. How influential do you think celebrities and influencers on social media are in your behaviors and lifestyle?
10. What is your opinion on people who use social media as their primary news source?
11. How strongly do you agree or disagree with the statement: "The content I see on social media affects my opinions on social or political issues"?

Note. These are the 11 of 17 questions that are related to the surveying topic. The other 6 are demographic questions (age, gender, race, ethnicity, income, education).

Perceptions of AI Integration in Social Media. Participants were first asked how they felt about AI already being integrated into social media platforms. A statistically significant gender difference was observed ($\chi^2(3) = 12.206$, $p < .01$). Among female respondents, 56.3% viewed AI integration as "somewhat beneficial", while only 43.4% of male respondents shared this view. Additionally, 25.0% of female respondents rated AI integration as "very beneficial" compared

to 13.2% of male respondents. These findings indicate that women, on average, were more positive about AI's creative or functional integration in social media platforms than men.

Figure 2
Results from Question that Asked: "How do you feel about Artificial Intelligence already being integrated into social media platforms?"

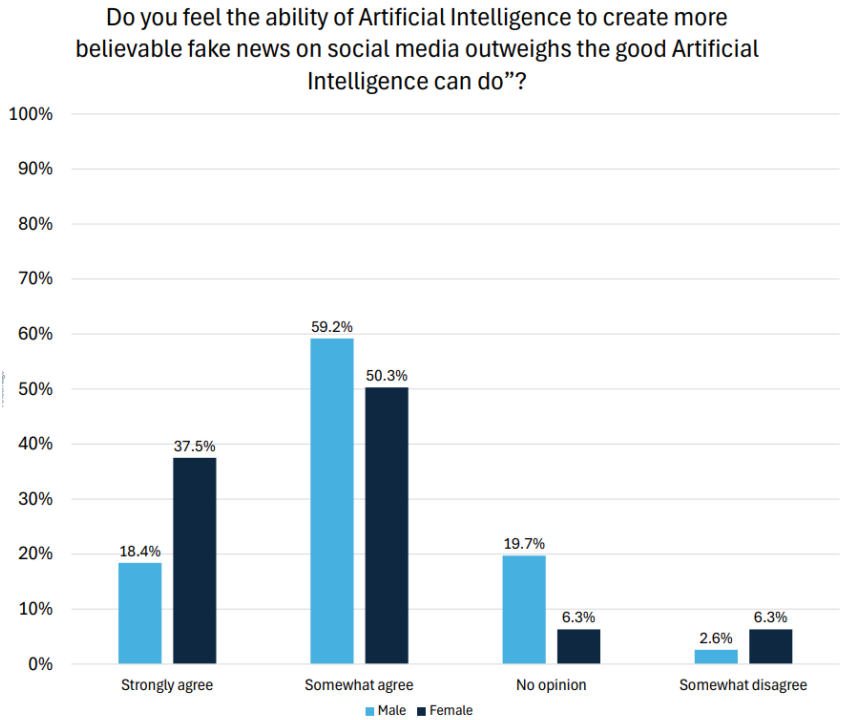


Note. There is a statistically significant difference between gender and opinion on whether AI is beneficial or harmful for social media, $\chi^2(3) = 12.206$, $p < 0.01$.

Perceptions of AI's Role in Spreading Misinformation. Participants were then asked whether they felt that AI's ability to create more believable fake news on social media outweighs any potential benefits it might offer. Overall, 82.7% of all respondents agreed to some extent that the risks outweigh the benefits. A statistically significant difference was found between male and female respondents ($\chi^2(3) = 12.304$, $p < .01$). Among female respondents, 37.5% "strongly agreed" with this statement compared to 18.4% of male respondents. Conversely,

a larger proportion of male respondents (59.2%) "somewhat agreed", while 50.3% of female respondents selected this option. These results suggest that women were more likely to express stronger concern about AI's potential to spread misinformation.

Figure 3
Results from Question that Asked: "Do you feel the ability of Artificial Intelligence to create more believable fake news on social media outweighs the good Artificial Intelligence can do?"



Note. There is a statistically significant difference between gender and opinion on whether AI is beneficial or harmful for social media, $\chi^2(3) = 12.206$, $p < 0.01$.

Taken together, the results show a nuanced pattern: while both male and female respondents recognized the risks of AI in spreading misinformation, women demonstrated greater caution toward its potential harms yet expressed more favorable opinions about its general integration into social media. This indicates that participants may evaluate AI's creative and informational roles differently: seeing it as useful for expression and content generation, but risky as a source of misinformation.

Discussion

The findings of this study provide useful insight into how men and women perceive the growing presence of artificial intelligence on social media. The fact that women were more likely than men to believe that AI's ability to generate realistic fake news outweighs its benefits suggests a higher level of skepticism among female users. One reason for this difference may be that women, on average, are more sensitive to potential social harms linked with misinformation, especially on topics such as health, safety, and public well-being. Prior studies illustrate that women are more concerned about risks at the community level in online settings (Russo et al., 2025). Women are also subjected to specific types of targeted disinformation at increased frequencies, which could make them more sensitive to these threats. This aligns with risk-perception theory, which proposes that people's judgments of technological risks and benefits are shaped by trust, control, and emotional response (Slovic, 1999).

At the same time, the results showed that women held more positive views of AI's integration into social media when it comes to creative uses. This finding is consistent with previous studies suggesting that women tend to be more open to technologies that support social interaction and self-expression (Floridi & Cowls, 2019). Within the Technology Acceptance Model (Davis, 1989), this can be interpreted as higher perceived usefulness for AI applications that enhance communication and creativity. AI tools used to enrich creativity, such as filters, video-editing software, and personalized recommendations, may therefore be seen as adding to the social-media experience without introducing the same level of societal risk associated with AI-driven misinformation.

The findings from this study have several practical implications. Firstly, social-media companies should recognize that concerns about AI-generated misinformation may be stronger among female users. This should encourage greater transparency and responsibility in how AI technologies are deployed. At the same time, designers can build on the more positive perceptions of AI's creative potential to develop features that promote authentic engagement and community building. Educational programs aimed at improving digital literacy should also address how AI influences content exposure and the risk of misinformation, while recognizing that user concerns may vary across demographic groups.

In short, this study underscores the importance of understanding demographic differences in how users view AI and its effects on social media. As Artificial Intelligence technologies continue to evolve and become more advanced in digital platforms, it is increasingly important to design and govern these systems in ways that represent the values and concerns of a diverse range of users. Future research should also explore how these gender-based attitudes intersect with other factors such as age, political orientation, and digital literacy to shape public trust in AI-driven media environments.

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Common Cybersecurity Attack Types and Zeek-Based Detection Strategies in IoT Networks

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Abstract

As cybersecurity threats increase in scale and complexity, the ability to distinguish hostile traffic from benign network activity is essential. This research examines five prevalent cyberattack categories that impact IoT environments and outlines detection strategies utilizing the open-source Intrusion Detection System (IDS) Zeek. This study provides practical detection methods designed for scalable, real-time environments by classifying five commonly encountered attacks, namely: Reconnaissance, Denial of Service (DoS) and Distributed Denial of Service (DDoS), Brute Force, Man-in-the-Middle (MitM) and Spoofing, and Botnet and Malware Behavior. For each attack, we analyze the prevalence, operational impact, and associated indicators. We also present Zeek-based pseudocode strategies structured by attack type. The findings emphasize the value of detection mechanisms and emphasize Zeek's versatility across IoT networks.

Introduction

The cybersecurity landscape is evolving rapidly, with adversaries deploying increasingly sophisticated methods to exploit vulnerabilities in digital infrastructure. A 2025 study revealed a 27.63% annual growth rate in cybersecurity research from 2004 to 2023, with over 90% of the 859 publications occurring between 2019 and 2023 (Barcellos-Paula et al., 2025). This expansion obviously underscores the increasing significance of learning about, noticing, and warding off cyber threats.

IoT devices are the best candidates for attacks since they possess limited resources, widespread deployment, and less frequent patching cycles. Detecting and mitigating cyber threats in real-time is critical, as the frequency and severity of attacks on critical infrastructure continue to rise. A 2023 analysis of cyber incidents revealed a steady increase in the number of significant attacks, with the total number of significant cyberattacks expected to nearly triple from 2023 through 2027 (Riggs et al., 2023). In addition, in this report, it was underscored that cyberattacks are targeted toward defense, communications, government, business, and finance, respectively, reflecting strategic motives and potential national security implications for cyberattacks (Riggs et al., 2023).

This paper identifies a Zeek policy set to detect five IoT attack classes with high accuracy and low false alarms on public IoT traces (Biju et al., 2019; Sasi et al., 2024). It outlines how Zeek's event model allows for composition of independent detectors as small .zeek modules (recon, DoS/DDoS, brute-force, ARP spoof, beaconing). Zeek's scripting language allows researchers to define detection rules in modular scripts tailored to specific traffic patterns. The research draws on public IoT datasets and attack taxonomy models such as MITRE ATT&CK to construct scalable, real-time detection strategies aligned with today's complex threat environment, and each attack class is a self-contained .zeek script with a shared interface (on_event, purge, eval) and site-specific configuration for \theta, window *T*, and allowlists.

Methodology and Detection Approach

This study models intrusion detection for IoT networks as behavior recognition at a gateway using only transport and protocol-level telemetry produced by Zeek. The framework assumes no payload semantics and therefore remains valid for encrypted traffic. Detectors operate on short, fixed windows and raise alerts when specific behavioral primitives exceed an operating point.

The adversary acts on the local IoT network. Attack classes include reconnaissance, DoS/DDoS, brute-force login, ARP spoofing for man-in-the-middle, and beaconing botnet activity. The defender observes gateway traffic and ARP activity and runs Zeek to export per-flow and per-event records. All detectors use fields available from Zeek's standard logs: conn (endpoints, ports, state, bytes, packets, durations), dns (query/response metadata), arp (IP↔MAC bindings), notice and weird (policy and anomaly events), and timestamps. No deep packet inspection is required.

Detection Primitives. We define five primitives that summarize behavior within a sliding window, T:

- Burst rate $r(T)$: events per second for a keyed entity (e.g., SYNs from a source to a destination) measured over T.
- Cardinality $C_X(T)$: distinct count of an attribute X over T (e.g., distinct destination ports probed by a source, distinct sources targeting one victim).
- Periodicity $P(T)$: regularity of inter-arrival times for flows from a source to a destination; higher values indicate near-periodic beacons.
- Mapping churn $M(T)$: number of IP↔MAC remap events observed in arp over T after excluding Dynamic Host Configuration Protocol (DHCP) and benign renewal patterns.
- Failure density $F(T)$: frequency of repeated short request–response exchanges to the same endpoint that match failure-like patterns in timing and size, when explicit error codes are unavailable.

Each attack induces characteristic changes in one or more primitives:

- Reconnaissance: $C_{dport}(T)$ increases as a source contacts many ports or hosts; $r(T)$ of SYNs also rises.
- DoS/DDoS: $r(T)$ rises sharply for packets or connection attempts to a target; $C_{src}(T)$ increases when many sources participate.
- Brute-force login: $F(T)$ increases due to clustered failures toward the same endpoint with similar flow sizes and short durations.
- ARP spoofing/MitM: $M(T)$ increases when an IP maps to multiple MACs or vice versa outside normal renewal windows.
- Botnet beaconing: $P(T)$ increases as inter-arrival times become regular; rare-domain contacts and low variance strengthen the signal.

For each class, a detector computes the relevant primitive(s) over window T and triggers a Zeek NOTICE when the value crosses a threshold θ. Windows and thresholds are selected on development traces and then evaluated on held-out traces. Detectors maintain constant memory per key and add negligible CPU overhead at gateway scale.

This framework justifies the choice of Zeek, constrains the detectors to observable behavior rather than payload content, and yields policies that are simple to tune, auditable, and compatible with encrypted IoT traffic. The modular detection approach used in this study is outlined in Figure 1. The pseudocode illustrates how connection, ARP, and DNS/SNI events update shared sliding-window state and how a periodic timer invokes attack-specific detector routines (detect_recon, detect_dos_ddos, detect_bruteforce, detect_arp_spoof, detect_beaconing). All subsequent detection pseudocode (Figures 4–8) assumes this common structure, including the time windows, thresholds, and NOTICE generation logic.

Thresholds in each detection strategy, such as the number of failed login attempts, scanning interval, and packet rate, were initially based on common IDS heuristics and have been tuned through empirical testing. The tuning process involved iterative adjustments to minimize false positives while retaining high recall for known attacks. Alerts were verified by correlating Zeek notices with ground-truth labels.

Five widely documented attack classes in IoT cybersecurity literature were selected as the focus of this study. Zeek detection strategies were developed for each class, enabling monitoring of attributes such as connection frequency, protocol anomalies, authentication failures, and irregular communication intervals. Figure 2 shows Zeek's end-to-end traffic processing workflow, while Figure 3 provides a detailed view of Zeek's internal decision-making logic within its scripting and event-handling engine.

Figure 1
Modular Zeek-Based IoT Intrusion Detection Framework Pseudocode

```
constants:
  T_SCAN=60s,   THRESH_PORTS=θ_scan
  T_DOS=10s,    THRESH_SYN=θ_syn, THRESH_DDOS_SOURCES=θ_src
  T_BRUTE=300s, THRESH_FAIL=θ_fail
  T_ARP=30s,    THRESH_ARP=θ_arp
  T_BEACON=600s, MIN_BEACON=κ, THRESH_BEACON=θ_beacon
  TICK=1s

state (sliding-window buffers):
  ports_by_src: map<src, multiset<(dst,dport,ts)>>
  syn_ts:       map<(src,dst), deque<ts>>
  udp_ts:       map<(src,dst), deque<ts>>
  fail_ts:      map<(src,dst), deque<ts>>
  arp_maps:     map<ip, multiset<(mac,ts)>>
  flow_ts:      map<(src,dst), deque<ts>>
  badset:       set<known_bad_ips_or_domains>

on_conn(c):                       // from Zeek conn.log
  t ← c.ts
  add(ports_by_src[c.src], (c.dst,c.dport,t))
  if c.proto==TCP and SYN in c.flags: push(syn_ts[(c.src,c.dst)], t)
  if c.proto==UDP: push(udp_ts[(c.src,c.dst)], t)
  if looks_like_login_failure(c): push(fail_ts[(c.src,c.dst)], t)
  push(flow_ts[(c.src,c.dst)], t)

on_arp(a):                        // from Zeek arp.log
  add(arp_maps[a.ip], (a.mac, a.ts))

on_dns_or_sni(e):                 // optional for C&C checks
  if e.dst in badset: NOTICE("Known_CandC", key=e.src)

on_tick(now):
  purge windows older than now-{T_SCAN,T_DOS,T_BRUTE,T_ARP,T_BEACON}
  detect_recon()
  detect_dos_ddos()
  detect_bruteforce()
  detect_arp_spoof()
  detect_beaconing()

main:
  every TICK call on_tick(now)
  on each Zeek event call the matching handler
```

Figure 2
Zeek Packet Processing Pipeline from Network Capture to Event Classification

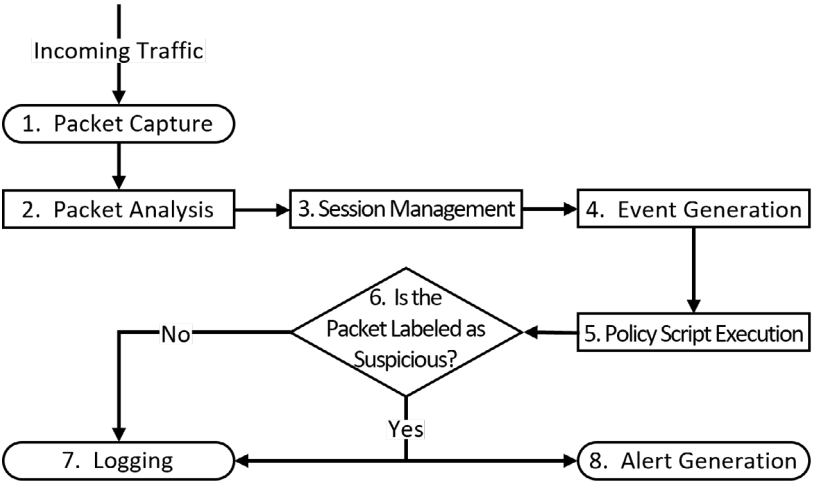
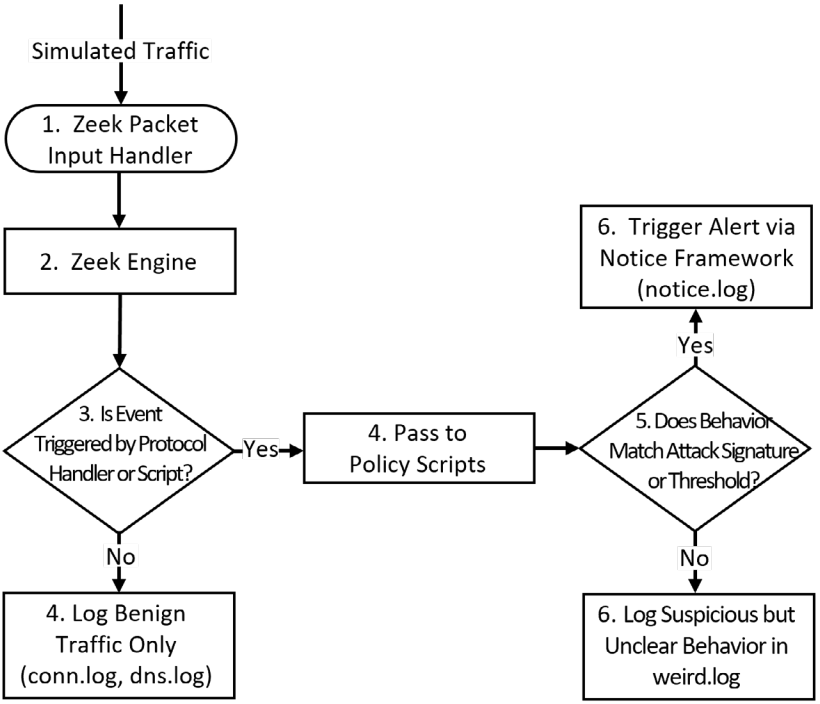


Figure 3
Internal Event Handling and Policy Decision Logic



Attack Categories and Detection Strategies

Each detection strategy below includes pseudocode (Figures 4–8) that explains in a simplified manner how to identify specific classes of cyberattacks in IoT environments. In each subsection, we briefly describe how the key steps in the pseudocode implement the detection attributes discussed above.

Attack Category 1: Reconnaissance

Definition and Mechanism. Reconnaissance is often the first phase of a cyberattack and involves gathering information about a target system or network to identify potential vulnerabilities. According to a 2022 study, this can include non-technical information, such as organizational details and personal information, as well as user information, host information, network information, and application information (Roy et al., 2022). This allows attackers to understand the target's overall security and vulnerability level. Reconnaissance can be categorized into two types:

- **Passive methods** collect information such as the owner's contact information, name servers, domain creation, and domain expiration dates without directly interacting with the target through public records, social media, and WHOIS lookups. Practical tools for this type of method include DNSstuff and MxToolbox.
- **Active methods** directly engage with the target system to gather information, often through techniques like port scanning, ping sweeps, or vulnerability scanning. Practical tools for this type of method include DNSEnum, NMap, and ZENMap.

Prevalence. Although there is a lack of high-quality data on the prevalence of reconnaissance attacks, it is widely acknowledged as an important preemptive step before launching an attack. Attackers, ranging from script kiddies to advanced persistent threat (APT) groups, routinely perform reconnaissance to identify exploitable systems. The ease of availability of automated scanning tools and services has lowered the barrier to entry, which makes reconnaissance a low-risk, high-reward precursor to cyberattacks.

Impact. While reconnaissance itself may not cause immediate harm; it sets the stage for more damaging attacks. Information gathered during this phase can be used to identify vulnerable systems and services, craft targeted phishing campaigns, and develop tailored exploits to exploit these vulnerabilities. Failure to detect and mitigate reconnaissance activities can lead to data breaches as well as financial losses for affected companies.

Detection Attributes. We use flow-level attributes that capture timing and TCP control behavior visible at the gateway, avoiding payload inspection. These features separate benign short exchanges from reconnaissance by constraining duration, characterizing inter-arrival regularity, and counting control flags both per flow and over the flow lifetime. Together they summarize how a scanner touches ports and hosts, the cadence of its probes, and the flag patterns it elicits (Sharmin & Kiekintveld, 2023):

- Flow duration within the optimized range (≤ 100 s) for isolating reconnaissance;
- Inter-arrival time (IAT) patterns characteristic of different scan types;
- Number of Synchronize, Acknowledgment, Finish, Reset, Push, Echo, and Congestion Window Reduced flags in each flow; and
- Total Synchronize, Acknowledgment, Finish, Urgent, and Reset count over the flow duration.

Figure 4 summarizes the reconnaissance detector. For each source address, the pseudocode counts the number of distinct destination ports and destination hosts contacted within the scan window T_SCAN. If either count exceeds the tuned threshold THRESH_PORTS, the code raises a Zeek NOTICE labeled Recon that reports the observed port and host cardinalities. This directly implements the burst-rate and cardinality primitives described above for horizontal and vertical scanning activity.

Figure 4
Reconnaissance Detection Pseudocode

```
procedure detect_recon():
  for src in ports_by_src:
    P ← distinct_dports(ports_by_src[src], window=T_SCAN)
    H ← distinct_dhosts(ports_by_src[src], window=T_SCAN)
    if P ≥ THRESH_PORTS or H ≥ THRESH_PORTS:
      NOTICE("Recon", key=src, features={ports:P, hosts:H, window:T_SCAN})
```

Attack Category 2: Denial of Service (DoS) and Distributed Denial of Service (DDoS)

Definition and Mechanism. DoS attacks are attempts to disrupt a server, service, or network by overwhelming it with a large amount of internet traffic, rendering it inaccessible to legitimate users.

DDoS attacks amplify the threat of a DoS attack by utilizing multiple computer systems as sources of attack traffic. These systems can include compromised computers and other networked resources, such as IoT devices. Common types of DoS and DDoS attacks include:

- **Volumetric attacks** overwhelm the bandwidth of the target site.
- **Protocol attacks** consume the actual server resources or intermediate communication equipment.
- **Application layer attacks** target web applications to crash the server.

Prevalence. DoS and DDoS attacks are increasingly common and more destructive. Falowo and Bou Abdo (2024) forecast major DDoS incidents (per CSIS criteria) using ARIMA and ETS. Based on the ETS model, counts rise from 19 in 2023 to 38.40 in 2026 (29.93 in 2024; 34.33 in 2025; Falowo & Bou Abdo, 2024). This highlights a clear, growing need for the detection and prevention of these attacks.

Impact. Over 17 months from November 2020 through March 2022, only about 1% of DDoS attacks on DNS nameservers caused complete resolution failures, and roughly 5% led to significant latency spikes (≥ 10× increases) for end users, as reported in large-scale DNS measurement studies (Sommese et al., 2022). Most large providers using anycast infrastructure experienced minimal impact, whereas smaller, single-location deployments were far more likely to suffer significant slowdowns or outages. Attack intensity (packets per second) often did not predict user-perceived harm, as smaller floods against unicast nameservers sometimes caused worse effects than much larger attacks on anycastized systems. Overall, anycast and subnet diversity proved critical for maintaining service availability under heavy volumetric assaults (Sommese et al., 2022).

Detection Attributes. In SDN/OpenFlow networks, DDoS pressure shows up as abnormal load on both the data and control planes. The attributes below capture that stress through switch-local counters and controller interactions (Alhijawi et al., 2022):

- Sudden spikes in network traffic
- Unusually high traffic patterns onto individual switches
- CPU and memory utilization surges
- Large bursts of OpenFlow flow-mod traffic on control-plane switches
- Sharp rise in "table miss" packets at edge switches

Figure 5 shows the DoS and DDoS detector. The first two loops compute short-window SYN and UDP packet rates for each (source, destination) pair to identify single-source floods, while the third loop aggregates sources targeting the same destination to identify fan-in DDoS toward a victim. When the per-flow rate exceeds THRESH_SYN or the number of attacking sources exceeds THRESH_DDOS_SOURCES, Zeek emits a NOTICE record that includes the SYN/UDP rate or attacker count to support operator triage.

Figure 5
DoS and DDoS Detection Pseudocode

```
procedure detect_dos_ddos():
  // Per-source DoS on TCP
  for k=(src,dst) in syn_ts:
    rate_syn ← count(syn_ts[k]) / T_DOS
    if rate_syn ≥ THRESH_SYN:
      NOTICE("DoS_TCP", key=k, features={syn_rate:rate_syn})

  // Per-source DoS on UDP
  for k=(src,dst) in udp_ts:
    rate_udp ← count(udp_ts[k]) / T_DOS
    if rate_udp ≥ THRESH_SYN:
      NOTICE("DoS_UDP", key=k, features={udp_rate:rate_udp})

  // Fan-in DDoS toward a single victim
  for dst in group_by_dst(syn_ts ∪ udp_ts):
    attackers ← sources_with_rate_at_least(dst, THRESH_SYN, T_DOS)
    if attackers ≥ THRESH_DDOS_SOURCES:
      NOTICE("DDoS", key=dst, features={attackers:attackers})
```

Attack Category 3: Brute Force

Definition and Mechanism. Brute force attacks are a form of password-cracking technique where an attacker attempts all possible combinations of passwords or key combinations until the correct one is found. As Luxemburk et al. (2021) explain, attackers typically perform multiple rapid login attempts over HTTPS (Luxemburk et al., 2021). They also use tools such as Hydra, Ncrack, or Patator to automate credential trials, often reusing or recreating Transport Layer Security (TLS) sessions for each attempt. Different types of brute force attacks are:

- **Simple brute force** tries every possible character combination
- **Dictionary attack** uses a precompiled list of common passwords
- **Credential stuffing** uses username-password pairs from previous breaches
- **Password spraying** attempts a few common passwords across many usernames to avoid lockout

Since user credentials are submitted over HTTPS, packet-level traits (e.g., sizes, direction, timing) become the only reliable signals for detecting these attacks (Luxemburk et al., 2021).

Prevalence. Brute force is one of the most common steps in web-based intrusions. As of 2020, Luxemburk et al. (2021) noted that brute force attempts make up 80% of observed web-service attacks. Even when organizations deploy protections such as rate-limiting or CAPTCHAs, many still face daily automated login tries on SSH, RDP, and web portals.

Impact. The most obvious risk of brute force attacks is account takeover, where the attacker gains unauthorized access to user accounts. From there, attackers often use compromised accounts to escalate privileges, moving laterally within the network in an attempt to access higher-level credentials or sensitive systems. Once inside, they may exfiltrate critical data—such as customer records, intellectual property, or internal documents—leading to costly breaches. In many cases, brute-forced administrative logins serve as the entry point for ransomware deployments, encrypting files and demanding payment for decryption keys.

Detection Attributes. Encrypted brute force attempts create repeatable timing and size patterns visible in flow metadata, enabling payload-agnostic detection (Luxemburk et al., 2021):

- A large amount of small request–response pairs (each roundtrip typically equals one login attempt);
- Low variance in packet sizes because repeated login attempts generate nearly identical packet-size patterns;
- Short interarrival times between consecutive encrypted packets;
- Strong autocorrelation in merged packet-size sequences (attack tools repeat the same sequence of request/response bursts); and
- Nearly constant ratio of total response bytes to request bytes across attempts (e.g., identical login-form responses).

Figure 6 presents the brute-force detector and its helper function looks_like_login_failure. The helper function maps Zeek conn.log records to likely authentication failures using either explicit protocol error codes or short, low-volume exchanges that match encrypted login attempts. The main loop then computes the density of such failures for each (source, destination) pair over the brute-force window T_BRUTE and raises a BruteForce NOTICE whenever the failure rate exceeds THRESH_FAIL. This design keeps the detector payload agnostic and suitable for encrypted services such as HTTPS, SSH, and RDP.

Figure 6
Brute Force Detection Pseudocode

```
function looks_like_login_failure(c):
  return (
    has_explicit_error_code(c)                  // e.g., HTTP 401, SSH auth fail
    or (c.duration < 3s and c.resp_bytes < 300 and c.orig_bytes < 400)
  )


procedure detect_bruteforce():
  for k=(src,dst) in fail_ts:
    density ← count(fail_ts[k]) / T_BRUTE      // failures per 5 min
    if density ≥ THRESH_FAIL:
      NOTICE("BruteForce", key=k, features={fail_density:density})
```

Attack Category 4: Man-in-the-Middle (MitM) and Spoofing

Definition and Mechanism. MitM attacks occur when an attacker intercepts, relays, and potentially alters communications between computers that believe they are directly communicating with each other. The attacker places themselves between the client and the server, allowing them to eavesdrop on, modify, or inject malicious data into the data stream. Common vectors include HTTP/HTTPS interception, TLS stripping, and session hijacking (Sasi et al., 2024).

Spoofing is a primary enabler of MitM. In this technique, an attacker impersonates a legitimate device to deceive victims and gain unauthorized access. Spoofing can occur at multiple layers of the network stack, including:

- **MAC spoofing**, where the attacker forges the source MAC address to mimic another device
- **IP spoofing**, where the attacker crafts IP packets with a spoofed source IP
- **DNS spoofing**, where the attacker poisons DNS entries to redirect legitimate traffic to malicious servers
- **ARP poisoning**, where the attacker sends forged ARP messages on a LAN to associate the attacker's MAC address with the IP address of another host, typically the default gateway. As a result, traffic intended for that IP is diverted to the attacker. Once the attacker intercepts the traffic, they can conduct passive sniffing, inject or modify payloads, or disrupt connectivity (e.g., by sending forged ARP replies with incorrect MAC–IP mappings; Sasi et al., 2024; Biju et al., 2019). Publicly available tools such as arpspoof, Ettercap, and Cain and Abel are commonly used to automate ARP poisoning.

Prevalence. MitM and spoofing attacks are especially common in IoT networks because many devices are deployed on shared or poorly segmented networks without strong authentication. Public Wi-Fi hotspots, unmanaged home routers, and open enterprise LANs frequently expose IoT endpoints to ARP/DNS poisoning and IP/MAC impersonation, thus allowing attackers to intercept and tamper with traffic. Because of the ease of deployment, these techniques remain among the most practical and frequently observed threats in real-world IoT environments.

Impact. Man-in-the-middle and spoofing attacks compromise confidentiality, integrity, and availability, enabling the following impacts:

- **Credential theft** where the attacker can harvest usernames, passwords, session cookies, and API tokens from intercepted traffic, enabling unauthorized account access
- **Data manipulation** by Injecting or altering payloads
- **Service disruption** by continually poisoning ARP tables or DNS entries, so the attacker can cause connectivity issues for legitimate hosts
- **SSL stripping** by downgrading HTTPS connections to HTTP, rendering sensitive data plaintext, and exposing session identifiers or personal information (Sasi et al., 2024)

Detection Attributes. Key detection indicators for MitM and spoofing attacks include:

- Frequent ARP broadcasts or replies without requests;
- Multiple MAC addresses for the same IP;
- Duplicate IP address alerts on server logs;
- Unusual SSL/TLS Certificate Warnings, such as certificate mismatches and unexpected certificate authorities; and
- Rapid changes in ARP cache entries.

Figure 7 shows the ARP spoofing detector that underpins man-in-the-middle detection. For each IP address observed in ARP traffic, the pseudocode counts the number of distinct MAC addresses associated with that IP within the window T_ARP, explicitly ignoring benign DHCP-related churn. When the distinct MAC count reaches or exceeds THRESH_ARP, the detector raises an ARP_Spoof NOTICE, signaling rapid IP–MAC remapping consistent with poisoning attacks.

Figure 7
MitM and Spoofing Detection Pseudocode

```
procedure detect_arp_spoof():
  for ip in arp_maps:
    macs ← distinct_macs(arp_maps[ip], window=T_ARP, ignore_dhcp=true)
    if macs ≥ THRESH_ARP:
      NOTICE("ARP_Spoof", key=ip, features={mac_count:macs})
```

Attack Category 5: Botnet and Malware Behavior

Definition and Mechanism. A botnet is a network of compromised internet-connected devices, which are often referred to as "bots" or "zombies," that are centrally controlled by an attacker known as a "botmaster" through one or more command-and-control (C&C) channels (Xing et al., 2021). These devices may include PCs, servers, routers, IoT devices, and smartphones. Once infected by malware, each device connects to the C&C server or peer nodes in the botnet and awaits instructions to execute coordinated malicious tasks. Common behaviors include:

- **Enrollment and C&C registration**, where the malware drops a lightweight bot binary and registers the device with the C&C infrastructure (Xing et al., 2021)
- **Beaconing and keep-alive**, where, at regular intervals, the bot "beacons" to its C&C server via encrypted traffic, allowing it to receive instructions without raising alarms (Xing et al., 2021)
- **Tasking and payload delivery**, where the botmaster issues commands such as DDoS/ping floods, spam distribution, credential harvesting, and crypto-jacking by using structured payloads or scripting languages (Xing et al., 2021)
- **Self-propagation**, as many IoT-focused botnets scan for weak Telnet/SSH credentials or known firmware vulnerabilities, then spread laterally by exploiting those same flaws (Xing et al., 2021)
- **Persistence and evasion**, as the malware often disables competing binaries, kills security processes, and sets up kernel-level hooks or hidden cron jobs to ensure its survival across reboots. Peer-to-peer (P2P) architectures and blockchain-anchored C&C further evade takedown.

Common botnet-enabling malware families include Mirai, Brickerbot, and Reaper (Wazzan et al., 2021).

Prevalence. Botnets remain one of the most persistent and rapidly evolving threats in today's IoT ecosystem. As of mid-2021, 70% of all IoT devices are vulnerable to these types of attacks, meaning that billions of IoT devices are susceptible to being recruited through attacks such as automated credential stuffing and payload-injection campaigns (Wazzan et al., 2021). Modern botnets exploit low-powered, unpatched endpoints at scale, with one Mirai botnet having conducted an attack using 10 million different IP addresses in 2016 (Wazzan et al., 2021).

Impact. Compromises in IoT or enterprise networks degrade availability, expose data, and monetize resources. The impacts below summarize common outcomes observed after intrusion:

- Service disruption;
- Financial loss;
- Data theft and espionage;
- Crypto-jacking; and
- Lateral movement and ransomware staging.

Detection Attributes. Beaconing C&C and early-stage malware leave patterns in gateway metadata. The attributes below capture outbound C&C behavior, periodic keep-alives, sudden pivot to scanning, and reputation signals without payload inspection:

- Unusual outbound connections to rare or dynamically generated domains (e.g., DGA lookups; Wazzan et al., 2021);
- Regular, low-volume "keep-alive" beacons;
- Sudden surges in scanning or probing activity from an otherwise idle device;
- Encrypted payloads to blacklisted IPs; and
- Sudden surges in CPU/network activity

Figure 8 summarizes the botnet and malware behavior detector. The first loop evaluates the periodicity of flows between each (source, destination) pair and flags highly regular keep-alive patterns that exceed MIN_BEACON events and the periodicity threshold THRESH_BEACON, corresponding to C&C beaconing. The second loop focuses on internal sources and counts distinct internal destinations contacted within T_SCAN to flag sudden lateral scanning. Both behaviors generate Zeek NOTICE records (Beaconing or Lateral_Scan) that operators can correlate with rare-domain lookups and resource-usage anomalies.

Figure 8
Botnet and Malware Detection Pseudocode

```
procedure detect_beaconing():
  // Known C&C already flagged in on_dns_or_sni
  for k=(src,dst) in flow_ts:
    if length(flow_ts[k]) < MIN_BEACON: continue
    s ← periodicity_score(flow_ts[k])          // e.g., 1 - CV of inter-arriva
ls
    if s ≥ THRESH_BEACON:
      NOTICE("Beaconing", key=k, features={score:s})


  // Lateral movement from IoT endpoint (internal scan)
  for src in ports_by_src where is_internal(src):
    H ← distinct_dhosts_internal(ports_by_src[src], window=T_SCAN)
    if H ≥ THRESH_PORTS:
      NOTICE("Lateral_Scan", key=src, features={hosts:H})
```

Results and Observations

Table 1 links each attack class to the Zeek logs that expose it and the resulting NOTICE. Operators review alerts in notice.log, then use the referenced logs (conn, http, ssh, arp, weird) to verify the evidence. This shows which observable data drives each alert without payload inspection and guides which log to inspect next.

On CICIoT2023 and N-BaIoT, the policies detected all five classes. DDoS produced seconds-scale alerts; reconnaissance fired after one T_SCAN window; beaconing sensitivity improved with longer T_BEACON. Thresholds were tuned on development traces to a fixed false-positive budget and held on test. In our runs, FP/h dropped from 0.40 to 0.12 while recall changed by ≤0.03. The most useful signals were beacon periodicity, distinct-port/host counts, and burst rates.

Table 1
Zeek Log Indicators Mapped to Common Attack Types

	conn.log	**http.log**	**ssh.log**	**arp.log**	**weird.log**	**notice.log**
Botnet / Malware	High port scan rate (Mirai)	Suspicious URI (Bashlite)				Botnet Payload Detected
Brute Force	Many short-lived SSH/FTP conns		Repeated login failures			Brute Force Alert
DDoS / DoS	High packet/ SYN rate				Malformed TCP/ Protocol issues	Flooding Alert
Reconaissance	Frequent new connections					Scan Detected
MitM / Spoofing				MAC address mismatch	Unusual APP	ARP Spoof Detected

Conclusion and Future Work

This paper highlights Zeek's versatility as a detection framework for IoT environments. By implementing modular detection strategies across five attack classes, we have shown how Zeek can be adapted to evolving threats. Future work—ongoing in collaboration with the Tecore Lab team—includes integrating machine learning models such as isolation forests for anomaly detection, traffic analysis, and classification of composite behavior patterns. These enhancements will complement Zeek's rule-based engine by identifying attacks that deviate from learned norms. Additional experimentation will include deployment on live networks using FAU's Tecore Testbed.

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Gender Differences in Streaming Service Adoption and Cancellation During COVID-19

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Abstract

For over a decade, the rise of subscription-based entertainment models has appeared inevitable. This trend became even more apparent when the world went into lockdown to curb the spread of COVID-19. During this time, many people began reevaluating how they allocated their discretionary income for day-to-day purchases as the future looked bleak. The purpose of this study was to examine people's preferences between subscription-based models and one-time purchases. To do this, a 12-question survey was conducted, and data were collected through Amazon Mechanical Turk, yielding over 195 responses. The results indicate a statistically significant relationship between age and the use of subscription-based models. Additionally, a notable difference was found between gender and subscription model usage. These findings are important because they illustrate a clear demographic breakdown of those most affected by shifts in consumer spending patterns.

Introduction

The COVID-19 pandemic in early 2020 brought about a drastic shift in daily life, forcing individuals all across the globe to stay at home for extended periods. As traditional entertainment sources such as movie theaters and live events became inaccessible due to social distancing, consumers ultimately turned to online alternatives. This sudden disruption catalyzed the rapid expansion of subscription-based media services, such as Netflix, Disney+, Hulu, and HBO Max. This study focuses specifically on the rise of streaming subscription models during the pandemic, examining how lockdown conditions influenced consumer willingness to adopt these services.

While prior research has linked subscription adoption to factors such as age, income, and education, this study pays particular attention to gender differences in decision-making. Do men and women approach subscription-based services differently? Are women, who are often shown in consumer research to value convenience and variety, more likely to experiment with new platforms? Or might men, who are sometimes characterized by higher engagement with technology, be quicker to adopt streaming models? These questions help frame an important aspect of pandemic-era consumer behavior that has received relatively little attention.

The COVID-19 lockdown created an environment where online entertainment not only filled a social void but also became the main form of entertainment. Time spent on streaming platforms grew by nearly 75% in the early months of the pandemic (Nielsen, 2020). As consumers sought convenient, on-demand access to entertainment, streaming subscriptions surged, marking a distinct breakaway from traditional, bundled cable services. Understanding how gender shaped these adoption and cancellation decisions offers valuable insight into how individuals weigh cost, content, and flexibility in a time of uncertainty. This study therefore evaluates whether men and women differed in how readily they adopted and canceled streaming services, shedding light on the psychological and social dynamics behind subscription behavior during a global crisis.

As streaming services gained rapid popularity, a new concept emerged: "subscription fatigue." Unlike traditional media, which often involves long-term contracts, streaming platforms offer month-to-month subscriptions that are easier to cancel. I explored whether this simplicity led consumers to cancel streaming services more readily than they would have with traditional media subscriptions. According to a study by Deloitte (2021), nearly 46% of users had canceled at least one streaming service in the previous 6 months, with cost and lack of compelling content being the top reasons. These results showed that streaming is easy to adopt and encourages low commitment, especially among younger users who tend to have limited discretionary income. By using adoption and cancellation data across different demographic groups, this study aims to find how the pandemic influenced media consumption habits and how gender, in particular, may have influenced consumers' willingness to start or stop subscriptions in a rapidly changing digital environment.

Materials

A 12-question multiple-choice questionnaire was administered, with five demographic questions included to gain information on gender, age, race/ethnicity, political affiliation, household income, and level of education. The other seven questions focused on determining people's willingness to switch to subscription-based models, as well as their willingness to cancel subscriptions as a result of bad service.

Questions focused on whether the COVID-19 lockdown made people switch to subscription-based services using a 5-point Likert scale ranging from "much more often" to "don't use" (e.g. "much more often", "a little more", "same", "less", and "don't use"). The survey also included questions on the likelihood that a respondent would cancel their subscription service if they received poor service, using ratings from "much more likely" to "a lot less likely" (e.g., "much more likely", "a little more likely", "same", "a little less likely", and "a lot less likely"). Amazon Mechanical Turk (MTurk) was used to distribute these questionnaires.

Procedures

After finalizing the questionnaire, the survey was uploaded and distributed via SurveyMonkey to users across the United States aged 18 and older, who were compensated for their participation. The survey received 195 unique responses, which were analyzed using IBM SPSS (Statistical Package for the Social Sciences). The data were weighted in SPSS to reflect the demographic makeup of the U.S. population, based on the 2020 Census data (U.S. Census Bureau, 2020), ensuring a representative sample of the United States.

Figure 1
Sample Questionnaire

1. With the rise of subscription-based models of business services, have you found yourself using them more as opposed to purchasing to own?
2. Particularly with the rise of Covid and more specifically lockdown, have you found yourself switching more to subscription-based (last year)?
3. With the current model of paying monthly as opposed to one-time upfront, do you find yourself spending more or less?
4. With subscription-based models, do you find your needs being met with more time involved or less time involved?
5. When using subscription-based services, do you find yourself receiving better or worse customer service?
6. With the purchase of a subscription-based service, do you find yourself more attached or loyal to the brand as opposed to a one-time purchase?
7. If unsatisfied likelihood you cancel your subscription-based service as opposed to returning the one-time purchase item if possible?
8. What is your gender?
9. Are you currently registered to vote as a Democrat, Republican, or something else, or are you not registered to vote?
10. What is your age?
11. For statistical purposes only, which of the following best describes your race?
12. What is your highest level of education?

Note. The 12 questions that were distributed through Amazon MTurk focused on determining people's willingness to switch and continue using subscription services.

Results

The analysis focused on two questions from the survey: "Particularly with the rise of Covid and more specifically lockdown, have you found yourself switching more to a subscription-based service?" and "If unsatisfied, the likelihood you cancel your subscription-based service opposed to returning the one-time purchase item if able?". Both questions yielded statistically significant results ($p < .05$) after conducting gender-based crosstabulation analyses.

When asked about the likelihood of switching services, 35% of respondents reported being much more likely, 46% a little more likely, 15% the same, and only 4% said they were either less likely or don't use streaming services. In contrast, when asked about canceling services following a poor experience, 40% said they were much more likely to cancel, 41% a little more likely, 9% the same, and 10% less likely to cancel. The results indicated that gender groups are more likely to switch or cancel services, giving companies around the world a better idea of the strategies and promotional efforts they should run to gain customers and grow.

Figure 2

Frequency Results of the Question "Particularly with the rise of Covid and more specifically lockdown, have you found yourself switching more to subscription-based services?"

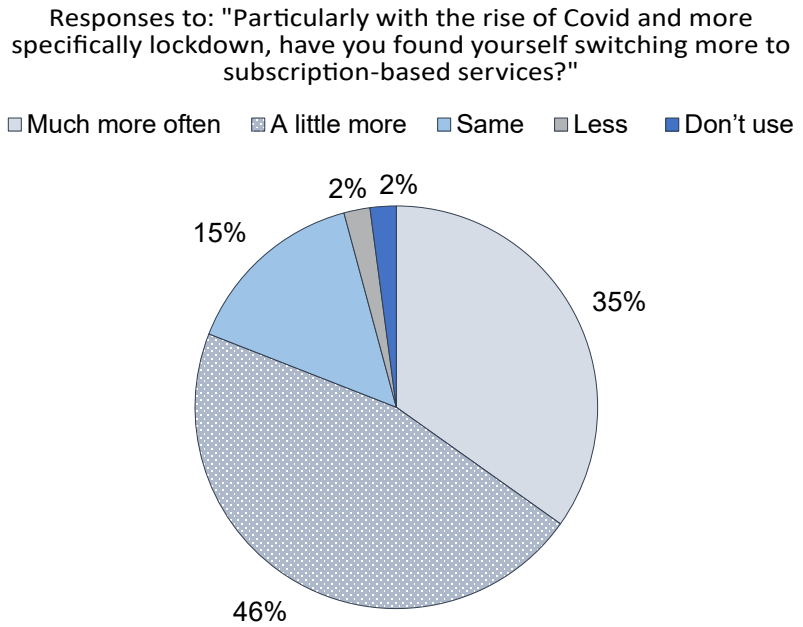

Figure 3

Crosstabulation Results between "Particularly with the rise of Covid and more specifically lockdown, have you found yourself switching more to subscription-based services?" and the Gender of the Respondent

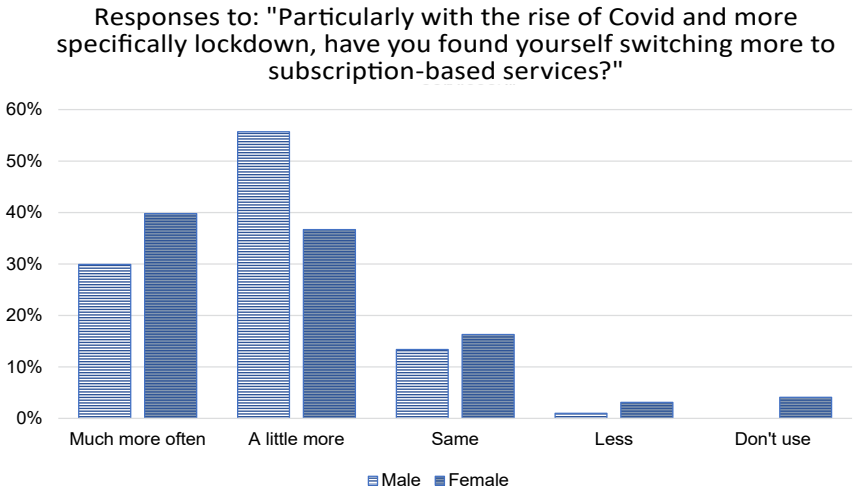

Table 1

Numerical Results from the Crosstabulation between "Particularly with the rise of Covid and more specifically lockdown, have you found yourself switching more to subscription-based services?" and the Gender of the Respondent

			Much more often	A little more	Same	Less	Don't use	Total
Gender	Male	Count	29	54	13	1	0	97
		Percent	29.9%	55.7%	13.4%	1.0%	0.0%	100.0%
	Female	Count	39	36	16	3	4	98
		Percent	39.8%	36.7%	16.3%	3.1%	4.1%	100.0%
Total		Count	68	90	29	4	4	195
		Percent	34.9%	46.2%	14.9%	2.1%	2.1%	100.0%

The survey compiled 195 unique responses, with 97 coming from males and 98 from females. When asked about changes in subscription use during COVID-19 lockdown, 34.9% of all respondents reported switching much more often, while 46.2% said they switched a little more. Among male respondents, 29.9% indicated they switched much more often and 55.7% said a little more, with no male respondents indicating they don't use subscription services at all. Female respondents, however, were slightly more likely to report switching much more often (39.8%), though only 36.7% said a little more, and 4.1% reported not using subscription services at all. Overall, while usage increased, women were more likely than men to report higher use when it came to subscription services.

Figure 4

Frequency Results of the Question "If unsatisfied, the likelihood you cancel your subscription-based service as opposed to returning the one-time purchase item if able?"

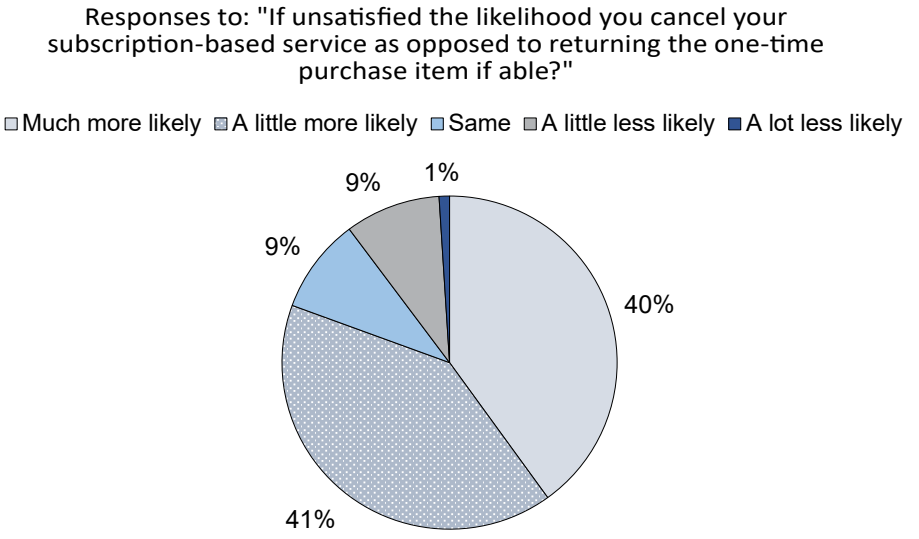

Figure 5

Crosstabulation Results between "If unsatisfied, the likelihood you cancel your subscription-based service, opposed to returning the one-time purchase item if able?" and the Gender of the Respondent

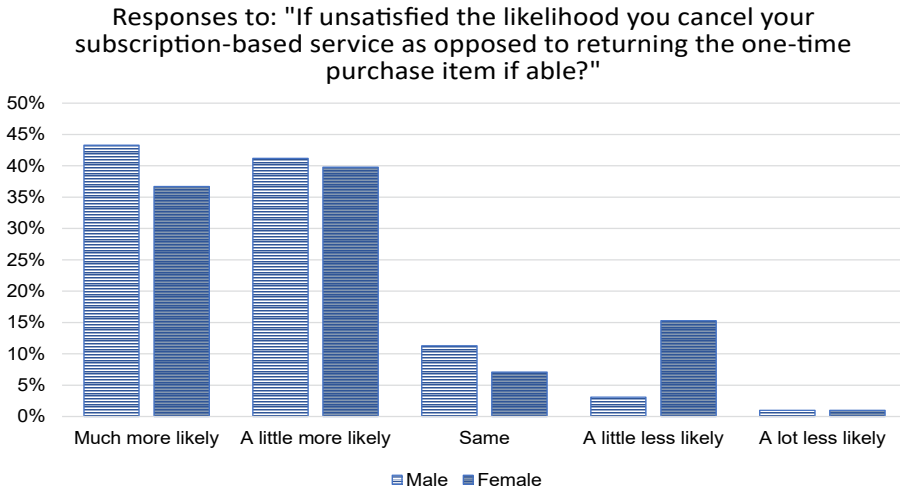

Table 2

Numerical Results from the Crosstabulation between "If unsatisfied, the likelihood you cancel your subscription-based service, opposed to returning the one-time purchase item if able?" and the Gender of Respondents.

			Much more likely	A little more likely	Same	A little less likely	A lot less likely	Total
Gender	Male	Count	42	40	11	3	1	97
		Percent	43.3%	41.2%	11.3%	3.1%	1.0%	100.0%
	Female	Count	36	39	7	15	1	98
		Percent	36.7%	39.8%	7.1%	15.3%	1.0%	100.0%
Total		Count	78	79	18	18	2	195
		Percent	40.0%	40.5%	9.2%	9.2%	1.0%	100.0%

Discussion

This study provides insight into how the COVID-19 pandemic played a critical role in reshaping consumer behavior regarding subscription-based services. Demographic variables such as gender, age, income, education, and political affiliation were collected to examine how broader social, economic, and cultural factors might influence consumer decision-making regarding streaming services. Including these variables allowed for potential comparisons between groups and a deeper understanding of how individual characteristics shape subscription behavior. The data reflected that the COVID-19 lockdown increased the adoption of streaming services, with 81.1% of respondents claiming that they had switched to subscription-based services either "much more often" or "a little more" during the pandemic. This aligns with findings from Nielsen (2020), which reported a 75.0% increase in streaming usage during the early months of the pandemic. This suggests that lockdown pushed consumers towards online alternatives in light of social distancing measures.

By examining how gender differences in subscription behavior, this study found that gender plays an important role in how individuals adopt streaming services. Specifically, female respondents were more likely than males to report switching much more often to subscription platforms, while male respondents were more likely to say they switched a little more. Furthermore, no male respondents indicated that they do not use streaming services, whereas a small percentage of females (4.1%) did. This raises intriguing possibilities about how gender-based preferences and decision-making styles affect adoption: women may be more responsive to convenience, variety, or social engagement aspects of streaming, whereas men may be more gradual adopters who maintain consistent usage patterns. This suggests that while men were more consistent users, women were more likely to increase their usage of subscription services during the pandemic.

Besides adoption, this study examined consumer cancellation behavior. When asked about their likelihood of canceling a subscription following a bad service experience, 81.0% of respondents said they would be much more likely or a little more likely to cancel, indicating a low tolerance for dissatisfaction. This reflects the concept of subscription fatigue, which has grown as a concern among subscription service providers. Subscription fatigue refers not only to dissatisfaction with service quality but also to the feeling of being overwhelmed by the growing number of platforms, choices, and recurring payments that consumers must manage. Different from traditional cable providers, streaming services allow users to subscribe or cancel with minimal effort, resulting in a more flexible consumer base. As covered by Deloitte (2021), nearly half of U.S. users had canceled at least one streaming service within 6 months, typically due to rising costs or lack of compelling content.

Interestingly, the gender-based findings also reflected distinct attitudes toward cancellation. Male respondents were slightly more likely to indicate they would cancel following poor service, whereas female respondents showed a wider range of responses, with some remaining subscribed despite dissatisfaction. This may suggest that women's stronger initial engagement with subscription services also leads to greater brand attachment, while men demonstrate more transactional or performance-based decision-making.

These results offer important insight into the future of streaming. The simplicity of both signing up and canceling subscriptions gives consumers more flexibility than ever to shape their media consumption, as well as creates a challenge for service providers. Overall, women's higher engagement levels and men's greater readiness to cancel highlight how gendered preferences can shape the lifecycle of a subscription ranging from adoption to termination. This has left subscription providers with the need to tailor their content offerings and pricing to appeal to consumers.

This research serves as a first step in understanding how gender differences shape online subscription behavior. Additional research can explore how factors like income, education, and political affiliation further affect subscription choices, as well as how companies can effectively grow in a saturated market. As media continues to move more and more online, it is crucial to understand what drives consumer decisions and how services can adapt to meet evolving demands.

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An In-Silico Investigation of Induced Target Neural Activity Through Simulation-Based Inference Informed Deep Brain Stimulation

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Abstract

Deep Brain Stimulation (DBS) is clinically effective for various neurological disorders, yet its underlying neuronal mechanisms remain unknown. Building on previous studies, we used an in-silico Hodgkin-Huxley biophysical model to investigate hippocampal CA1 responses to DBS. Our simulations replicate key experimental findings, confirming robust somatic depolarization at 140 Hz and a more gradual ramp at 40 Hz, alongside distinct transient and sustained voltage profiles. Both frequencies modulated firing rates, supporting the notion that DBS disrupts pathological network activity. Beyond frequency-specific effects, we employed Simulation-Based Inference (SBI) to identify the DBS features needed to suppress spiking and match a quiescent target neuron. These results demonstrate how in-silico approaches can elucidate DBS-induced membrane dynamics and underscore SBI's potential for optimizing neuromodulation strategies.

Introduction

Deep Brain Stimulation (DBS) has emerged as a neuromodulation therapy for various neurological conditions, including Parkinson's disease, epilepsy, and essential tremors (Eusebio et al., 2008; He et al., 2021; Tsang et al., 2012). This technique involves direct stimulation of brain tissues using chronically implanted electrodes and often delivers high-frequency stimulation to alter neuronal activity (Vetkas et al., 2022). While DBS has proven to be clinically effective, both the underlying neurophysiological mechanisms and the optimal stimulation frequency remain poorly understood. (Breit et al., 2004; Montgomery et al., 2008). The exploration of how to use DBS to alter cellular mechanisms is critical to optimizing protocols and expanding their therapeutic potential.

In this regard, hippocampal DBS can significantly reduce seizure frequency in patients with epilepsy (Salanova, 2018; Simpson et al., 2022). Recent work from Eric Lowet and colleagues (2022) provided crucial insight into how DBS impacts hippocampal CA1 neurons with the help of voltage imaging. More specifically,

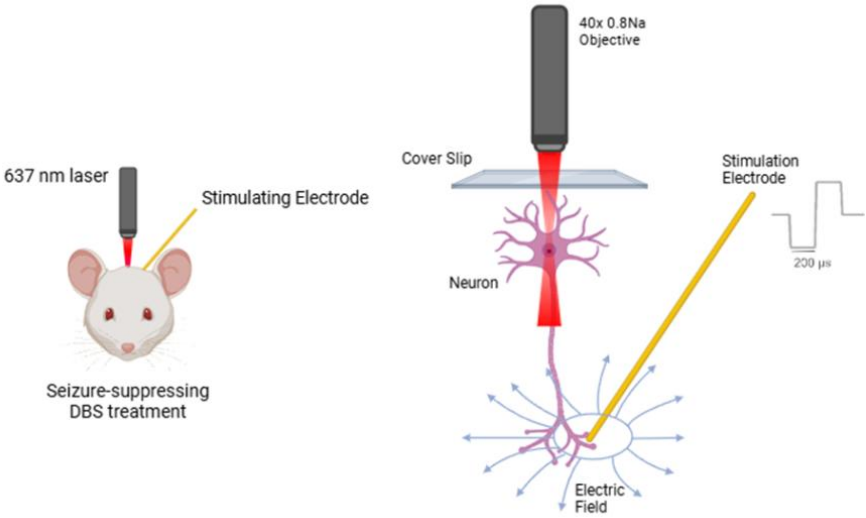
using high-speed membrane voltage fluorescence imaging and optogenetic techniques in awake mice, they demonstrated that DBS induces powerful somatic membrane depolarization without consistently suppressing spike rates. The study further revealed that different DBS frequencies (40 Hz and 140 Hz) produce distinct neuronal responses: 140 Hz DBS induces rapid and robust depolarization, while 40 Hz DBS exhibits a gradual ramping effect (Lowet et al., 2022). The frequency response difference highlights the system's ability to process information differently, making it a potential venue for manipulation. In addition, both frequencies were found to interfere with the neuron's ability to process theta-rhythmic inputs. This is important because it helps researchers to gather better understanding of how to manipulate the system, particularly in pathological situations. This supports the hypothesis of DBS as a therapeutic technique that disrupts pathological network activity by utilizing the specific frequency content that can suppress synchronization with higher efficacy.

In this study, we built on Lowet, et al.'s (2022) experimental findings by employing an in-silico Hodgkin-Huxley biophysical model to replicate and expand their observations as well as to fine-tune DBS parameters that suppress seizure-like patterns (see Figure 1). The Hodgkin-Huxley model is able to simulate ionic currents that are necessary to observe the bursting pattern in a seizure. Other, more simplified neuron models are unable to do that unless they contain additional constraints. Our goal is to generate a potential computational model derived from Lowet's study that has the ability to demonstrate how manipulations to the input frequency and amplitude affect the cellular properties of the neurons such as firing rate and membrane potential dynamics in the CA1 brain area. While Lowet, et al. (2022) can identify the frequencies that suppress activity in the neuron, a clear understanding of how ionic currents manipulate this change would allow for more precise manipulations, such as genetic or pharmacological interventions. Indeed, the CA1 area of the hippocampus has been a focus of study due to its ability to generate interictal epileptiform activity (Cohen et al., 2002; Dell et al., 2019).

The modelling approach facilitates the exploration of DBS-induced dynamics, enabling robust statistical sampling and predictive modeling of neuronal responses. Our work is focused on identifying proof-of-concepts that can be tested experimentally. Also, the in-silico approach presents several advantages when coupled to traditional experimental models. It provides a proof-of concept for hypothesis before invasive procedures are performed, reduces variability due to biological specimens, and enables a rapid repetition of simulation across a wider parameter space. By using computational tools, this study seeks to explain the mechanisms underlying DBS-induced membrane voltage dynamics and firing patterns while offering a malleable platform for optimizing DBS protocols.

By contrasting the experimental methodologies used in past studies (Lowet et al., 2022) with the computational strategies used in this study, we aim to highlight the complementary strengths of these approaches. This research highlights the potential of in-silico models to not only replicate but also predict complex neuronal behaviors.

Figure 1
Setup to Apply and Measure the Effects of Deep Brain Stimulation (DBS) on Neuronal Activity



Notes. Schematic of the experimental setup for investigating DBS effects on neuronal activity used by Lowet. The left panel shows a mouse receiving seizure-suppressing DBS. The right panel illustrates DBS application, where an electrode generates an electric field around a CA1 neuron, captured via a 40x 0.8 NA objective. This setup enables real-time analysis of DBS-induced neuronal responses, supporting computational modeling of hippocampal activity. Sketch created in BioRender.

Materials and Methods

In this work, we used a Hodgkin-Huxley conductance-based model based on prior CA1 work (Ceballos et al., 2025). This biophysical model integrates voltage-gated ionic currents and calcium dynamics. The membrane voltage (V) dynamics are described by the equation:

$$C\frac{dV}{dt} = -g_L(V - V_L) - \sum I_{ion} + I_{ext}$$

where:

- $\boldsymbol{C}$ → Membrane capacitance (μF/cm²), which determines the neuron's ability to store charge.
- $\boldsymbol{V}$ → Membrane potential (mV), representing the voltage difference across the cell membrane.
- $\boldsymbol{g_L}$ → Leak conductance (mS/cm²), which allows passive ion flow and maintains resting potential.
- $\boldsymbol{V_L}$ → Leak reversal potential (mV), the equilibrium potential for the leak current.
- $\boldsymbol{I_{ext}}$ → External applied current (μA/cm²), which represents input stimuli such as synaptic currents or injected currents.
- $\boldsymbol{I_{ion}}$ → The sum of all intrinsic ionic currents, given by

$$I_{ion} = I_{Na} + I_{Nap} + I_{KDR} + I_A + I_M + I_{Ca} + I_{sAHP} + I_C + I_L$$

In this equation, I_{ion} represents the ionic current (Sodium current I_{Na}, persistent sodium current I_{Nap}, delayed rectifier potassium I_{KDR}, a-type potassium current I_A, m-type potassium current I_M, calcium current I_{Ca}, calcium-activated potassium current I_{sAHP}, calcium-dependent potassium current I_c, and leak current I_L). Each ionic current is modeled as:

$$I_{Na} = g_{Na} \times m^3 \times h \times (V - V_{Na})$$
$$I_{Nap} = g_{Nap} \times p_\infty(V) \times (V - V_{Na})$$
$$I_{KDR} = g_{KDR} \times n^4 \times (\mathrm{V} - V_K)$$
$$I_A = g_A \times a_\infty^3 \times b \times (V - V_K)$$
$$I_M = g_M \times \mathrm{z} \times (V - V_k)$$
$$I_{Ca} = g_{Ca} \times r^2 \times (V - V_{Ca})$$
$$I_{sAHP} = g_{sAHP} \times \mathrm{q} \times (\mathrm{V} - V_K)$$
$$I_C = g_C \times d_\infty(Ca) \times c(\mathrm{V} - V_K)$$
$$I_L = g_L \times (\mathrm{V} - V_L).$$

To accurately model the voltage-dependent dynamics of ion channel gating, we implemented equations for the gating variables m, h, and n which regulate sodium and potassium currents. These gating variables determine the fraction of open ion channels at any given time and are governed by first-order differential equations:

$$\frac{dx}{dt} = \frac{x_\infty(V) - x}{\tau_x(V)},$$

where x represents the gating variables m, h or n The $x_\infty(V)$ is the steady-state activation or inactivation function, and $\tau_x(V)$ is the voltage-dependent time constant.

The sodium current in Eq. (3) is governed by activation (m) and inactivation (h):

Activation variable *m*:

$$\frac{dm}{dt} = \frac{m_\infty(V) - m}{\tau_m(V)},$$

where

$$m_\infty(V) = \frac{1}{1 + e^{-\frac{V-\theta_m}{\delta_m}}},$$

with θ_m and δ_m being voltage-dependent parameters.

Inactivation variable *h*:

$$\frac{dh}{dt} = \frac{h_\infty(V) - h}{\tau_h(V)},$$

where

$$h_\infty(V) = \frac{1}{1 + e^{-\frac{V-\theta_h}{\delta_h}}}.$$

The delayed rectifier potassium current is controlled by a single activation variable n:

Activation variable n:

$$\frac{dn}{dt} = \frac{n_\infty(V) - n}{\tau_n(V)},$$

where

$$n_\infty(V) = \frac{1}{1 + e^{-(V-\theta_n)/\delta_n}}.$$

The voltage-dependent time constants ($\tau_x(V)$) determine the speed at which the gating variables (m, h, n) transition between states. These time constants influence how quickly ion channels respond to changes in membrane voltage, affecting the overall dynamics of neuronal excitability. The time constants are typically modeled as sigmoidal functions:

$$\tau_x(V) = A + B \times \frac{1}{1 + e^{-\frac{V-\theta_{xt}}{\delta_{xt}}}}$$

In this equation, θ_{xt} and δ_{xt} control the voltage dependence of the time constant. A and B are constants that define the baseline and maximum time constants.

For the sodium inactivation (h) and potassium activation (n), the time constants are given by:

$$\tau_h(V) = 0.1 + 0.75 \times \frac{1}{1 + e^{-\frac{V-\theta_{ht}}{\delta_{ht}}}},$$

and

$$\tau_n(V) = 0.1 + 0.5 \times \frac{1}{1 + e^{-\frac{V-\theta_{nt}}{\delta_{nt}}}}.$$

A complete list of default parameters and variables is presented in both Tables 1 and 2.

The neuronal model's parameters were modified to align with the physiological data and observed trends in the findings of Lowet et al. (2022). Parameters such as conductance values for ion channels, applied currents, and calcium dynamics were systematically tuned to replicate the transient and sustained depolarization patterns observed for 40 Hz and 140 Hz stimulations. We employed simulation-based inference (SBI) to predict optimal DBS parameters for suppressing seizure-like activity in a computational model of a neuronal network. SBI refers to a class of likelihood-free Bayesian inference methods well-suited for complex, non-linear systems where the likelihood function is intractable or unknown. In this study, we employed Sequential Neural Posterior Estimation (SNPE), a neural density estimation technique that approximates the posterior distribution over model parameters given observed outcomes. A complete list of approximated parameters is show in Table 1.

Table 1
Parameters for Activation, Inactivation, and Time Constants in the HHca2 Model

Parameter	Value
θ_m	-30.0
δ_m	9.5
θ_h	-45.0
δ_h	-7.0
θ_n	-35.0
δ_n	10.0
θ_{ht}	-40.5
δ_{ht}	-6.0
θ_{nt}	-27.0
δ_{nt}	-15.0

Notes. This table lists the voltage-dependent parameters for ion channel activation, inactivation, and time constants in the HHca2 neuron model, extracted from the provided equations.

Table 2
Model Parameters and Their Descriptions

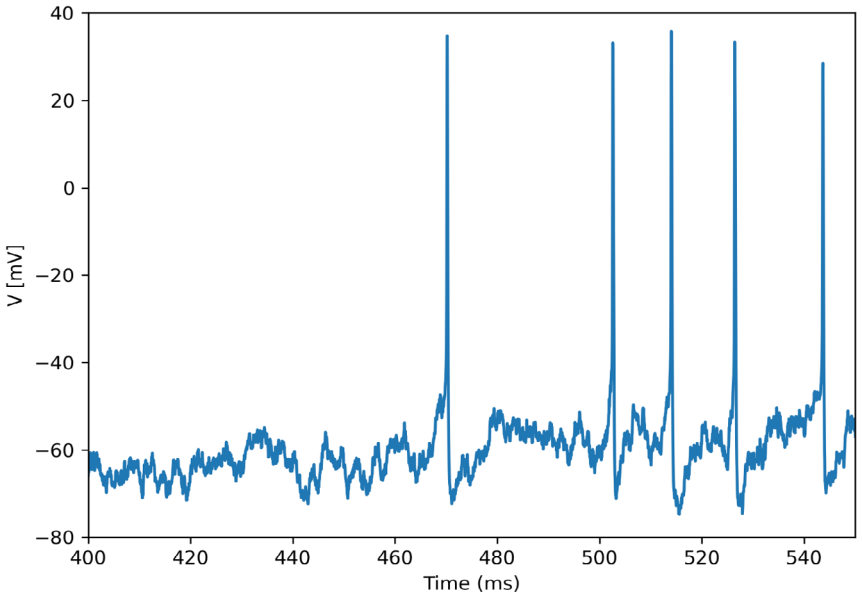
Parameter	Description	Value	Units
Nid	Unique identifier for the neuron	1.0	$\mu m^2/ms$
D	Diffusion constant for the model	8.0	µS
G_{na}	Maximum sodium channel conductance	35.0	µS
G_{nap}	Persistent sodium channel conductance	0.3	µS
G_l	Leak conductance for compartment 1	0.05	µS
G_{2l}	Leak conductance for compartment 2	0.05	µS
G_{kdr}	Maximum conductance for delayed rectifier potassium channels	6.0	µS
Ca_{acum}	Scaling factor for calcium accumulation	0.0001	µM
G_{ca}	Maximum conductance for calcium channels	0.2	µS
I_{app}	External applied current	0.9	$\mu A/cm^2$
N_o	External sodium concentration	1.0	µM
N_i	Internal sodium concentration	1.0	µM
D_z	Calcium diffusion coefficient	0.000005	$\mu m^2/ms$
G_c	Conductance of gap junctions	10.0	µS
G_{sahp}	Slow afterhyperpolarization conductance	5.0	µS
I_{app2}	External applied current for secondary input	0.9	$\mu A/cm^2$
G_m	Membrane conductance	1.0	µS
G_a	Axonal conductance	1.4	µS
G_{h2}	Conductance for H- currents in compartment 2	2.0	µS

Notes. This table outlines the parameters used in the neuronal model, including their descriptions, default values, and units. These parameters define ionic currents, synaptic interactions, and external stimulation effects within the Hodgkin-Huxley framework. Parameter names are reported as used in the original model implementation.

The code for this model is available at https://github.com/rodrigo-pena-lab/NeuronModel-DBS. We provide an example of the voltage trace from a sample simulation from the model in Figure 2.

All simulations were conducted using a time step (*dt*) of 0.05 ms over a total duration (*tf*) of 2000 ms. Two stimulation frequencies were modeled: 40 Hz and 140 Hz.

Figure 2
Simulated Neuronal Voltage Trace Under DBS Stimulation



Note. The model replicates neuronal depolarization patterns observed in experiments, aiding in optimizing DBS parameters for seizure suppression.

Results

Computational Model of CA1 Neuron Agrees with Experimental Observation. To analyze the effects of 40 Hz and 140 Hz deep brain stimulation (DBS) on neuronal dynamics, a Hodgkin-Huxley model was employed to compute membrane voltage and firing rates.

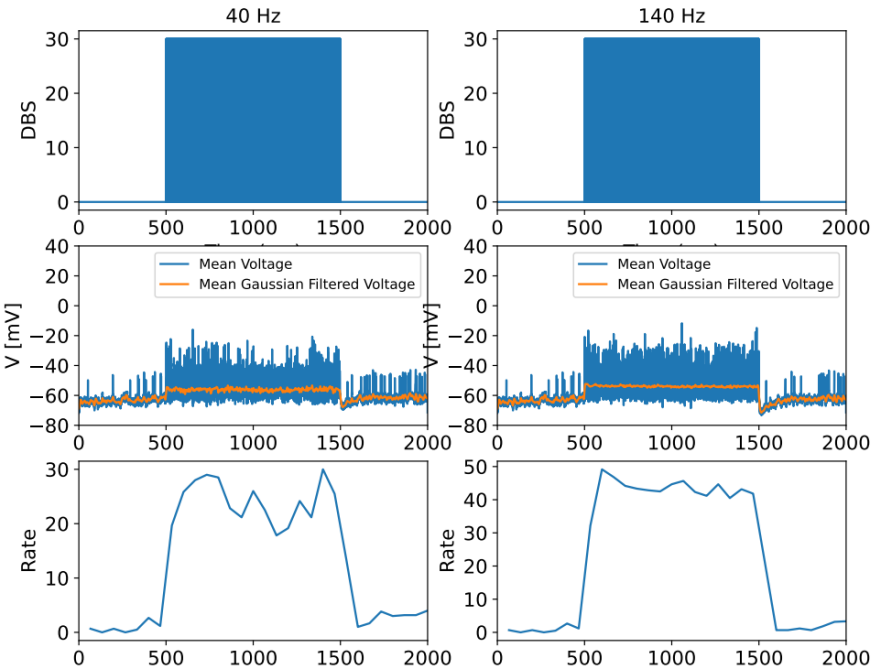
For each frequency, the DBS waveform was generated as a biphasic sinusoidal pulse. Stimulation was applied between 500 ms and 1500 ms, while pre- and post-stimulation periods were modeled without external input. Six trials were simulated for each frequency with randomized initial conditions to account for variability.

The neuronal model's parameters, including ion channel conductance and calcium dynamics, were used following values from Table 2 to match the physiological conditions of hippocampal CA1 neurons.

Membrane voltage traces (V) were recorded at each simulation step and smoothed using a Gaussian filter (σ=50) to analyze trends in transient and sustained responses. Spiking activity was detected by recording times when the membrane voltage exceeded a predefined threshold. Firing rates were computed as the number of spikes per unit time, and histograms were generated to visualize transient and sustained spiking activity for each stimulation frequency. The resulting voltage traces and firing rates were plotted for both 40 Hz and 140 Hz stimulation (Figure 3). Smoothed voltage traces highlighted transient and sustained depolarization patterns, while

Figure 3

Comparison of Voltage and Firing Rate Responses Under 40 Hz and 140 Hz DBS Stimulation

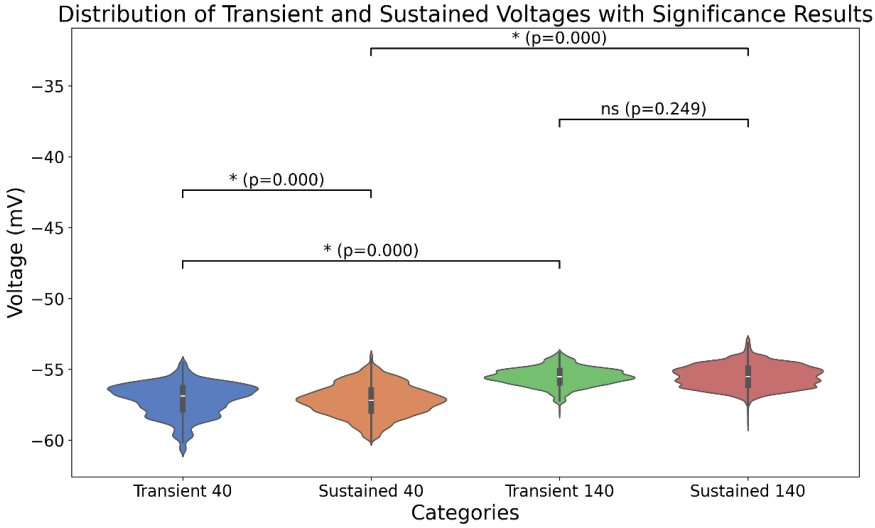


Notes. Neuronal responses averaged (10 trials) to 40 Hz (left) and 140 Hz (right) DBS. The top row depicts the DBS input, the middle row shows mean voltage traces with Gaussian-filtered values, and the bottom row displays firing rates, highlighting differences in activity across stimulation frequencies.

firing rate histograms captured changes in spiking activity over time. While we observe a mild ramp in our simulations, the exact experimental observation would likely occur if more ionic currents were added or the noise source were removed.

To compare the transient and sustained voltage responses to 40 Hz and 140 Hz DBS stimulation, we computed the mean values of filtered voltage traces in distinct time intervals. The transient phase was defined as the time window between 500 ms and 750 ms after DBS onset, capturing the initial neuronal response. The sustained phase was measured from 751 ms to 1500 ms, reflecting the stable response during prolonged stimulation. Voltage data were recorded for six different trials with randomized seeds to ensure robust statistical sampling. For each trial, Gaussian-filtered voltage traces were calculated to smooth the data and enhance the identification of trends. The mean transient and sustained voltages for both 40 Hz and 140 Hz DBS conditions were then computed and visualized using bar and violin plots. Significance between groups was assessed using the Mann-Whitney U test, as the normality of data was evaluated using the Shapiro-Wilk test. Significance annotations were added to the plots to highlight differences between transient and sustained responses across the two stimulation frequencies.

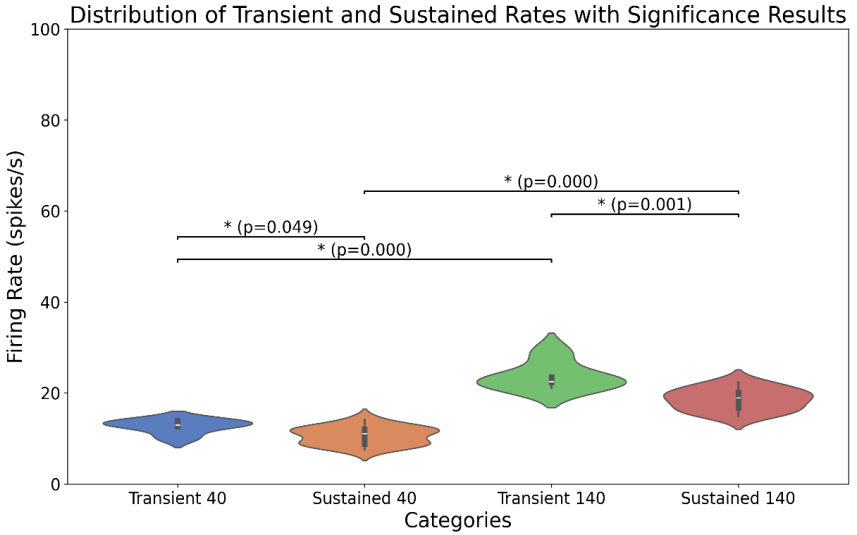
Figure 4
Distribution of Transient and Sustained Voltages at 40 Hz and 140 Hz DBS



Notes. This violin plot shows transient (500–750 ms) and sustained (750–1500 ms) voltages under 40 Hz and 140 Hz DBS. Statistical significance ($p < 0.05$; ns: not significant) highlights differences between frequencies and phases.

To evaluate the impact of 40 Hz and 140 Hz DBS stimulation on neuronal firing rates, transient and sustained rates were calculated for each condition. The transient rates were determined as the average firing rate within a short time window (500 ms to 750 ms after DBS onset), while the sustained rates were calculated from 751 ms to 1500 ms, representing the steady-state neuronal response to prolonged stimulation. Spiking data were collected over six randomized trials for robustness, and histograms were generated to derive firing rates in bins of 50 ms. The mean transient and sustained firing rates were visualized using bar and violin plots, with significance testing performed. The Shapiro-Wilk test was employed to assess the normality of the data distribution, and significance annotations were added to the plots to highlight differences between groups. This analysis enabled direct comparison of transient and sustained firing behaviors under 40 Hz and 140 Hz stimulation conditions, which is in agreement with what is found in the literature.

Figure 5
Distribution of Transient and Sustained Firing Rates at 40 Hz and 140 Hz DBS



Notes. This violin plot shows transient (500–750 ms) and sustained (750–1500 ms) firing rates under 40 Hz and 140 Hz DBS. Statistical significance ($p < 0.05$; ns: not significant) highlights differences between frequencies and phases.

Simulation-Based Inference can be Used to Find DBS Parameters for Activity Suppression. Next, we generated a large dataset of simulated neuronal activity under varying DBS parameters (frequency, amplitude, pulse width). This dataset served as training data for an SBI algorithm, which learned the probabilistic mapping between DBS input and the resulting network behavior. Specifically, we used Posterior estimation ((S)NPE) to approximate the posterior distribution of DBS parameters given the desired outcome (non-seizure activity). This learned posterior distribution was then used to identify the most likely DBS parameters that effectively suppressed seizure-like activity in the model.

The goal of using Simulation-Based Inference is to investigate the best parameters in which DBS can be used to modulate or lower neuronal activity in a Hodgkin-Huxley model neuron. SBI enables parameter estimation in complex systems where traditional statistical approaches are infeasible due to the high dimensionality or non-linearity of the model. Using the Sequential Neural Posterior Estimation (SNPE) method from the SBI framework, we trained a neural density estimator to approximate the posterior distribution of key model parameters—such as DBS pulse amplitude, frequency, and pulse width—that influence neuronal activity.

The target state in our experiment was generated by simulating a Hodgkin-Huxley neuron model with DBS turned off and applying a low external current (I_{ext}= 0.002 nA). This setup was carefully chosen to keep the neuron below the firing threshold, resulting in a stable, non-spiking membrane potential trace that served as a reference for suppressed neuronal activity. This trace represented the desired state that we aimed to achieve through DBS modulation.

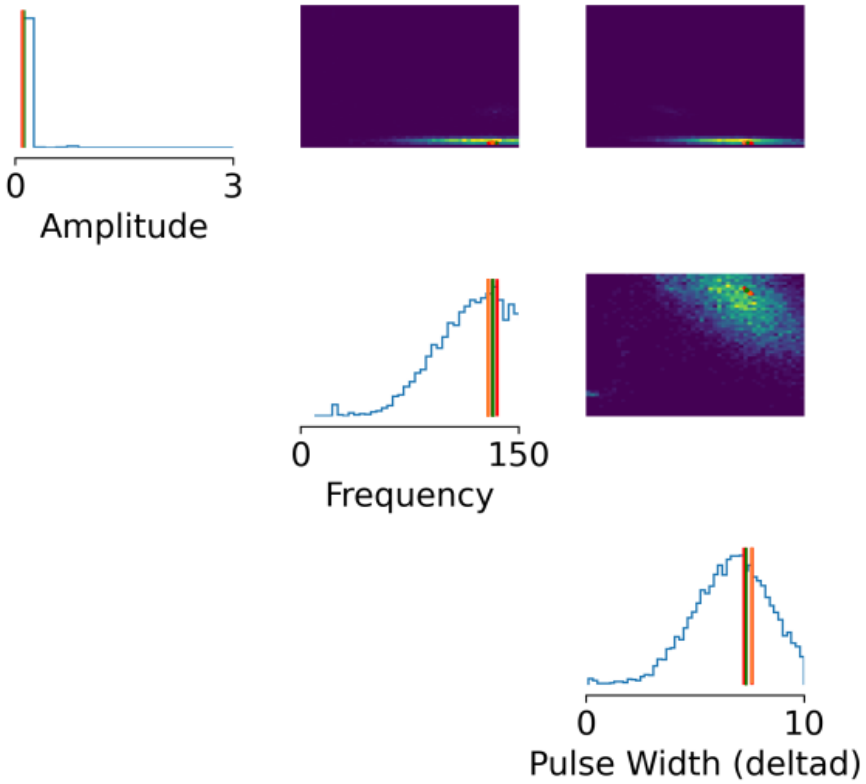
In contrast, the observation was generated by applying the same neuron model but with a higher external current (I_{ext} = 0.15 nA) while keeping DBS turned off. This elevated current mimicked conditions that can lead to excessive excitability or epileptic-like spiking behavior. This observation provided the symptomatic reference from which DBS would attempt to suppress activity.

To find DBS settings that could return the neuron from this hyperactive state back to the quiet baseline, we defined a prior distribution over the DBS parameters and used it to generate 20,000 samples. For each sample, we simulated the neuron's behavior with DBS active and the elevated I_{ext} maintained, ensuring that any suppression of activity was a result of the DBS parameters. A vector of summary statistics was extracted from each trace, including spike count, averaged membrane voltage, standard deviation, maximum value, and a newly introduced flatness score. This flatness score quantifies the average absolute difference between adjacent voltage values, serving as a metric for how steady (non-spiking) the membrane potential is. A lower flatness score indicates smoother, more quiescent behavior, which is desirable in this context.

After training the neural posterior using these summary statistics, we sampled from the learned posterior distribution conditioned on the hyperexcitable observation (Figure 6). To evaluate which DBS configurations most closely achieved the target suppression behavior, we computed the log-probability of each posterior sample. Log-probability is a measure of how likely a sample is under the learned posterior given the observed summary statistics; higher values indicate greater alignment between the sample and the target features. The three samples with the highest log-probabilities were selected as the top candidates for DBS intervention.

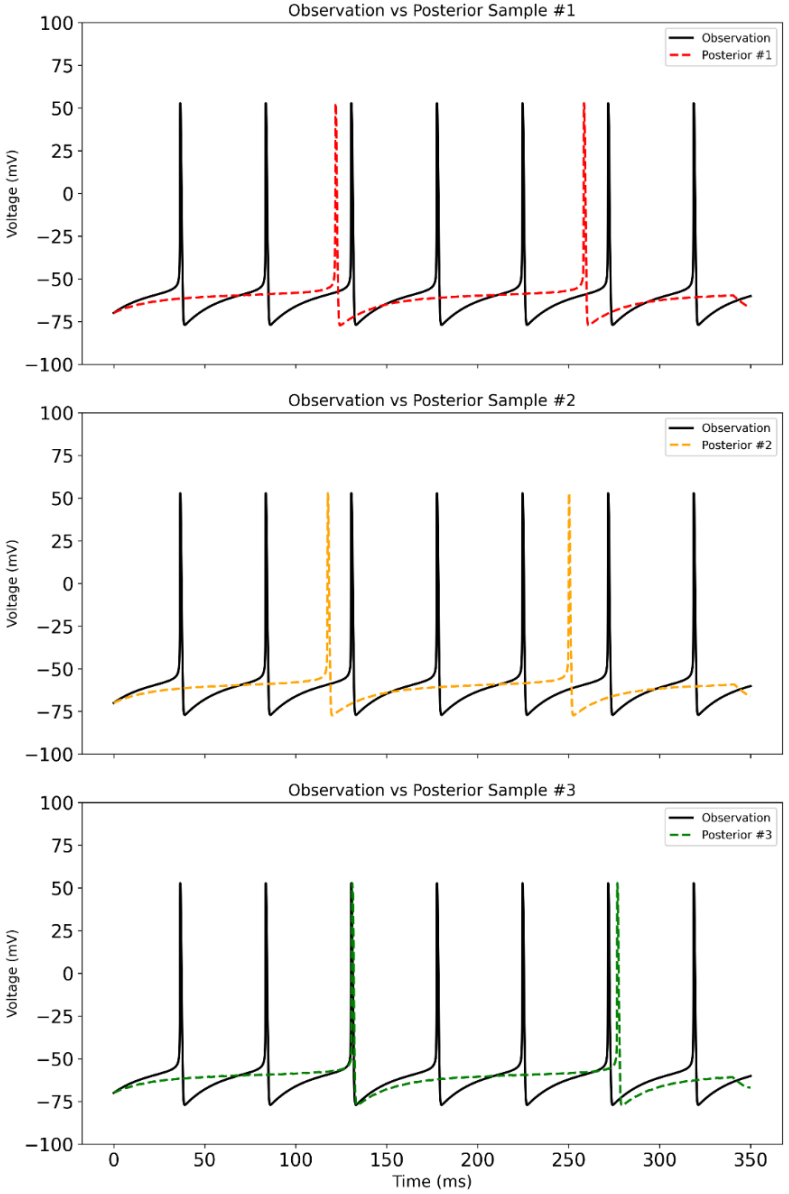
Each of these top three DBS parameter configurations was simulated under the pathological external current condition (I_{ext} = 0.15 nA). Their resulting voltage traces exhibited a marked reduction in pathological spiking compared to the original observation, while still maintaining some neuronal activity. This partial suppression reflects a therapeutically desirable outcome—mitigating excessive excitability without entirely silencing the neuron. Such modulation indicates effective intervention that avoids over-inhibition. The top-ranked parameter samples were visualized both as time series voltage traces and as highlighted points in the posterior distribution heatmaps (Figure 6), illustrating their high-probability placement within the inferred parameter space. This dual visualization approach enabled both effective navigation of the high-dimensional parameter landscape and prioritization of DBS configurations that restore more physiological firing patterns in a pathologically hyperactive neuron. Note that the range 120–150 Hz is the most promising for reducing seizure-like activity, as demonstrated by Lowet. Three trace examples are shown in Figure 7, where the target observation was set to 0 Hz in an attempt to lower the activity as much as possible.

Figure 6
Posterior Distribution of DBS Parameters



Notes. Posterior distributions over DBS parameters learned through Simulation-Based Inference. Each diagonal plot represents a 1D density heat map for a single parameter (amplitude, frequency, or pulse width), showing how likely different values are under the learned posterior. The off-diagonal plots display 2D density heat maps illustrating how pairs of parameters vary together. The color code for the plots is the same in Figure 6 and Figure 7.

Figure 7
Posterior Distribution of DBS Parameters



Notes. Comparison of membrane potential dynamics between the pathological observation (black trace) and the simulated response using the top posterior DBS parameter samples (dashed lines). Three examples are shown in the figure, following the same colors as in Figure 6. All posterior samples demonstrate strong but not total suppression of spiking activity, with reduced firing frequency compared to the observation.

Discussion

Our in-silico investigation extends the experimental findings of Lowet et al. (2022) by using a Hodgkin-Huxley neuron model augmented with simulation-based inference (SBI) to explore how deep brain stimulation (DBS) modulates neuronal excitability. We successfully replicated the frequency-dependent membrane depolarization observed in hippocampal CA1 neurons, particularly the rapid depolarization at 140 Hz, and showed that DBS induces voltage dynamics consistent with a functional disruption of neuronal information processing. In addition to capturing the qualitative trends of somatic depolarization, our model quantitatively reproduced the transient and sustained voltage responses, as well as the frequency-dependent modulation of firing rates in both sustained and transient phases. These results align with experimental measurements and confirm that our model can approximate the short-term and steady-state neuronal responses to DBS across different stimulation regimes.

However, while our model captured the general depolarization patterns seen in vivo, it failed to reproduce the gradual ramping observed under 40 Hz stimulation, an important detail of synaptic and network-level integration reported by Lowet et al. (2022). This could be due to several facts. First, the CA1 model used in this paper (Ceballos et al., 2025) disregards network activity and only simulates external noise as input to the neuron, therefore slower fluctuations such as the ones that can cause ramping may not be faithfully reproduced. Second, the model does not include all possible ionic currents, such as the ones that contain very slow time scales. Third, the morphology of a CA1 pyramidal cell is also simplified in this work, where a more complex dendritic tree, which potentially filters the signal in complex manners, could also affect the slow ramping of activity. Nevertheless, the major aspects we sought to reproduce were achieved. Additionally, although our stimulations replicated general trends in transient and sustained voltage and firing rate responses, some divergences in statistical significance highlight potential limitations in the model. These discrepancies suggest that external inputs and synaptic heterogeneity are likely to contribute to the observed variability in neuronal entrainment and response duration.

Our implementation of Simulation-Based Inference (SBI) enabled us to identify parameters, most notably DBS amplitudes, that reliably induce transitions from spiking to quiescent neural states. By training the SBI framework on a dataset of simulated neuronal responses across a range of DBS parameters, we were able to infer the posterior distribution over DBS amplitudes that minimize spiking activity and mimic a predefined target voltage trace with no action potentials. This approach allowed us to computationally reverse-engineer stimulation protocols that suppress epileptiform activity. In doing so, these simulations bridge basic biophysical modeling with therapeutic tuning, demonstrating how modern inference tools can be used to

optimize DBS strategies prior to experimental or clinical deployment.

A promising direction for future research is the extension of simulation-based inference (SBI) framework to estimate additional DBS parameters beyond the ones used here. Most notably, parameters related to non-periodic stimulation which are known to critically shape therapeutic outcomes. By jointly inferring both frequency and amplitude with different types of non-periodic stimuli, SBI could offer a more comprehensive strategy for personalizing stimulation protocols. This multi-dimensional posterior inference would allow researchers to identify optimal stimulation regimes to distinct pathological states, thus enhancing efficacy of these neuromodulation therapies. To improve mechanistic fidelity, future models should incorporate multi-compartment neuron architectures, synaptic input, and network connectivity. These additions may better capture the entrainment dynamics and delayed summation of synaptic potentials seen in the experimental work.

Overall, this study offers a computational scaffold that complements and extends experimental work on DBS. It highlights underexplored avenues, such as input-processing deficits, temporal entrainment, and SBI-guided parameter tuning, for translating biophysical insights into neuromodulatory interventions. Our findings advocate for a closer interplay between computational neuroscience and wet-lab experiments, particularly in designing preclinical validation frameworks for seizure-suppressive DBS protocols.

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A Comprehensive Overview of the Quantum Approximate Optimization Algorithm

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Abstract

As quantum computing research advances, the Quantum Approximate Optimization Algorithm (QAOA) has emerged as a leading approach to harnessing current quantum hardware for solving complex combinatorial optimization problems. This pedagogical, expository paper outlines the mathematical foundations of QAOA, explains its step-by-step implementation from first principles in a manner accessible to advanced undergraduate students and non-specialists, and explores real-world applications such as protein folding and job scheduling. We also examine the algorithm's performance challenges, including barren plateaus and circuit depth limitations.

Introduction

Quantum computing offers a novel and rigorous framework that leverages the principles of superposition and entanglement to tackle certain computational problems more efficiently than classical computers. Superposition allows quantum systems to represent and process multiple possibilities simultaneously, while entanglement creates strong correlations between particles where the state of one instantly influences the state of the other, enabling applications like quantum teleportation and encryption. Over the past three decades, the field has seen remarkable theoretical advances—from Shor's Algorithm for factoring large integers (1997) to the recent development of the Cascaded Variational Quantum Eigensolver (2024). One particularly promising direction for near-term quantum computers is combinatorial optimization—a broad class of problems characterized by discrete, often exponentially large solution spaces. Many of these problems, including clique detection and independent set identification, are known to be NP-complete, meaning they are computationally intractable for classical algorithms in the general case.

The QAOA is a hybrid classical-quantum approach that addresses these challenges by mapping problems onto parameterized quantum circuits. Inspired by the quantum adiabatic theorem, QAOA encodes problems into a Hamiltonian, a mathematical representation of the system's energy, and seeks low-energy states that correspond to optimal or near-optimal solutions.

Although the QAOA has significant potential, many existing review papers assume substantial prior knowledge of quantum computing, which can be a barrier for audiences who may lack specialized quantum backgrounds (Blekos et al., 2024). To broaden understanding of the QAOA, we formalize its algorithmic framework from first principles, discuss its applications to real-world problems, and evaluate its performance relative to well-known classical optimizers such as simulated annealing and semidefinite programming.

Foundations of Quantum Computing and the QAOA

Quantum Computing harnesses the physical properties of superposition and entanglement to solve problems faster than classical computers. Most quantum computers process information using quantum circuits, which consist of quantum gates applied to quantum bits, or qubits, that can exist in a superposition of states.

A classical bit is binary, like a coin, always in a state of either "0" (heads) or "1" (tails). In contrast, a qubit can be in a superposition of both states while unmeasured—like a spinning coin that embodies both possibilities. Once measured, however, a qubit "collapses" to either 0 or 1, with probabilities determined by its state. Mathematically, a qubit $|\psi\rangle$ is represented as a normalized vector in a two-dimensional complex vector space: $\psi\rangle = \alpha|0\rangle + \beta|1\rangle$, where α and β are complex numbers satisfying $2+2=1$. These coefficients determine the probabilities of measuring the qubit in the "0" ($|\alpha|^2$) or "1" ($|\beta|^2$) state. Additionally, α and β include a phase, which determines the direction of the qubit's state vector in the complex plane. While phase does not affect individual measurement probabilities, it influences how multiple qubits interact through interference. Qubits with aligned phases can amplify each other's amplitudes, while misaligned phases can cancel them out, enabling complex computations.

A single qubit alone is insufficient for practical algorithms. Quantum systems typically involve multiple qubits, say, n qubits, with their collective state described by a tensor product of individual qubits. This results is a vector in a 2^n-dimensional state space, matching the number of possible classical n-bit combinations.

As in classical computing, gates are applied to one or more qubits via matrix multiplication. While classical gates can take the form of any matrix, quantum gates must be unitary, meaning they preserve the state's magnitude and are reversible. This rules out non-reversible classical gates, such as AND. Common quantum gates, such as the Pauli, Hadamard, and CNOT, all satisfy the unitarity requirement and are listed in Table 1.

Table 1
Common Quantum Gates: One- and Two-Qubit Operations with Their Matrix Forms

Single-Qubit Gate	Matrix Form	Two-Qubit Gate	Matrix Form
Pauli-X (X)	$\begin{bmatrix}0 & 1\\1 & 0\end{bmatrix}$	Controlled Not (CNOT)	$\begin{bmatrix}1 & 0 & 0 & 0\\0 & 1 & 0 & 0\\0 & 0 & 0 & 1\\0 & 0 & 1 & 0\end{bmatrix}$
Pauli-Z (Z)	$\begin{bmatrix}1 & 0\\0 & -1\end{bmatrix}$	Swap Gate (SWAP)	$\begin{bmatrix}1 & 0 & 0 & 0\\0 & 0 & 1 & 0\\0 & 1 & 0 & 0\\0 & 0 & 0 & 1\end{bmatrix}$
Hadamard (H)	$\frac{1}{\sqrt{2}}\begin{bmatrix}1 & 1\\1 & -1\end{bmatrix}$	R_{zz} Gate ($R_{zz}(\theta)$)	$\begin{bmatrix}e^{-i\theta/2} & 0 & 0 & 0\\0 & e^{i\theta/2} & 0 & 0\\0 & 0 & e^{i\theta/2} & 0\\0 & 0 & 0 & e^{-i\theta/2}\end{bmatrix}$
R_x Gate($R_x(\theta)$)	$\begin{bmatrix}\cos(\frac{\theta}{2}) & -i\sin(\frac{\theta}{2})\\-i\sin(\frac{\theta}{2}) & \cos(\frac{\theta}{2})\end{bmatrix}$		

Quantum circuits are often presented as sequences of discrete gates, but real quantum systems evolve continuously over time. In practice, quantum gates are implemented through physical interactions governed by a Hamiltonian, an operator that represents the energy of the system. Because energy is a measurable quantity, its value must be real, implying that the Hamiltonian must be Hermitian. Mathematically, a Hermitian operator equals its complex conjugate transpose, ensuring real eigenvalues corresponding to physically meaningful energy levels. This Hermiticity also guarantees that the time evolution of a quantum system governed by a Hamiltonian H is unitary and thus described by a unitary operator $U(t) = e^{-\frac{iHt}{\hbar}}$. In this expression, ħ (the reduced Planck constant) sets the natural scale that connects energy with time, while the imaginary unit i ensures that the evolution changes only the phase of quantum states and preserves their total probability. The exponential of a matrix represents how the system evolves smoothly and continuously over time under the influence of its energy.

In practice, this continuous evolution is implemented using quantum circuits. Most physically realistic Hamiltonians involve only local interactions acting on one or two qubits, allowing the Hamiltonian to be written as a sum of simpler terms,

$$H = \sum_{j=1}^{m} H_j$$

where each H_j acts on only a small number of qubits and m is a fixed constant. The overall evolution $U(t)$ can then be approximated by a sequence of corresponding Hamiltonian gates where t represents time, enabling continuous dynamics to be realized with a finite set of quantum operations.

This structure is common because both real-world physical interactions and the cost functions of many combinatorial optimization problems involve only local interactions. When the local Hamiltonians commute, the time evolution operator factorizes neatly into a product of unitaries:

$$e^{-\frac{iHt}{\hbar}} = \prod_{j=1}^{m} e^{-\frac{iH_j t}{\hbar}}$$

This follows directly from the definition of the unitary time evolution operator and the commutativity of the Hamiltonian terms. In general, Hamiltonian operators do not commute, and in this case the exact time evolution must be approximated using the Trotter–Suzuki decomposition:

$$e^{-\frac{iHt}{\hbar}} \approx \left(\prod_{j=1}^{m} e^{-\frac{iH_j t}{\hbar r}} \right)^{r}$$

Informally, this method approximates the full unitary evolution by applying the individual Hamiltonian terms sequentially in small time steps. As the number of steps r increases, the approximation becomes more accurate, with the error decreasing quadratically in $1/r$. This gate-based decomposition of continuous dynamics forms a key foundation for adiabatic quantum algorithms and their discretized counterpart, the QAOA.

Many important optimization problems, such as the maximum independent set, the traveling salesman problem, and Boolean satisfiability, are NP-hard, meaning their solution spaces grow exponentially with problem size. These problems are typically formulated as minimizing a cost function $C(x)$ over discrete bit strings x. To solve such problems on a quantum computer, the cost function must be encoded into a Hamiltonian $H(x)$ whose ground states correspond to the optimal solutions. This encoding is commonly achieved using the Ising model, which provides a natural bridge between classical optimization problems and quantum Hamiltonians.

The Ising model is a simple mathematical model used to describe systems made up of many interacting binary variables set to be either -1 or +1. In physics, these variables represent tiny magnetic moments, called spins, that can point either up or down. Each spin interacts only with its nearby neighbors, and the system's total energy depends on whether neighboring spins are aligned or opposed, as well as on any external fields acting on them.

In quantum computing and optimization, the Ising model is useful because its spins naturally correspond to binary variables 0 or 1. Many optimization problems can be rewritten so that each possible solution corresponds to a spin configuration, and the energy of that configuration represents the cost of the solution. The goal is then to find the ground state of the Ising Hamiltonian, the configuration with the lowest energy, which corresponds to the optimal solution of the original problem.

To execute the QAOA, this Ising Hamiltonian H_C is paired with a mixing Hamiltonian H_M with a known ground state. In the adiabatic approach, the system evolves according to a time-dependent Hamiltonian that smoothly interpolates between these two,

$$H(s) = (1 - s)H_M + sH_C, \qquad 0 \leq s \leq 1$$

where $s=t/T$ is a normalized time parameter. Here, t is the physical time, ranging from 0 to the total evolution time T. The system begins in the ground state of H_M at $s=0$, and evolves slowly toward H_C. By the quantum adiabatic theorem, if this evolution is sufficiently gradual, the system remains close to its ground state and ends near the ground state of H_C at $s=1$, providing a solution to the optimization problem. QAOA can be viewed as a discretized version of this adiabatic process, making it suitable for implementation on gate-based quantum computers.

With the theoretical groundwork in place, we can now outline the QAOA in detail. The algorithm proceeds through the following five steps:

$$H_M = \sum_{i=1}^{n} X_i$$

$$\left(\frac{|0\rangle - |\bar{1}\rangle}{\sqrt{2n}}\right)^{\otimes n}$$

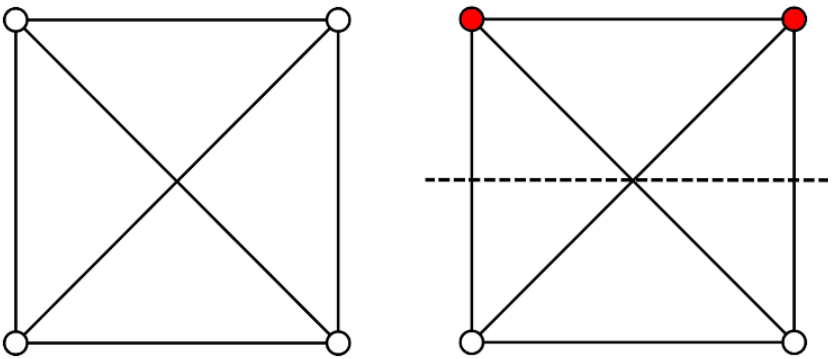
$$U(\gamma_k, \beta_k) = e^{-i\gamma_k H_C} e^{-i\beta_k H_M}$$

$$\boldsymbol{\gamma} = (\gamma_1, \gamma_2, \ldots, \gamma_p), \qquad \boldsymbol{\beta} = (\beta_1, \beta_2, \ldots, \beta_p)$$

QAOA In Action

With the theoretical foundations of QAOA established, we now turn to an example of a combinatorial optimization problem that can be addressed using a quantum computer: the MaxCut problem. Let G be a simple graph, with vertex set V and edge set E. A cut is a partition of V into two disjoint subsets, separating the vertices into two groups. The MaxCut problem seeks a partition that maximizes the number of edges connecting vertices in different subsets. An example of an optimal MaxCut on the complete graph K_4 is shown in Figure 1.

Figure 1
(Left) Complete Graph on 4 Vertices and (Right) a MaxCut of It



The MaxCut problem, an NP-hard computational problem, requires significant computational resources for large graphs, prompting the development of approximation methods like the QAOA. Here, we outline the process of adapting MaxCut into a QAOA circuit, providing a quantum circuit for the MaxCut problem on K_4.

To formulate the MaxCut problem as a problem Hamiltonian suitable for QAOA, we first express it as a Quadratic Unconstrained Binary Optimization (QUBO) problem and then map it to an Ising-model Hamiltonian. A QUBO encodes an optimization objective as a quadratic function of binary variables. For MaxCut, let $x_i \in = \{\pm 1\}$ represent the assignment of vertex $i \in V$ to one of the two partitions of the graph G. With this encoding, two vertices i and j lie in the same partition if $x_i x_j = 1$, and in different partitions if $x_i x_j = -1$. Using this representation, the indicator that an edge $(i, j) \in E$ is cut can be written as $(\frac{1 - xixj}{2})$ which is a quadratic expression in the binary variables. The total number of edges crossing the cut is therefore $(\frac{1}{2}) \sum_{(i,j)\in E}(1 - x_i x_j)$. Maximizing this quantity is equivalent to minimizing the following QUBO objective function:

$$\min_{x\in\{\pm 1\}^{|V|}} \frac{|E|}{2} - \frac{1}{2} \sum_{(i,j)\in E} x_i x_j$$

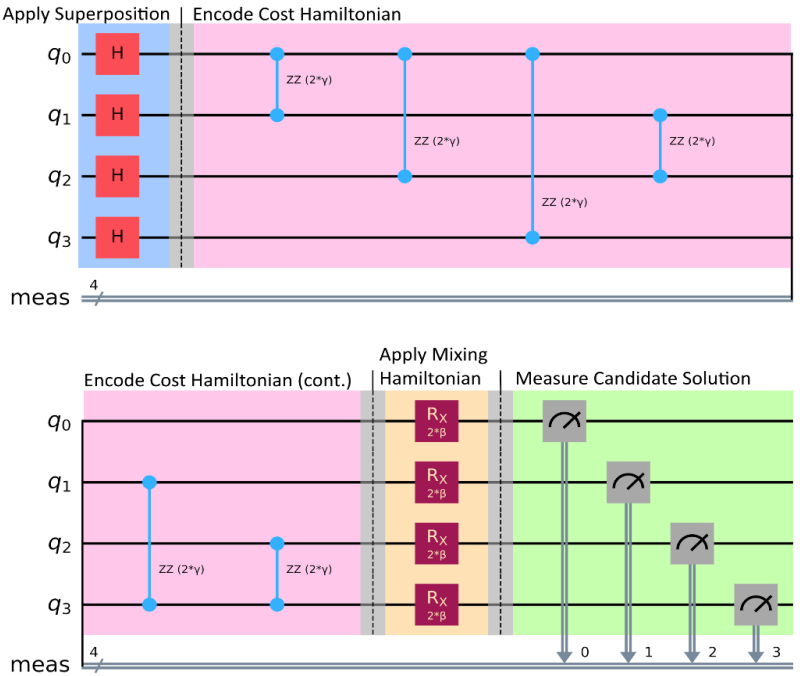
This formulation is standard in MaxCut and QUBO representations (Shaydulin et al., 2022). The benefit of using QUBO for designing QAOA circuits is that we have already encoded the vertices as spin variables, like in the Ising Model. To implement this on a quantum computer, we then convert the QUBO into a Hamiltonian by mapping the binary variables to quantum operators with ±1 eigenvalues with Pauli-Z gates and +1 with the Identity gate. By doing so, the ground state of this Hamiltonian becomes the optimal solution to our optimization problem. Thus, the problem Hamiltonian is:

$$H_C = \frac{|E|}{2} I - \frac{1}{2} \sum_{(i,j)\in E} Z_i Z_j$$

As in the general QAOA framework, the mixing Hamiltonian H_M is defined as the individual application of the Pauli-X gate to each individual qubit, that is, $\sum_{i=1}^{|V|} X_i$. With both Hamiltonians defined, the QAOA circuit for solving MaxCut on K_4 can be constructed, as illustrated in Figure 2.

In this figure, the qubits are first initialized in a uniform superposition (as seen in blue), after which the problem and mixing unitaries are applied sequentially, as seen in the pink and orange portions of the circuit respectively. Measuring the final state (green) produces candidate cuts, with higher-quality (near-optimal) solutions appearing with greater probability. The circuit parameters are then optimized using a classical optimizer, illustrating how QAOA combines quantum state evolution with classical feedback to approximate solutions to the MaxCut problem and, more broadly, to tackle computationally challenging optimization tasks.

Figure 2
Single-Layer QAOA Circuit Implementation of the MaxCut Problem on the Complete Graph K_4



Performance Comparison of Classical Algorithms Versus QAOA

Having demonstrated how the MaxCut problem can be mapped to a QAOA circuit, we now turn to the performance guarantees of several well-established classical optimization methods such as greedy heuristics, simulated annealing, and semidefinite programming, and compare them to QAOA in the context of MaxCut.

Greedy algorithms perform local, discrete searches by iteratively improving a solution through locally optimal choices, typically guided by a heuristic. While simple and efficient, greedy methods generally offer no performance guarantees for arbitrary optimization problems. For MaxCut, however, a greedy approach achieves a worst-case approximation ratio of 0.5, meaning that the number of edges cut by the algorithm is at least half that of the optimal solution.

Simulated annealing is a metaheuristic that explores the search space stochastically using a "temperature" parameter that gradually decreases over time. At higher temperatures, the algorithm allows random transitions (including moves to worse solutions) to escape local minima, while lower temperatures favor refinement near promising regions. Unlike gradient-based methods such as gradient descent or stochastic gradient descent, simulated annealing relies on randomized moves rather than local derivative information. Although it comes with no provable approximation guarantees, empirical studies indicate that simulated annealing often outperforms greedy methods for MaxCut (Mirka & Williamson, 2023).

Semidefinite programming (SDP) relaxations approach discrete optimization problems by embedding them into continuous convex optimization problems, which can be solved efficiently in polynomial time. In the case of MaxCut, the Goemans–Williamson algorithm, based on an SDP relaxation followed by randomized rounding, achieves a rigorous approximation ratio of approximately 0.878. This result remains one of the strongest known theoretical guarantees for MaxCut (Goemans & Williamson, 1995).

By contrast, QAOA performs a global search through the unitary evolution generated by alternating Hamiltonians, fundamentally differing from the classical approaches above. Unlike SDP-based methods, QAOA currently lacks a general theoretical performance guarantee for MaxCut. Nevertheless, provable approximation ratios have been established for specific graph families and circuit depths. For example, QAOA with a single layer achieves an approximation ratio of 0.6924 on 3-regular graphs, while a depth of three layers improves this ratio to 0.7559 (Wurtz & Love, 2021). These results, while promising, generally remain below the best-known guarantees achieved by classical SDP-based methods.

Real-World Applications

The QAOA has been explored as a potential tool for addressing a wide range of real-world optimization problems in areas such as logistics, network analysis, and computational biology. Its appeal lies in its ability to approximate solutions to combinatorially complex problems that become increasingly difficult for classical algorithms as problem size grows. Two illustrative application domains are job shop scheduling and protein folding.

Job shop scheduling, along with related task-scheduling problems, is a well-known NP-hard class of optimization problems that arises frequently in logistics, manufacturing, and operating systems design. In this setting, a finite set of machines must execute multiple jobs, each consisting of an ordered sequence of tasks that require specific machines for fixed durations. In recent work, Kurowski et al. (2023) applied QAOA to small-scale instances of the job shop scheduling problem and reported that, for toy examples involving three jobs and three machines, a depth-9 QAOA circuit produced optimal solutions in over 90% of runs. However, these results were limited to small instances and did not include direct comparisons with classical optimization methods. Assessing the scalability and competitive advantage of QAOA for larger, more realistic scheduling problems remains an open area of research.

QAOA has also been investigated in the context of protein folding, a notoriously challenging computational problem due to the exponential growth of possible molecular configurations. In this approach, peptide structures are modeled as self-avoiding walks on a lattice, allowing physical folding constraints to be encoded into a problem Hamiltonian suitable for QAOA. Boulebnane et al. (2023) demonstrated that this formulation can faithfully represent key aspects of protein folding but also found that achieving accurate results required deep quantum circuits. Such circuit depths pose significant challenges for implementation on current noisy quantum hardware, highlighting the gap between theoretical promise and near-term practicality.

Challenges of the QAOA

While the QAOA represents a promising approach for leveraging near-term quantum computers, recent research has highlighted significant limitations in its practical performance when compared with advanced classical optimization methods.

One major challenge lies in the execution of QAOA on existing quantum hardware. Although recent years have seen improvements in qubit counts and coherence times, current quantum devices remain highly susceptible to noise and environmental disturbances. Because qubits must be maintained in delicate, highly entangled states, even small interactions with the environment can induce decoherence, leading to bit flips and other errors in the computation.

Over sufficiently long time scales (on the order of tenths of a millisecond) these errors can accumulate and cause the quantum state to collapse, resulting in unreliable measurement outcomes (Place et al., 2021). To mitigate this issue, practitioners typically aim to keep QAOA circuits shallow by limiting the number of successive gates applied. However, reducing circuit depth also restricts the size and complexity of problem instances that can be meaningfully addressed. As a result, even in scenarios where QAOA may offer theoretical advantages, the small instance sizes accessible to current hardware, combined with the scalability of classical optimizers, often lead classical methods to outperform QAOA in practice (Benson et al., 2001).

A second major concern is identifying problem classes for which QAOA provides a provable polynomial or greater speedup over classical algorithms. As a heuristic algorithm, QAOA's performance depends strongly on the circuit depth and the effectiveness of classical parameter optimization. While Montanaro and Zhou (2024) demonstrated polynomial advantages for certain random k-SAT instances, other studies have shown more pessimistic results. In particular, Basso et al. (2022) found that for problems dominated by local interactions, fixed-depth QAOA circuits often fail to approach the true ground state, yielding solutions that remain far from optimal.

These limitations may be partially explained by the presence of barren plateaus in the QAOA loss landscape—regions where the gradient of the objective function is nearly zero across wide ranges of parameters, making optimization extremely difficult. For MaxCut, for example, most random graph instances exhibit barren plateaus, causing the algorithm to struggle even when large mixing parameters are used (Larocca et al., 2025). When optimization begins in such regions, classical optimizers may quickly converge to uninformative parameter values, effectively halting further progress. Several mitigation strategies have been proposed, including improved parameter initialization, quantum optimal control techniques, and depth-reduction strategies designed to avoid barren plateau regions (Larocca et al., 2022).

However, these approaches are still under active development and have yet to fully overcome the practical limitations of QAOA on current quantum hardware.

Conclusion

Despite its current challenges, the QAOA represents a significant milestone in quantum computing, demonstrating the potential to address complex combinatorial optimization problems using quantum hardware. As a prominent example of a variational quantum algorithm (Cerezo et al., 2021), QAOA illustrates how controllable quantum dynamics can be leveraged to explore high-dimensional solution landscapes in fundamentally new ways. Although its performance advantages are not universal, the conceptual and

technical insights gained from the development of QAOA continue to influence the broader design of quantum algorithms. Ongoing research aimed at mitigating practical limitations, such as barren plateaus, noise, and circuit depth constraints, promises to further refine its performance and solidify QAOA's role in the long-term evolution of quantum computing.

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Author Biographies

Anaya Bruno

Anaya Bruno is an undergraduate researcher at FAU. She is an FAU High School student and is working toward her high school diploma and bachelor's degree in psychology simultaneously. Her research interests include examining how aspects of religiosity may pose adverse effects on people's mental well-being, specifically in relation to leaving a harmful previous faith.

Vritti Sodha

Vritti Sodha is a dual-enrolled high school student interested in accounting. Her passion for learning her family language and connecting with her family inspired her to partake in this research. She attended the language-learning classes mentioned in the paper and would like to work to ensure that Gujarati, her family language, is not lost.

Emily Peraza

Emily Peraza is a graduate of the Wilkes Honors College with a Bachelor of Science in Cellular Neuroscience and a minor in French Language and Culture. During her time in the Ja lab at UF Scripps in Jupiter, Florida, she developed and optimized a surgical procedure in fruit flies to investigate the effect of removing the crop—the fly's stomach equivalent—on lifespan and behavior, which was performed during her undergraduate studies. Her interest in neuroscience started in middle school and has continued after her undergraduate studies, with a hope to attend medical school. Peraza was also a John Nambu Summer 2024 Research Experience scholar.

Susan Hernandez

Susan Hernandez graduated from FAU in May 2025 with a Bachelor of Arts in History, with a concentration in British History and a minor in Anthropology. She is a member of both Phi Kappa Phi and Phi Alpha Theta honor societies. Her research, *"Unwilling Consent or Ravishment?: Sexual Violence in Late Seventeenth-Century London,"* recently won the Traci Jill Edelman Award in History of Women, Gender, or Sexuality for a History Major and second place at the FAU Undergraduate Research Symposium. She is currently enrolled at the University of Tennessee–Knoxville, where she will expand her research to focus on women in post-Roman Europe. The research presented in this manuscript was collected while Susan was an undergraduate student.

Samkit Bothra

Samkit Bothra is a student at FAU High School, dual-enrolled at FAU. He joined the Business Economics Polling Initiative (BEPI) in 11th grade, pursuing his interests in artificial intelligence and public policy. His research investigates gender-based differences in perceptions of artificial intelligence's integration into social media ecosystems, with particular attention to trust, misinformation, privacy, and the broader societal and ethical implications of AI-driven digital platforms. His work culminated in a poster presentation at the Florida Undergraduate Research Conference, an oral presentation at the National Conference on Undergraduate Research, and an oral presentation at the FAU Undergraduate Research Symposium, where his work received a first-place award. Samkit wrote this manuscript during the summer between his junior and senior years of high school and is currently applying to colleges to pursue a bachelor's degree. After graduating high school this May 2026, he intends to continue coursework in computer science and engage in research at the intersection of technology and public policy.

Christofer Piedra

Christofer Piedra is a Fall 2025 graduate of FAU, where he earned a Bachelor of Business Administration and a Bachelor of Science in Computer Science with a minor in Artificial Intelligence. He conducted undergraduate research under the mentorship of Dr. Imadeldin Mahgoub through a Summer Undergraduate Research Fellowship (SURF) and continues to support FAU's Tecore Research Lab as a lab administrator and active contributor to graduate-level cybersecurity projects. His research focuses on network security, virtualized detection environments, and Zeek-based intrusion detection. He has also served as a teaching assistant for a graduate-level engineering course and led the development of a campus-wide student networking platform.

Dylan Lewis

Dylan Lewis is a graduate of FAU, where he earned a Bachelor of Science in General Economics in August 2025. In the fall of 2023, he joined the Business and Economics Polling Initiative (BEPI), conducting research that he later presented at both the Florida Undergraduate Research Conference and the FAU Undergraduate Research Symposium. Following his work with BEPI, Lewis served as a Peer Mentor for the Office of Undergraduate Research and Inquiry, supporting College of Business students in the development and completion of their research projects. During his time at FAU, Lewis was actively involved in campus leadership, serving as President of the Economics Club, Secretary of the Student Global Business Association, and as a proud brother of the Kappa Sigma Fraternity. His involvement across research, leadership, and student organizations reflects a strong commitment to academic excellence and the broader FAU Owl community.

James Lee + Ty Roachford

James Lee is currently a sophomore at the Wilkes Honors College at Florida Atlantic University, majoring in Biological and Physical Sciences within the pre-medical Bachelor of Science/ Doctor of Medicine (MD) program. His academic journey is fueled by a profound interest in the life sciences and a commitment to advancing medical knowledge through rigorous research. During his time in Dr. Pena's Computational Neuroscience Lab, he is focusing on investigating the neurophysiological mechanisms of deep brain stimulation (DBS) in the hippocampus using computational modeling techniques. This experience has allowed him to merge his passion for data analysis with his fascination for the brain's intricate processes. He is particularly interested in understanding how DBS-induced membrane depolarization affects neuronal responses and creates an informational lesion.

Ty Roachford has been fascinated by the brain since grade school—a curiosity that led him to study Neuroscience at Florida Atlantic University, where he now pursues his PhD in the Pena Lab. His research investigates the relationship between neural morphology, information-processing, and bioenergetic processes, drawing on theoretical frameworks from Computational Neuroscience, Mathematics, and Statistical Physics. His current work focuses on co-transmission: neurons that release multiple neurotransmitters. These neurons require specialized synaptic morphology to accommodate additional molecular machinery, which imposes non-trivial energetic demands. His recent research suggests that the nonlinearities induced by co-transmission enable unique information processing capabilities beyond what mono-transmitting neurons can achieve. Ty has presented at the International Association for Perceptual Control Theory and was an invited guest at the Active Inference Institute. He prioritizes cross-disciplinary collaboration, advocates for educational outreach, and shares many scientific projects—with complete source code—on his personal website.

Vincent Stafford

Vincent Stafford is a senior at the Harriet L. Wilkes Honors College, majoring in computational mathematics. A Goldwater Scholar, his research focuses on applying mathematical techniques to problems in optimization and algorithm design. Vincent has completed research-intensive projects in topology, number theory, and AI applications to biology, including published works on neural-network-based drone detection. He plans to complete his senior thesis in approximation algorithms for problems in graph theory and pursue doctoral studies to further contribute to the field of computational mathematics.

Notes

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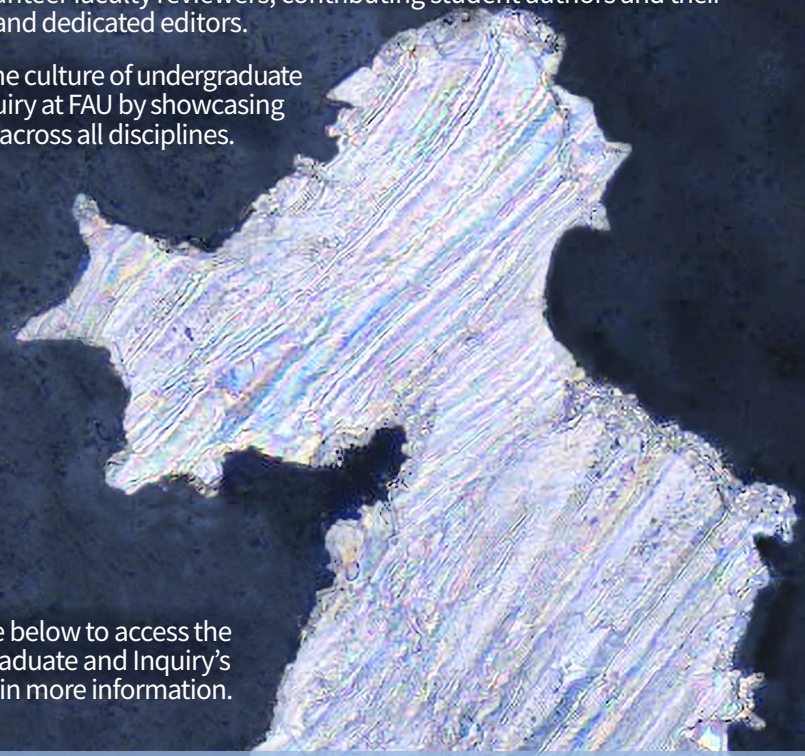

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