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Competition, Collaboration, and Learning Mathematics through Games

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Abstract

This study investigates how gameplay format shapes mathematical reasoning and social dynamics in primary classrooms. We compared one-against-one (1v1) and paired (2v2) versions of five non-digital games implemented by five Year 3/4 teachers (≈90 students). A mixed-methods design triangulated teacher interviews, student reflections (n≈40), and video-recorded gameplay from 20 focus students, coded for reasoning (generating, evaluating, justifying, clarifying, predicting, reflecting, prompting/helping, and connecting) and interactional moves (game management, emotional tone, self-talk, and off-topic talk). Across classes, 2v2 play elicited more visible reasoning than 1v1. Frequencies rose for Generating (104 vs. 42), Evaluating (217 vs. 136), and Justifying (68 vs. 30), as students proposed ideas, weighed alternatives, and negotiated shared decisions. Prompting/Helping was also higher, reflecting peer teaching. Importantly, mathematical connections occurred more often in 2v2 (26 vs. 5), with students applying concepts such as primes, factors, and multiples to guide play. Teachers reported richer discussion and conceptual talk during 2v2. However, 2v2 also introduced challenges: Game Management (311 vs. 223), Emotional Tone (70 vs. 37), and Off-Topic Talk (47 vs. 16) all increased, signaling coordination demands and uneven participation. Student reflections preferred 2v2 (≈65%), citing teamwork, while 1v1 supporters valued autonomy. We conclude that 2v2 competition fosters co-constructed reasoning, yet its success depends on intentional facilitation.

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Introduction

Mathematical games are increasingly recognised as a valuable tool in primary classrooms, not just for engagement but also for deepening learning. Surveys consistently show high rates of game usage among teachers. For instance, in a large-scale Australian study (Russo et al., 2021), an overwhelming majority of teachers (nearly 80%) reported using games multiple times per week, with an even higher percentage (92%) agreeing that games are effective for generating rich mathematical discussions. Approximately nine in ten teachers endorsed the role of games in supporting all four mathematical proficiencies (Understanding, Fluency, Problem Solving, and Reasoning), which together describe how students make sense of mathematical ideas, develop efficient skills, apply mathematics to unfamiliar situations, and justify their thinking (ACARA, 2025). This indicates that teachers perceive games as more than just tools for practising basic facts but potent vehicles for fostering deeper mathematical understanding and discourse. Teachers frequently use games to make learning enjoyable, motivate students, and cultivate critical thinking (Russo et al., 2021).

Indeed research shows that using games in mathematics classrooms, beyond their use for developing computational fluency, can improve mathematical thinking, reasoning, problem-solving, and understanding (Cramer, 2019; McFeetors & Palfy, 2018; Pintér, 2010; Russo & Russo, 2020, 2025). While the general benefits of integrating games into the curriculum are widely acknowledged, the specific impact of different game formats on mathematical reasoning and student interaction within the classroom remains an area requiring further investigation. Investigating how game formats influence mathematical discourse and conceptual understanding is crucial for informing pedagogical practice. This paper explores the differential impacts of one-against-one (1v1) and paired (2v2) mathematical game formats on student reasoning and social dynamics in primary school settings. Drawing on triangulated data from teacher perspectives, detailed analysis of student-to-student interactions, and student reflections, we aim to provide insights into how game format shapes mathematical discourse, peer support, and classroom management. This paper first reviews relevant literature, followed by methods, findings, discussion, implications, and limitations.

Literature Review

Theoretical Framing: Social Constructivism

This study is grounded in social constructivism, where knowledge is co-constructed through social interaction and discourse (Clements, 1997; Fosnot, 2005). Within this paradigm, the mathematics classroom functions as a “mathematics-talk community” (Fosnot, 2005), where dialogue clarifies and extends thinking, and ideas are “objects of reflection, refinement, discussion and amendment” (NCTM, 2000, p. 60). This view of learning positions “talk “as central to conceptual understanding (Clements, 1997) as students externalise thinking by reasoning aloud and justifying choices (Fosnot, 2005); the quality and nature of student discussion become key indicators of learning.

Mathematical games offer a promising context for engaging in mathematical discussion. Gameplay inherently involves turn-taking, decision-making, negotiation, and crucially, opportunities for students to make their thinking public. However, not all games, and not all gameplay structures, promote reasoning in the same way. This study examines how different gameplay formats, one-against-one and paired games, shape students' opportunities to reason, communicate, and construct mathematical understanding. The study explores how the game format mediates reasoning by analysing student-student interactions during gameplay and drawing on teacher insights.

This theoretical framing shapes the study's design and the findings' interpretation. It views reasoning not as a private, individual process, but as something that happens through social interaction. In this view, reasoning is expressed through talk, shaped by peer interactions, and influenced by the game format (playing one-on-one or working with a partner against another pair).

Mathematical Reasoning and Discourse in Games

Mathematical reasoning is a cornerstone of mathematical proficiency, defined in the Australian Curriculum: Mathematics (ACARA, 2025) as the ability to explain thinking, deduce and justify strategies, and adapt learning across contexts. This dynamic process of refining ideas toward conceptual understanding is reflected in the "verbs of mathematical reasoning" (McFeetors & Palfy, 2018, p. 106), such as generalising, conjecturing, and justifying.

Games have the potential to uniquely promote purposeful dialogue, often requiring players to articulate and justify their reasoning (Russo et al., 2023). Indeed, there is research showing that game-based lessons prompt significantly more on-task mathematical talk compared to non-game lessons (Bragg, 2012b), fostering active communication as students build and refine convincing mathematical arguments, thereby co-constructing understanding (McFeetors & Palfy, 2018; Putra et al., 2020). Games inherently create opportunities for interaction and discussion due to their multi-player nature (Ernest, 1986; Gough, 1999). As Ernest (1986) noted, "Children cannot play games passively; they must be actively involved, making the concepts and skills of mathematics their own" (p. 3). Similarly, Skemp (1986) emphasised that games allow students to get their thinking "out on the table" (see Stacey & MacGregor, 2022, p. 219). Stacey and MacGregor (2022) explain that this was a key insight, as Skemp demonstrated that games provide a window into children's thinking, making their thought processes externally visible and accessible. The "games" thus provide a structured context for the underlying mathematical ideas to be explored discursively. Ultimately, the enduring appeal of games in mathematics education is seen in both earlier and recent research, with the work of Russo et al. (2023) reaffirming that their unique ability to get students' thinking "out on the table" and into the open for discussion is fundamental to their pedagogical value.

However, the quality of this discourse is not always uniformly positive. Heshmati et al. (2018) report lower quality teacher-student interactions during gameplay, compared with non-game lesson components, often focusing on the progress of gameplay (e.g., who is winning and whose turn it is) rather than on rich mathematical reasoning. Furthermore, Bragg (2006a), observed that while students learned to play the game and followed the rules, their inability to explain their gameplay actions indicated a procedural, rather than conceptual, engagement with the mathematics. This highlights a critical point: for games to effectively support mathematics, the discourse, both between teachers and students and between students, should extend beyond basic procedural dialogue. It needs to encompass a deeper mathematical discourse that includes explicit reasoning, explaining, justifying moves, and negotiating strategies. This articulation of thinking ultimately allows students to construct and refine ideas, thereby developing a robust mathematical understanding (Oldfield, 1991; Stigler & Hiebert, 2004).

These findings suggest that the benefits of discussion depend not only on the game chosen but also on how the discourse is facilitated to promote purposeful dialogue. While the quality of teacher-student interactions during gameplay warrants careful attention and indeed was examined as part of our larger research project (forming the focus of a separate paper; see Klooger et al., 2026), this current study investigates how different gameplay formats shape mathematical reasoning by examining student-to-student discourse during gameplay.

Researchers have developed various tools to assess mathematical reasoning. Trakulphadetkrai's (2022) "Student-to-Student Mathematical Talk" (SSMT) framework, for instance, captures reasoning types through categories of verbal interactions. Loong et al. (2013) developed a rubric for primary classrooms, assessing reasoning actions like analysing, generalising, and justifying. These frameworks aim to capture the dynamic and iterative reasoning process, aligning with McFeetors and Palfy's (2018) concept of reasoning being a "work in progress" (p. 104). In this study, we used these frameworks as sensitising references: they seeded our initial code list and later served as a comparative lens to check construct coverage. However, we did not apply either instrument verbatim; instead, we developed a concise, gameplay-specific scheme. Appendix 1 includes an alignment table linking their constructs to our reasoning verbs.

Well-designed Mathematical Games: Design Principles and Cognitive Conflict

Well-designed mathematical games integrate mathematical content and strategic gameplay to support deep learning (Gough, 1999; Russo et al., 2023; Russo & Russo, 2025), requiring students to apply reasoning, explore patterns, and make purposeful decisions. Building on recent work highlighting that instructionally rich games embed strategic agency, mathematical representations, and opportunities for reflection (Russo & Russo, 2025), this study employed five games deliberately designed to keep mathematics at the centre of play, encourage meaningful decision-making, prompt opportunities for reflection and discussion, and balance skill, strategy, and chance to support optimal cognitive demand (see Appendix 2).

For effective discussions to build understanding, they must often be centred around a cognitive conflict. This mental tension happens when new or contradictory information challenges a learner's thinking (Onslow, 1990). From a constructivist perspective, experiencing disequilibrium is vital when learning mathematics (Fosnot & Perry, 1996). Gameplay is a prime context where cognitive conflict can arise in several ways: when rules or outcomes contradict expectations, when teammates disagree on a move, when an opponent presents an unexpected strategy, or when gameplay reveals a gap in conceptual understanding (see Table 1 for an example of cognitive conflict in the games used in this study).

When students are challenged by unexpected outcomes, need to justify complex procedures, or reflect on why a strategy worked or failed, it naturally leads to articulation, debate, and resolution of misconceptions, the very mechanisms through which mathematical discourse and reasoning builds conceptual understanding. As others such as Bragg (2007) have observed, “students’ aspirations to win encourages them to wrestle with mathematical concepts” (p. 39), constructing meaning from the problem-solving process and highlighting the crucial role of challenge in fostering mathematical thinking. However, cognitive demand alone is insufficient; games may not support deeper understanding unless students actively engage in reasoning and reflection (Stein & Smith, 1998), which requires deliberate teacher facilitation (Heshmati et al., 2018).

Table 1. Examples of Cognitive Conflict in the Study’s Games

Type of conflict	Description and Example
Rules or outcomes contradict expectations	Occurs when a student’s existing assumptions are challenged by how the game rules or results unfold Example (*Reverse Landgrab*): A student rolls a prime number (e.g., 17) and attempts to form multiple arrays, only to realise it can only be a 1x17 array, which does not fit the gameboard grid. This directly contradicts their assumption about number factorisation (e.g., “multi-digit numbers have many factors/ belong to many counting patterns”), highlighting the unique properties of prime numbers.
Teammates disagree on the correct move	Arises in collaborative play when partners hold differing mathematical strategies or understandings of the optimal move Example (*Three-in-a-Row Lucky Numbers*): Partners disagree on marking ‘18’ after landing on a lucky number. Partner A argues for choosing 18, while Partner B argues for choosing a number with fewer factors. This leads to a discussion about probability, prime numbers, and strategic placement.
Opponent presents a better or unexpected strategy	Happens when a student observes an opponent’s more efficient or mathematically sophisticated strategy Example (*Choc-Chip Cookies Game*): Player 1 uses repeated addition to calculate the total choc chips (e.g., “For 19 × 5: 19 plus 19 is 38, plus another 19 is 57…”). Player 2 quickly applies the distributive property (e.g., “20 × 5 minus 5”), prompting Player 1 to recognise, and potentially adopt, a more efficient mathematical strategy.
Gameplay reveals a gap in conceptual understanding	Occurs when the mechanics or outcomes of the game directly expose a student’s mathematical misconception Example (*Skip Counting Bingo*): A student consistently chooses only even numbers as Bingo numbers (e.g., 26, 32). This reveals a misunderstanding that when skip counting, you will always be more likely to land on an even number. It highlights a gap in their understanding of factors and multiples of even/ odd numbers.

In a study of 32 Year 7 students who played three different integer games (Go-High/Go-Low, Integer Product, and Integer 24), Nurnberger-Haag and colleagues (2023) found that gameplay could demand complex reasoning, spark cognitive conflict, and provide the very conditions for rich mathematical discourse. Students often judged such games to be more than entertainment, valuing them as meaningful opportunities for learning. Importantly, game features such as turn-taking (Go-High/Go-Low, Integer Product), requirements to justify and verify solutions (Go-High/Go-Low, Integers 24), the role of chance elements (Go-High/Go-Low), and strategic blocking

(Integer Product) were observed to prompt discussion between players, thereby elevating the cognitive demand of the tasks. Strikingly, these discussions arose in the context of one-against-one play (i.e., 1v1 games), indicating that opportunities for mathematical dialogue and heightened cognitive demand can emerge even within 1v1 gameplay without requiring explicit collaborative structures.

Gameplay Formats: Competition and Collaboration

The gameplay format is a critical design element that significantly influences student interaction and learning outcomes in educational contexts. Research on its effects in educational settings indicates mixed findings, and its effectiveness often depends on how it is implemented and the specific conditions of use. Prensky (2001) distinguishes between competitive play, in which success is defined in relation to outperforming others, and collaborative play, in which participants work together toward a shared goal.

A review of 32 studies on non-digital mathematical games by Russo et al. (2024) found competitive formats to be predominant (15 studies), while purely collaborative games were rare (4 studies). The remaining studies incorporated a blend of competitive and collaborative elements (2 studies) or featured solo gameplay/unspecified structures (11 studies). Russo et al. (2024) note the scarcity of research on collaborative gameplay formats with non-digital games. It is worth noting that in their operationalization, collaboration referred to players working together within a pair or team toward a shared outcome, even where teams then competed against one another, whereas competition described formats in which individuals sought to outperform others without intra-team cooperation.

This differs somewhat from how we operationalized competition and collaboration in the current study, where gameplay format (1v1 vs 2v2) provided the structural context, but collaboration was examined as an interactional process that could also emerge within competitive settings through moments of shared reasoning, peer support, or cross-team dialogue.

Competition in Gameplay

Competition is a common design element in games often assumed to foster motivation, engagement, and persistence (Delahunty & Roche, 2024; Nurnberger-Haag et al., 2023; ter Vrugte et al., 2015). Students often express a strong preference for competitive gameplay, citing enjoyment of the competition and winning, with some explicitly preferring to work individually (Delahunty & Roche, 2024; Nurnberger-Haag et al., 2023). In Delahunty and Roche's (2024) study, 85 Year 3–4 students each played three mathematical card games (Nearest to the Gnarly Number, RowCo and The Same As) in competitive, cooperative, and collaborative forms before indicating which version they enjoyed and learned from the most. The authors defined *competitive* gameplay as players striving to outperform others without supporting one another, *cooperative* gameplay as players supporting each other's progress while still pursuing individual goals, and *collaborative* gameplay as players working together as one team toward a shared outcome. Notably, those who preferred one-against-one gameplay often reported learning effectively in that mode, indicating that for some learners, the autonomy of playing individually may contribute to both enjoyment and opportunities for learning.

The broader impact of competition in educational games is often mixed with studies revealing varying outcomes on learning. Plass et al. (2013) found that adding a competitive element to an arithmetic game motivated players to solve more problems than those who played alone. Yet, these gains did not translate into improved out-of-game fluency, suggesting that the motivation to win may not necessarily support deeper or transferable mathematical learning. Similarly, Çelik's (2017) compared game-based learning for third-grade students in geometry with other instructional methods, such as creating physical models of geometric shapes and traditional teacher-led instruction. While the game-based group reported some positive experiences, their learning gains were not statistically significant compared to the modelling-based approach. This study highlighted that the effectiveness of game-based learning depends less on the inclusion of a game element alone, and more on alignment with learning goals and the quality of implementation. However, other studies present more positive outcomes. Cagiltay et al. (2015), for instance, found that competition in games significantly boosted learners' motivation and improved post-test performance, suggesting a role for competitive play in fostering conceptual understanding and fluency when games are well aligned with instructional goals, thoughtfully designed and implemented.

Critically, competition also carries potential drawbacks, particularly for less secure learners. It can induce tension, anxiety, and feelings of frustration or inferiority, which may diminish working memory capacity, lead to avoidance, and reduce performance (Dondio et al., 2023; Nurnberger-Haag et al., 2023; Plass et al., 2013). To mitigate these pitfalls, especially those related to stress from speed-based competition, incorporating asynchronous play (turn-taking) and balancing mathematical skill with elements of chance (e.g., dice, cards) can create more equitable and less stressful experiences for diverse learners, given they have a reasonable chance of winning (Nurnberger-Haag et al., 2023; ter Vrugte et al., 2015). Teachers can mitigate negative effects by rebalancing teams, rotating partners, or varying the task structure so that success is distributed more equitably. Importantly, the focus can be shifted from *winning* to *strategic improvement or personal growth*, for instance by prompting students to articulate what they might try differently next round. Such moves sustain emotional engagement and preserve self-efficacy while maintaining the motivational benefits of competition. Furthermore, high student engagement in competitive games can be problematic if driven primarily by a desire to win rather than engagement with mathematical objectives (Heshmati et al., 2018). As Gough (1999) warned, an excessive focus on competition can distract students from educational content, leading them to be "so distracted by their natural interest in playing to win, that they fail to focus on the mathematics" (p. 14). Therefore, student behaviors must be directly related to the learning process, with energy expended on understanding complex ideas beyond merely winning.

Collaboration in Gameplay

Collaboration, viewed as a social process of knowledge construction, generally benefits learning by fostering shared meaning and problem-solving (Fosnot, 2005). In educational games, collaboration can provide continuous support, encourage knowledge externalisation, and lead to positive affective outcomes, such as improved attitudes towards mathematics (Ke & Grabowski, 2007; McFeetors & Palfy, 2018). Students favouring cooperative or collaborative formats value working with partners and opportunities to help or be helped (Delahunty & Roche, 2024; Dondio et al., 2023).

However, research findings on combining collaboration with competition in games remain complex and mixed. While some studies, such as Cichy et al. (2020), found collaborative gameplay resulted in faster acquisition of mathematical skills and knowledge, others report decreased performance or no significant effect on learning outcomes (e.g., Plass et al., 2013). The impact can also vary significantly based on individual student characteristics. For example, ter Vrugte et al. (2015) studied pairs of students collaborating on mathematics tasks within a digital game, with some pairs additionally placed in competition against other pairs. They found that for below-average students, competition undermined the benefits of collaboration, whereas for above-average students, competition in a collaborative setting showed a positive trend. Collaborative games also present challenges like uneven participation or social friction (Plass et al., 2013).

As Dillenbourg (1999) cautions, collaborative learning is not inherently productive; rather, its success depends on carefully designed situations that increase the likelihood of specific, productive interactions that facilitate learning. Peers do not learn simply because they are grouped together, but because they engage in particular activities such as explanation, disagreement, and mutual regulation, that activate learning mechanisms. To foster these processes, group members must share a valued common goal, and the activity's success must depend on each member's contribution and individual accountability (Dillenbourg, 1999). This highlights the importance of deliberate design, including thoughtful group composition, clear task structure, defined roles, interaction prompts, and teacher facilitation (Dillenbourg, 1999).

Measuring the Impact of Mathematical Games

The presence of conflicting findings on the impact of playing games on mathematical learning reported in meta-analyses and systematic reviews may in part stem from limited or incongruent outcome measures, with many studies frequently neglecting broader aspects of mathematics learning beyond procedural knowledge (e.g., Abdul Jabbar & Felicia, 2015; Kacmaz & Dube, 2022; Russo et al., 2024). Measuring the impact of mathematical games on learning requires assessing not just knowledge of procedures but also the development of a variety of mathematical proficiencies, which encompass:

- Understanding: making connections and explaining concepts.
- Fluency: recalling facts and applying procedures.
- Problem-solving: formulating, representing, and solving problems.
- Reasoning: explaining thinking and justifying strategies (ACARA, 2025).

Russo et al. (2024) found that achievement tests were used in roughly three-quarters of the studies reviewed. However, they also highlighted the importance of complementing such narrow, easily quantifiable measures with interviews, observations, student-produced artefacts, and reflections to capture outcomes more comprehensively. Building on this, the present study employs probing assessment methods that focus on student gameplay as well as teacher and student reflections. This multi-faceted approach is designed to capture the rich and diverse learning outcomes fostered by mathematical games, that might otherwise be overlooked if more traditional, reductive measures of achievement are employed exclusively.

Aims of the Current Study

Taken together, the literature highlights the need for closer examination of how different mathematical game formats influence students' reasoning and discourse, supported by richer forms of evidence. Addressing this gap, the present study set out to investigate how one-against-one (1v1) and paired (2v2) gameplay formats shape students' opportunities to reason and construct mathematical understanding. Specifically, the aims were to:

- Explore teachers' perceptions of mathematical reasoning during gameplay.
- Investigate students' preferences for different gameplay formats.
- Analyse student-to-student interactions during gameplay sessions to understand how reasoning is manifested and influenced by game format.

Method

This study employed a mixed-methods design, collecting data from teacher interviews, student reflections, and video-recorded gameplay transcripts, analysed through an interpretivist lens focused on mathematical discourse.

Research Context and Participants

The study involved five Year 3/4 teachers and approximately 90 students from two Victorian (Australia) state schools. Two classes ($n \approx 40$) completed written reflections, and 20 focus students (four from each class) were video-recorded during gameplay. Teacher interviews provided additional insights. Each teacher selected and used two multiplication games from a curated bank of carefully designed, non-digital games (see Appendix 2).

For each selected game, teachers taught two lessons: Lesson 1 in a one-against-one (1v1) format and Lesson 2 in a pair-based (2v2) format. These five games, adapted for both one-against-one (1v1) and paired-based (2v2) formats, were specifically designed to align with educationally rich game principles (see Russo et al., 2023; Russo & Russo, 2025). This structure supported comparisons of gameplay format through drawing on a common design framework. Table 2 summarises the games used.

Table 2. Games played by teachers across Lesson 1 and Lesson 2

Teacher	Lesson 1 (One-against-one)	Lesson 2 (Team-based)
Ashleigh	Three-in-a-Row Lucky Numbers	Reverse Landgrab
Emily	Choc-chip Cookies Game	Reverse Landgrab
Joel	Choc-chip Cookies Game	Reverse Landgrab
Morgan	Reverse Landgrab	Three-in-a-Row Lucky Numbers
Ryan	Skip Counting Bingo	Three-in-a-Row Lucky Numbers

Data Collection and Analysis

Data were collected from three primary sources:

1. Teacher Interviews: Semi-structured interviews were conducted with the five teachers at the beginning of the project, following each lesson, and again at the end, probing their perceptions of the 1v1 and 2v2 game formats.
2. Student Reflections: Written reflections were collected from approximately 40 students after each lesson, detailing their format preferences and affective responses as to why they preferred one game format over the other.
3. Video-recorded Gameplay Transcripts: Video recordings of the 20 focus students during gameplay sessions were transcribed.

Following data collection, teacher interview transcripts and student reflections were analysed through an open-ended process aimed at identifying recurring patterns in teachers' perceptions and students' experiences and preferences for game format. Quantitative preferences from students were tallied. Video-recorded gameplay transcripts were analysed using an iteratively developed coding framework. Initial inspiration was drawn from Trakulphadetkrai's (2022) Student-to-Student Mathematical Talk (SSMT) framework. However, early attempts to apply the extensive SSMT framework to our game-based video data proved too cumbersome. Recognizing the dynamic nature of gameplay, the coding process was refined through multiple rounds of viewing and discussion until a concise and contextually relevant set of categories emerged**.** These included categories for mathematical reasoning (e.g., Generating Ideas, Evaluating, Justifying, Predicting, Reflecting, Helping/Prompting, and Connecting) and broader interaction dynamics (e.g., Game Management, Emotional Tone, Student Talk, and Off-Topic Talk). The final code book retained shared "reasoning verbs" (e.g., generating, evaluating, justifying) and added interaction codes suited to gameplay (e.g., game management, emotional tone), and we cross-checked code coverage against the SSMT framework and Loong et al. (2013) to support validity. All codes and their application were systematically discussed and refined to ensure rigor. This process involved collaboration and refinement with the third author. This framework served as the analytical lens to systematically examine the nature and quality of mathematical reasoning in student-to-student discourse across game format. For details of the full coding framework (see Appendix 3).

Finally, triangulation was performed through validating emerging patterns and deepening interpretations by comprehensively comparing findings from all three data sources (teacher interviews, student reflections, and gameplay transcripts). This multi-perspective analysis aimed to provide a robust account of the study's key aims: teachers' perceptions of mathematical reasoning across different gameplay formats, students' preferences for different gameplay formats, and how gameplay formats shaped student mathematical reasoning and discourse.

Findings

Teachers' Perceptions of Mathematical Reasoning across Different Gameplay Formats

This study investigated teachers' perceptions of mathematical reasoning across one-against-one (1v1) and paired

(2v2) game formats. Teachers consistently expressed enthusiasm for the richer discussions and novel opportunities for mathematical reasoning afforded by the paired games, a format new to all five participating teachers. This perception emerged with Morgan explicitly noting, “for the paired one the discussion was far richer than the other one,” a sentiment echoed by Joel, who found the collaborative aspect a “real eye opener.” These observations align with the general teacher perception that games are potent vehicles for fostering deeper mathematical understanding and discourse (Russo et al., 2021).

Teachers observed students engaging in mathematical reasoning, particularly in justifying their mathematical ideas and evaluating others’ ideas. For instance, Ashleigh recounted students exploring prime numbers in *Reverse Landgrab*, where “one suggested it wouldn’t work because 19 is a prime number. You can only make long skinny arrays,” demonstrating students connecting prior knowledge and justifying their reasoning. Similarly, Morgan described students exceeding expectations with discussions on factors for “39,” in *Three-In-A-Row Lucky Numbers*, recounting: “Why did you choose that number? What other factors does it have? A student then asked, Is 39 prime? With another child saying no, you can divide it by three, but you just can’t make it with these dice.” She added, “I’ve never heard these kids more on task, when playing a game.” These anecdotes illustrate students’ engagement in the “verbs of mathematical reasoning” (McFeetors & Palfy, 2018) and directly correspond to types of cognitive conflict inherent in the games such as when rules contradict expectations, thereby creating conditions for rich mathematical discourse (Nurnberger-Haag et al., 2023; Onslow, 1990).

This enthusiasm for the 2v2 format also marked a notable shift in teacher perceptions regarding collaborative gameplay. Morgan acknowledged that the richer discussion emerging through this format was not something she had anticipated, stating:

> “I think, you know, in classrooms, sometimes we try and avoid, you know, too many kids working together, and it gets loud and messy and oh, my goodness. But I honestly thought that that was the better lesson.”

This sentiment underscores a notable shift in her perception, valuing the depth of interaction over potential management concerns, and indicating her intent to “use this structure again” when using mathematical games. Joel concurred, noting that he had “never done it this way” with his students, who would typically engage in playing games one-on-one. Ryan also explained that normally he would play games where students would play “against another person, whereas with the paired game you have to work as a team.” This novelty in teachers’ experience with structured paired gameplay aligns with Russo et al.’s (2024) observation on the scarcity of studies on collaborative non-digital game formats, potentially explaining the limited research in this area, as teachers’ prior practice has not often extended to such formats.

Teachers also highlighted significant peer support and emotional benefits in the paired format. Joel observed students naturally taking on “teaching roles,” explaining concepts, while Ryan noted how peer support strengthened connections between peers, recalling one student who offered, “Let me show you how I figured that out.” Morgan further emphasised the relational benefits, such as fluent speakers assisting English language learners. These observations corroborate literature on collaborative learning benefits, including knowledge externalisation (McFeetors & Palfy, 2018) and positive affective outcomes (Dondio et al., 2023; Ke & Grabowski, 2007).

Despite these benefits, teachers identified significant management and social challenges in managing four players in the 2v2 setup. These issues revolved around coordination and equitable participation, rather than fundamental problems with the games' mathematical content. Ashleigh's reflection vividly illustrates these complexities. She noted that while her class was "very good at that [working with anybody]," some students still "struggled in that situation." She recounted a specific incident during *Reverse Landgrab* where a grade three girl, "after rolling a 19 and being unable to place it, didn't want to listen to her partner," leading to significant interpersonal friction. "She sat on the floor and pulled apart a dice mat, and she just could not join back in." Joel further underscored these social challenges, noting that while "most of the students did okay with the collaborative side of it," there were "more than a handful of glaring problems working collaboratively." He also recounted an incident with a student who refused to cooperate with her partner and was asked to leave the room. These anecdotes highlight how the dynamics of a four-player setup, particularly social-emotional factors and student relationships, could significantly impede the flow of mathematical reasoning and game engagement.

Ashleigh also observed that "the paired games took longer to play because there were more people to negotiate," indicating that coordinating actions and turn-taking in a larger group added complexity. Morgan similarly commented that "some students did not view their participation as essential," suggesting uneven contributions sometimes emerged within a team of four. Emily echoed these management concerns, finding the one-against-one game "quicker to run compared to the pair game." She observed that "some pairs were focused more on the rules than the actual collaboration of talking and working together in a pair and completely dismissed their partner altogether and just took the reins." This directly impacted the perceived effectiveness of the paired format for "actual learning content," as students were sidetracked or dominant players overshadowed others. These findings align with research indicating that collaborative activities present challenges like uneven participation or social friction (Plass et al., 2013). Teacher reflections on these incidents highlight the importance of considering student groupings for effective collaborative learning (Dillenbourg, 1999).

To further address game management and social challenges, Ashleigh also used "built-in prompts" suggested by Dillenbourg (1999) to enhance collaboration between students, intervening during lessons with questions like, "Did you talk to him before you made that decision?" She later reflected, "I've never thought to play games in pairs before. I think I need to teach them how to work together when playing a game." Ashleigh noted she "would definitely like to try that again," but "with the focus of, well, now you're working with a partner, what does that mean?" Joel extended this idea, stating that "doing more doesn't necessarily mean it's going to get any better" and advocated for "breaking it down and modelling how you work collaboratively" would be valuable. In practice, this meant that teacher facilitation played a central role in keeping gameplay productive, with teachers stepping in to redirect unproductive dynamics, prompt inclusive decision-making, and model effective turn-taking. This proactive role aligns with Dillenbourg's (1999) recommendations for monitoring, guiding, and providing interaction prompts, underscoring that while the games themselves created potential for rich discourse, successful implementation of the 2v2 format required intentional pedagogical facilitation to overcome social and game management issues, nudging groups back towards constructive dialogue when necessary (Heshmati et al., 2018).

Students' Preferences for Different Gameplay Formats

Written reflections collected after gameplay reveal students' one-against-one or paired gameplay preferences. As shown in Figure 3, nearly two-thirds (65%) preferred the paired format, while about one-third (35%) favoured the one-against-one format. This finding contrasts with Delahunty and Roche (2024), who reported stronger preferences for one-against-one play. This discrepancy might be due to the paired format in this study retaining competitive elements, whereas their study removed them entirely. Maintaining the excitement and challenge typically associated with gameplay while fostering cooperation, this hybrid paired competition offered a middle ground, combining opportunities for discussion with the motivational benefits of competition.

Students who preferred one-against-one play often cited reasons related to autonomy and streamlined decision-making. Comments such as, "I don't need to discuss things. I have my own opinion," and "You don't need to decide together, which takes up time," highlight a value for independent action, quick decisions, and full control over gameplay. This aligns with prior research suggesting that competitive formats appeal to individuals who prefer independent strategy and self-reliance (Delahunty & Roche, 2024; Nurnberger-Haag et al., 2023). Some students also described one-against-one play as calmer and more predictable, allowing them to focus solely on their own strategy. This reduced the need for social negotiation, enabling a more focused individual strategy (Plass et al., 2013).

Conversely, students who preferred the paired format often emphasised the enjoyment of playing with a partner and relational benefits. Common responses included: "Because I have someone else's opinion," "You get to tell your partner what you think," "I love teamwork," and "Because you have a friend to help you." These findings strongly corroborate literature on collaborative play, consistently highlighting positive affective outcomes such as increased enjoyment for learning mathematics, mutual responsibility, and strengthened social connections (Dondio et al., 2023; Ke & Grabowski, 2007;). Some also noted that "more people have a chance to win or lose," suggesting that having a partner increased perceived chances of success. However, not all experiences were positive; several students mentioned frustration, such as, "I didn't like the 2v2 game because my partner didn't let me have a turn." In some cases, unequal participation or dominance by one player reduced the enjoyment, underscoring the challenges of collaboration also seen in teacher observations and the literature (Plass et al., 2013).

While most students who preferred team-based play emphasised enjoyment, some also described it as "more challenging" due to the need to agree on moves and justify choices. For others, the one-against-one format provided a clearer space to work independently on strategies, with comments like, "I get less help, which means I can improve better," and "Because I'm very competitive, so it's more fun to win on your own." This highlights that competitive formats can be perceived as conducive to self-directed learning and the development of individual strategic thinking. A few students, however, specifically valued the opportunity in team-based play to "discuss things with others," pointing to the role of peer discussion in refining strategy and problem-solving, which is a key benefit of collaborative learning contexts and a core tenet of social constructivism (Clements, 1997; Fosnot, 2005).

The one-against-one format appealed to those seeking independence and efficiency, while paired gameplay required negotiation and shared control. Team-based competition fostered belonging and enjoyment when peer dynamics were positive but caused frustration when peer dynamics when were not, making one-against-one play more appealing to students seeking predictability. Overall, these findings indicate that the preferred gameplay format often aligns with students' individual learning preferences and characteristics (ter Vrugte et al., 2015), competitive spirit, and ability to navigate group dynamics, demonstrating that different formats offer distinct advantages for personal growth and mathematical learning.

How Gameplay Formats Shaped Student Mathematical Reasoning and Discourse

Analysis of student-to-student interactions reveals how game formats fundamentally reshaped students' mathematical reasoning and discourse. While both formats indicate that an outcome of playing games is that they can stimulate rich mathematical reasoning, prompting students to externalise their thinking, debate possibilities, and evaluate their own and their opponent (s) strategies, the data indicates that all reasoning behaviours were notably less frequent in one-against-one games compared to the paired format (see Figure 1). While paired games prompted more reasoning overall, the purpose of that reasoning differed. Essentially, a 2v2 game transforms the activity from an individual problem-solving task into a collaborative one, demanding more explicit communication, shared planning, and consideration of multiple perspectives, all manifesting as increased external "reasoning". This profound transformation in the nature of mathematical discourse aligns with social constructivist principles, where knowledge is co-constructed through social interaction and dialogue (Clements, 1997; Fosnot, 2005).

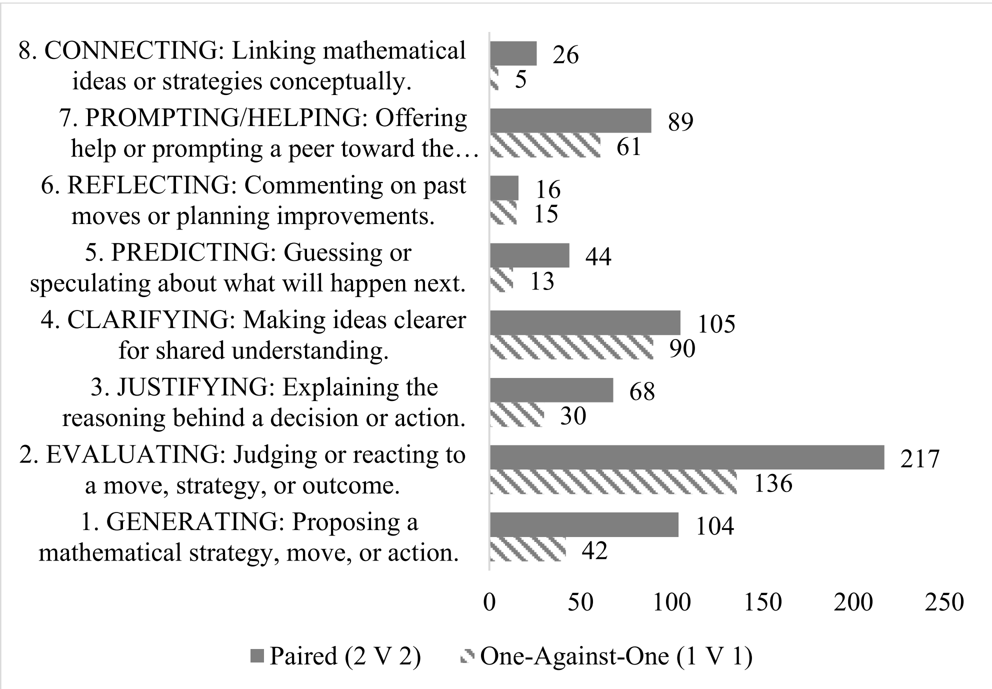

Figure 1. Frequency of Student Interaction Codes Observed during One-against-one (1v1) and Paired (2v2) Gameplay (Codes reflect distinct types of reasoning-related moves, including (e.g., Generating, Evaluating, Justifying) identified in gameplay transcripts.)

Generating Ideas: From Individual Strategy to Collective Problem-Solving

The "Generating" code (proposing a mathematical strategy or move) appeared significantly more often in 2v2 games (104 times) compared to 1v1 games (42 times). This increase signals a shift from individual strategy to collaborative problem-solving. In 2v2, students generated ideas for their team, brainstorming aloud and proposing a wider range of possibilities in *Reverse Landgrab*: "What we could do is block them so they can't get in?"; "Should we do 5 × 2 or 1 × 10?"; and "We can fill the gap with smaller numbers. Is that right?" This contrasts with 1v1 gameplay, where students typically generated ideas for their strategy and mostly did not share these openly with their opponent.

The collaborative format encouraged students to make their thinking visible, with generating ideas notably increasing for Joel's class (from 3 to 35), Ashleigh's (3 to 21), and Emily's (4 to 15). However, Morgan's students showed high generation in both formats (28 in 1v1 and 25 in 2v2), suggesting her facilitation ("We need to hear your ideas") encouraged explicit reasoning regardless of structure. Conversely, Ryan's more modest increase (from 4 to 8) indicates that while 2v2 offers more opportunities, teacher practices remain crucial.

In 1v1 gameplay, discussion was more individualistic and often used to outmanoeuvre an opponent, as seen in *Reverse Landgrab* with comments like: "That was stupid, why did you go over there? You should have gone on one of the edges." Although students in both formats often presented something they had noticed or a strategic idea, in 1v1, these ideas were more likely to be ignored by the opponent, a pattern not seen as readily in 2v2 games.

The *Choc-chip Cookies Game* (1v1) vignette vividly illustrates this lack of collaborative engagement:

> Player 1: "Okay, so I'm thinking my strategy is right because we've got a 10-sided dice and we've got 5 different rows. I divided 10 by 5, which is 2. Because we rolled a 3, it would go in the 2 column. Either 3 or 4 would go in here, which is times 2, which is 4. What's yours?"
>
> Player 2: "I just risked it. I put it there hoping we rolled a 1 or a 2."
>
> Player 1: "Okay go ahead, what's our next number?"
>
> Player 2: "Five. If you roll a number higher than 5, my risk is worthless. Next number? (Rolls) No… I can still win."
>
> Player 1: "Alright, our last number? (Rolls) My strategy of dividing won me."
>
> Player 2: "Let's just add up, just to check."

Here, Player 1 uses proportional reasoning to explain their strategy, but their partner does not engage with it. Instead, Player 2 offers a risk-based approach and misses the opportunity to evaluate or build on Player 1's explanation. The interaction remains parallel rather than dialogic, with each player working independently, with little collaborative interrogation or mathematical negotiation. At the game's completion, Player 1 again justified their winning strategy, saying, "Okay, I think my strategy won me," with Player 2 responding with "Let's just add it up and check." This highlights how reasoning in 1v1 was often for self-validation rather than shared construction of understanding. Notably, however, if an opponent made a suggestion, it was likely to benefit both players, for example, in *Reverse Landgrab*, "Let's just save that spot [so that if either of us roll a 17, we would be able to have a turn].”

Evaluating and Justifying: From Self-Validation to Negotiated Reasoning

“Evaluating” (judging a move or outcome) occurred 217 times in 2v2 games versus 136 in 1v1 games, and “Justifying” (explaining a decision) more than doubled in 2v2 (68) compared to 1v1 (30). In 1v1 games, reasoning primarily served individual validation or defence. Evaluations were often internal or competitive, and justifications rarely invited further discussion, appearing as a series of publicly voiced individual assessments. An example from *Three-in-a-Row Lucky Numbers* illustrates this:

Player 1: “Oh my gosh, there are so many 24s.”
Player 1: “We are getting high numbers now.”
Player 1: “Oh my gosh, 24 is a good number.”
Player 1: “I did a partial array.”

In this dialogue, Player 1 voices a series of individual evaluations. The observation that 24 has many factors is integral to playing *Three-in-a-Row Lucky Numbers*; when rolling a product previously rolled, players can choose any number on the board, making it strategic to select numbers with fewer factors (like primes). However, this key observation is presented as an internal thought voiced publicly, not an invitation for collaborative discussion.

Conversely, in 2v2 collaborative games, reasoning was distributed, dialogic, and responsive. Ideas were collaboratively generated, immediately evaluated by peers, and justified in ways that invited agreement, critique, or revision. For example, a suggested strategic placement in *Reverse Landgrab* was met with: “That won’t work because you can’t fit it” or “This works better because it blocks them.” These justifications were typically offered in response to a teammate’s suggestion and grounded in the shared goals of the team. In this way, students explained why a choice made sense given the game’s constraints, collectively weighing multiple possibilities during gameplay. The sharp increase in evaluation instances and more than doubling of justification utterances in 2v2 reflects a clear need for externalised and negotiated reasoning in team settings, where the aim was often to reach consensus. However, at times, players would unilaterally make decisions without full agreement.

These collaborative reasoning sequences were often embedded within larger chains of interactions, blending evaluations, suggestions, justifications, and clarifications. For example, in *Reverse Landgrab*, the following discussion where teams debated prime numbers, array placement, and strategic consequences across team boundaries unfolded:

Team 2 rolls 17
Player 2 (Team 2): Okay 1 times 17 is the best option (Codes: 1 – Generating; 2 – Evaluation)
Player 2 (Team 1) “You have to do 1 times 17. You have to do an array.” (Codes: 4- Clarifying, 1-Generating)
Player 1 (Team 2) “It’s impossible to do that kind of array though (gets up to speak to the teacher).” (Codes: 2 – Evaluation, 3 – Justification)
Player 2 (Team 2): “12, 15, 17 times 1... I think it’s the best option. It’s the only one we have.” (Codes: 1 – Generating, 2 – Evaluation, 3 – Justification)

Player 2 (Team 1) “Go this way or the other way” (Pointing to vertical columns or horizontal rows)
(Codes: 1 – Generating, 7 – Helping)
Player 2 (Team 2): “You can’t really use them going this way but actually let’s try.”
(Codes: 2 – Evaluation, 1 – Generating)
Player 1 (Team 2) Counts the squares “1,2,3,4…”
(Code: ST- Self Talk)
Player 2 (Team 2): “So only one block could go there (pointing to the horizontal row), which is not a good idea.”
(Codes: 3 – Justification, 2 – Evaluation)
Player 1 (Team 2): “ What we could do is also risk it and block them for going there.”
(Codes: 2 – Evaluation, 3 – Justification)
Player 2 (Team 2): “But still, we are early in the game, so going up is still the best way to win for now.” (Codes: 2 – Evaluation, 3 – Justification, 1 – Generating)

This pattern highlights a fundamental shift: in 1v1 games, reasoning was a tool of strategic persuasion or defence**,** while in 2v2 games, it became a tool of co-construction; a means of negotiating shared mathematical understanding.

Clarifying: Coordination and Shared Understanding

Clarifying (clarifying ideas) saw a modest increase from 90 instances in 1v1 games to 105 in 2v2 games. However, a significant portion of 2v2 clarifying interactions were procedural rather than conceptual. Teammates were not always simultaneously focused on the task; players often needed to restate or confirm dice rolls, rules, results, or defend intended moves before progressing. This procedural clarification reflects the coordination demands of multi-person play, where turn-taking, attention shifts, and shared decision-making require constant realignment. As noted earlier by the teachers about game management and pacing, 2v2 games introduced more negotiation and waiting time, which sometimes enhanced dialogue but also created moments where clarification served to simply re-synchronise the group rather than deepen mathematical reasoning.

Prompting and Helping: Fluency Support and Strategic Input

Prompting and helping were notably more frequent in 2v2 games (89 times compared with 61 times), indicating that this format consistently promotes peer teaching, mutual support, and collaborative problem-solving. This aligns with Joel’s and Morgan’s observation of students “helping one another” and suggests that the paired format naturally creates opportunities for “fluency support”. This pattern aligns with teachers’ observations and literature suggesting that mutual help is a key benefit of collaborative learning (Dondio et al., 2023; Ke & Grabowski, 2007; Mc Feetors & Palfy, 2018). Collectively, these findings imply that group-based competition, particularly with mixed-ability pairs, may provide a productive balance between challenge and collaboration, effectively mediating the anxiety often associated with competitive environments, especially where speed is a factor (Dondio et al., 2023; Nurnberger-Haag et al., 2023).

In 1v1 format, games often prompted a competitive or corrective tone, framed as “telling” rather than “working out together.” Support was usually triggered by noticing a peer’s mistake or inaction and keeping the game moving but was often met with resistance (“I know what I’m doing, okay!”). Players were largely expected to be independent, make individual decisions without prolonged discussion, and therefore showed little investment in genuinely supporting their opponent. For example: “I only helped you; I don’t really care.” An exchange from the *Choc-Chip Cookies Game* further demonstrates how help was offered as a challenge rather than collaboration:

Player 1: “I’ve still got a strategy.”

Player 2: “You should have gone for the highest one,” she challenged. “You can’t do it now, though.”

The tone and reception of prompting in 1v1 games varied widely. It was openly competitive and even provocative in some games: “I have a feeling I’m smarter than you.” Offers of help were frequently resisted, as seen in this example from *Reverse Landgrab*:

Player 1: “Twenty-one.”

Player 2: “Oh, actually, I know one. It’s 3 times… I’ll tell you; it’s 3 times something.”

Player 1: “3×7, you dumb, dumb.”

Player 2: “What?”

Player 1: “3×7.”

Player 2: “I was just trying to give you a clue.”

Player 1: “I know my timetables.”

Player 2: “19+4 is 23”

Player 1: “No, you can do another one and 19 + 14 is 33, 3 X …. (giving a hint).”

Player 2: “I can do ones, alright?”

Player 1: “I’m just telling you. You can also do 3 X 11.”

Player 2: “I count quicker than you now.”

Player 1: “Oh, you’re doing what I told you.”

Player 2: “Yeah, I was just counting by ones, but [then I saw] you blocked the way.”

Player 1: “I’m not going to do it (help) again.”

At other times, prompting in 1v1 games was more collaborative, with players offering scaffolded help to keep the game moving: “Okay, I’ll help you make sixes” [counting by sixes together]. In these cases, assistance was welcomed and often essential for progressing in the game, rather than resisted.

In 2v2 play, prompting and helping occurred in two distinct ways. First, within teams, players encouraged contributions and discussed strategy together: “What should we do?” and “Go on, you say your idea.” These interactions focused on building a shared approach and supporting teammates. Second, prompting and helping sometimes extended across team boundaries, with players voicing comments or questions that invited responses from anyone, teammate or opponent. For example: “Anyone know what 6 sixes is?” was asked aloud to the whole group, prompting others to supply the answer. In other cases, cross-team interactions involved offering strategic suggestions or warnings, such as advising an opponent to choose a certain move:

Player 1 (Team 1): “Let’s choose 45.”

Player 2 (Team 2): “You should choose 36. I’m saying this because of this. I think we can’t block you if you do that.”

Player 1 (Team 1): “Oh yes that’s true. Thank you for that.”

Player 2 (Team 1): “Yeh, but there’s still these two areas.”

Player 2 (Team 2): “But you have this one, and if you get that one, then this is blocked and so is that. They are all blocked.”

These exchanges showed opponents sharing reasoning, weighing trade-offs, and negotiating possible moves, even on different teams. At times, these strategic prompts were aimed at preventing a move that could shift the balance of the game:

Player 1 (Team 1): “Should we do 5 × 2 or 1 × 10?”

Player 2 (Team 1): “Do it this way (pointing to a horizontal line). We’re winning so far.”

Player 1 (Team 2): “Do not do 1 × 10.”

Player 2 (Team 1): “Why?”

Player 1 (Team 2): “Only if it’s up and down, because then it will block if someone has 17 again.”

Reasoning could also become a shared group process, with players discussing the implications of a move for everyone:

Player 1 (Team 1)— to teammate: “But now we can’t do 17.”

Player 2 (Team 1): “Okay, there won’t be 17 anymore.”

Player 1 (Team 2): “What do you mean?”

Player 2 (Team 1)— to all players: “Because then you can’t do 17 because she took the whole bottom.”

Player 1 (Team 1)— to all players: “Making it hard for all of us.”

Player 2 (Team 1)— to all players: “If you get anything above 17 or 17, you are missing a turn.”

Player 1 (Team 1)— to all players: “It will have to be under 13, now.”

Here, the opportunity to notice aspects of the game was not confined to one’s turn or team; reasoning was readily voiced by any player from any team. These across-team exchanges blended competition and collaboration, sometimes helping the opposition, but also showing awareness of the broader game state and inviting shared reasoning about strategic consequences.

Notably, as in 1v1 games, a competitive edge could surface even in team format:

Player 1 (Team 1): “24, I’ll block them.”

Player 2 (Team 2): “You should have done 34, you know.”

Player 1 (Team 1): “Where’s the eraser?”

Player 1 (Team 2): “No, no, no, you can’t change your mind.”

Here, competition completely overrides any collaborative intent built into the 2v2 structure. These findings suggest that in competitive contexts, the drive to win can, at times, override collaborative reasoning. This “override effect” reminds us that while team formats may be designed to encourage cooperation, the competitive framing of the game can still dominate student behaviour, and teachers may need to actively scaffold interactions to maintain a balance between collaboration and competition (Dillenbourg, 1999; Heshmati et al., 2018).

Across both formats, prompting and helping served dual purposes: sometimes it offered fluency support, while at other times it involved extended reasoning or strategic debate that slowed the pace but deepened mathematical discussion. Teachers may need to scaffold interactions, for example, through post-game reasoning discussions or targeted prompts, to balance collaboration and competition (Klooger et al., 2025). Structuring these opportunities, as Heshmati et al. (2018) highlight, ensures that rich exchanges between students become a deliberate and expected part of gameplay.

Reflecting and Connecting: Surface Noticing and Strategic Use

The data shows that "reflecting" was relatively rare across both formats, occurring with similar frequency in paired and one-against-one games. By contrast, "evaluating" and "generating" were far more common, suggesting that students were more engaged in immediate reactions and proposals than in stepping back to reconsider their actions or strategies. This may reflect the fast-paced nature of games or the developmental stage of the students, who may be more focused on playing.

By contrast, although still comparatively unusual relative to the other reasoning categories, students were far more likely to make mathematical connections in 2v2 formats (26 instances) compared with 1v1 formats (5 instances). This suggests that a collaborative environment, with its shared goals, provides more opportunities and incentives for students to engage in deeper discussions and explicitly link mathematical concepts.

In paired games, students more regularly tied number properties to their strategies. For instance, in *Reverse Landgrab*, one student observed, "You got a square number," while another reasoned, "If we make it a square, we can complete this row." Students also used concepts to block opponents, such as "We want a prime number so they can't make a square," or to justify properties, such as "The number 1 is not a prime number." They sometimes defined concepts for their peers: "A square number is a number multiplied by itself." The dialogic nature of paired games appeared to foster these richer explanations, with students questioning "What's a prime number?" and clarifying one another's reasoning. By contrast, one-against-one games yielded few connecting comments, and those that did appear tended to be individual reflections rather than shared elaborations. For example, in the *Choc-Chip Cookies Game*, a student commented on the likelihood of rolling a large number, saying, "Maybe it's a 50 or 60% chance." The collaborative demands of paired play more readily prompted students to articulate and apply mathematical connections within the flow of the game.

A closer look at the "connecting" comments reveals two distinct functions. Many were directly tied to the immediate action of a turn, where a student noticed a mathematical connection, such as "It's 2 × 2, which is a square number" or "It's a multiple of 4." These comments demonstrate awareness of mathematical ideas but remain descriptive, limited to explaining why a move is possible or constrained, as in "You can't do anything else because seven is prime." Other comments where students made mathematical connections, operated strategically, using mathematics to guide and influence play. For example, "We want a prime number" in *Three-in-a-Row Luck Numbers* was not simply a statement of fact but a deliberate, goal-oriented move. In such moments, students verbalised their reasoning as part of a collective game plan, leveraging mathematical properties to pursue advantageous outcomes. This dual role, sometimes descriptive, sometimes strategic, highlights the richness of particularly paired games where students' collaboration created both the need and the space for such connections. These discussions demonstrate the potential of games to serve as powerful contexts for teaching mathematics and fostering deeper conceptual understanding of mathematical ideas.

Game Management and Social Dynamics of Paired Play: Implications for Reasoning

Figure 2 illustrates the distinct frequencies of Game Management (GM), Self-Talk/Metacognition (ST), Emotional Tone (ET), and Off-Topic Talk (OTT) observed in paired versus one-against-one game formats.

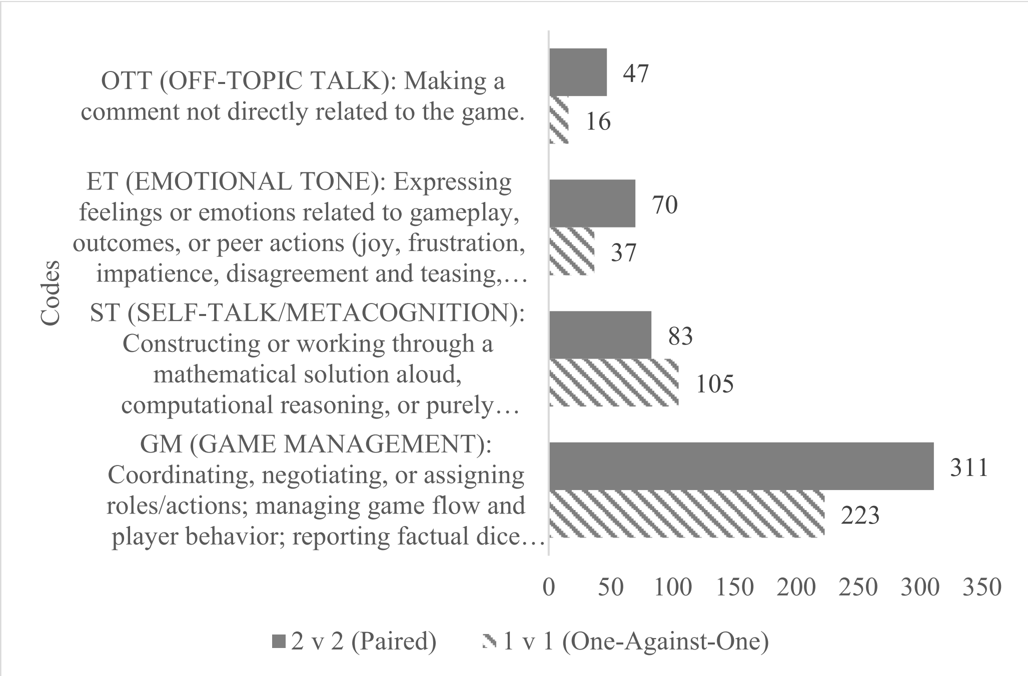

Figure 2. Frequencies of Game Management (GM), Self-Talk/Metacognition (ST), Emotional Tone (ET), and Off-Topic Talk (OTT) in Paired vs One-against-one Games

Game Management (GM) interactions were markedly higher in 2v2 play (311 vs. 223), reflecting the greater need for coordination and negotiation in a four-person structure. While increased GM reflects active engagement, it does not always equate to productive reasoning. Teachers directly linked this to the game management challenges; Ashleigh noted that managing interpersonal dynamics could override mathematical focus, including silent refusals or emotional outbursts. Joel observed "glaring problems working collaboratively," and Emily saw pairs sidetracked by rules or dominant players. Student reflections corroborated this, with several students expressing similar views. One student preferred 1v1 precisely because "you don't need to decide together, which takes up time," while another described frustration in 2v2 when "my partner didn't let me have a turn." This highlights how the negotiation required in 2v2 could be perceived as challenging or lead to unequal participation (Plass et al., 2013).

Emotional Tone (ET) also more than doubled in 2v2 play (70 vs. 37), echoing teacher accounts of heightened social-emotional dynamics, both positive and negative. The paired format amplified celebrations, encouragement, and playful banter, but also increased frustration, teasing, and disengagement. Ashleigh's and Joel's examples show that these emotions could spill over into behaviour that disrupted reasoning and required teacher intervention. While some students valued the relational benefits of 2v2, stating “I love teamwork” or “Because you have a friend to help you,” the increased negative tone also aligns with the frustrations reported by students regarding partner dynamics, such as feeling sidelined when a partner dominated play or took control of the turns. Self-Talk (ST) was higher in 1v1 games (105 vs. 83), consistent with individual formats allowing players to think aloud independently without constant coordination. Student preferences for 1v1, such as “I don’t need to discuss things. I have my own opinion,” underscore this value for independent thought and streamlined decision-making, which could improve game flow but limit opportunities for co-constructed reasoning. Off-topic talk (OTT) was also far more common in 2v2 games (47 vs. 16), underscoring the challenge of redirecting attention in larger groups; some digressions aided social bonding, but others detracted from mathematical engagement.

Collectively, this data and teacher and student reflections suggest that while 2v2 games foster more visible coordination and emotional engagement, they also introduce greater management complexity and a higher risk of non-mathematical talk. Teachers recognised these were not game flaws, but a natural consequence of the larger-group format. As Ashleigh noted, explicitly teaching and modelling “how to work together” is crucial, ensuring increased Game Management (GM) and Emotional Tone (ET) become vehicles for collaboration and reasoning rather than barriers (Dillenbourg, 1999).

Discussion

Synthesising findings across the three data sources, we see that game format significantly influenced the nature and depth of mathematical reasoning, peer support, and socio-emotional dynamics during gameplay. While novel for teachers, 2v2 (paired) formats emerged as powerful stimulus for richer collaborative reasoning, despite presenting distinct management and social challenges.

Teachers unanimously expressed enthusiasm for the richer discussions and opportunities for mathematical reasoning in 2v2 games. They observed students engaging in explicit reasoning, like discussing prime numbers and factors, justifying ideas, and evaluating peers’ strategies. This qualitative observation is strongly supported by the student interaction data, with all reasoning behaviours notably more frequent in 2v2 games than 1v1 (see Figure 1). In 2v2 games, reasoning became distributed, dialogic, and responsive, with ideas immediately evaluated and justified, inviting critique and negotiation, grounded in shared team goals. This contrasts with 1v1, where reasoning was primarily for self-validation or outmanoeuvring an opponent, with justifications rarely inviting discussion. This convergence of teacher perceptions and interaction data demonstrates that 2v2 transforms the activity from an individual task into a collaborative one, demanding more explicit communication, shared planning, and consideration of multiple perspectives. What is crucial is that, in a 1v1 setting, neither player needs to say anything.

Typically, one-against-one play can be completed silently, with each player thinking privately, much like doing mental arithmetic or silent reading. By contrast, 2v2 requires overt verbalizing between partners, meaning that thinking becomes socially visible and linguistically expressed. This shift from silent, internal reasoning to spoken, shared reasoning adds a vital dimension: language becomes both the *medium* and the *evidence* of mathematical thinking. Talking not only facilitates coordination but also deepens conceptualization, engaging students in articulating, negotiating, and refining ideas that might otherwise remain unspoken.

Teachers frequently observed students actively clarifying mathematical ideas and offering peer support in 2v2 games, with some naturally taking on “teaching roles” and others strengthening emotional connections through offering and accepting assistance (Dondio et al., 2023; Ke & Grabowski, 2007; McFeetors & Palfy, 2018). This aligns closely with the student data regarding the reasoning category “Prompting and Helping”. The nature of “helping” differed by format: In 1v1 games, help often carried a competitive or corrective tone, framed as “telling” and frequently resisted, with interactions sometimes openly provocative. In 2v2 games, “prompting and helping” occurred both within teams (encouraging contributions and discussing strategy) and across team boundaries (voicing questions to the group and offering strategic suggestions to opponents). These cross-team exchanges blended competition and collaboration, showing awareness of the broader game state and inviting shared reasoning. However, a competitive edge could still surface in team formats, occasionally overriding opportunities for collaboration.

Student reflections further support these social dynamics. While a minority preferred 1v1 for autonomy, nearly two-thirds preferred the 2v2 team-based format, often citing relational reasons like “having someone else’s opinion,” “teamwork,” and “having a friend to help.” This preference for collaboration and shared experience underscores the social benefits of 2v2.

Despite the many benefits, teachers and students identified significant management challenges with the 2v2 format, impacting game flow and mathematical reasoning (Dillenbourg, 1999). These issues included managing four players, coordination, equitable participation, and interpersonal issues. Game Management (GM) interactions were markedly higher in 2v2 (311 vs. 223), reflecting the greater need to coordinate moves and manage player behaviour. Emotional Tone (ET) more than doubled in 2v2 play (70 vs. 37), indicating amplified social-emotional dynamics, both positive and negative (e.g., celebrations, but also frustration and disengagement). Off-Topic Talk (OTT) was also far more common in 2v2 games (47 vs. 16), suggesting that managing more players often required redirecting attention. Conversely, Self-Talk (ST) was higher in 1v1 games (105 vs. 83), allowing for independent thought. Teachers noted that 2v2 games “took longer to play” due to increased negotiation and observed communication breakdowns or dominant players. These observations are echoed in student reflections, where some preferred 1v1 for “streamlined decision-making” and “calmness,” while some 2v2 players expressed frustration due to unequal participation. Crucially, teachers recognised that these challenges were not inherent flaws in the games but a consequence of the larger group size and the novelty of paired play. They highlighted the need to explicitly teach and model “how to work together when playing a game,” advocating for scaffolding collaborative skills to maximise the games’ potential for rich mathematical reasoning.

Finally, the fact that connecting interactions were far less common than other reasoning categories indicates that such moments are not automatic outcomes of play, but rather valuable openings where games can be harnessed to help students make meaningful links between gameplay and mathematical ideas.

Practical Implications

The collaborative efficacy of 2v2 games stems from their intentional design and facilitation. Effective 2v2 play, often unfamiliar to students, requires explicit teacher modelling and instruction in teamwork. Teachers should demonstrate how to:

- discuss and compare strategies
- justify and explain choices
- offer and accept help
- navigate disagreements constructively.

Drawing on Dillenbourg (1999), enhancing collaborative potential in 2v2 games involves:

- setting initial conditions: pair students carefully and assist them in allocating roles (e.g., dice roller, recorder);
- scaffolding interaction rules: use prompts (e.g., requiring partner agreement before moves) to maintain focus and reduce dominance;
- monitoring and regulating interactions: circulate to deliver targeted prompts, encourage mathematical noticing, ensure contributions are equally distributed, and redirect off-task groups.

While the games provide a rich context for students to connect with mathematical concepts, this type of reasoning may not happen spontaneously. The data suggests that teacher facilitation is necessary to help students move from simply noticing mathematical properties to using them strategically. Teachers may need to act as a bridge, guiding their students toward deeper connections by asking targeted questions. For example, after a student remarks in *Three-in-a-Row Lucky Numbers,* “We seem to be rolling 24 a lot,” it is the teacher’s role to extend that noticing into a mathematical connection. The teacher could prompt, “Why do you think this is?” or “Why do you think rolling 24 is good for you in this game?” This type of intervention can shift the focus from just noticing something to actively using the mathematical ideas to inform strategy, leading to a broader and more purposeful engagement with mathematics.

A structured post-game discussion can further support this shift. The relative rarity of “reflecting” in the data suggests that students are not naturally inclined to analyse their own play. A debriefing session provides space to do so, allowing students to explicitly link their decisions to underlying mathematical concepts. This not only reinforces understanding but also develops their capacity for strategic, long-term mathematical thinking. Replaying the game after reflection strengthens this process: by applying new insights in a second round, students move from playing simply to win toward playing to learn (Klooger et al., 2025).

To keep reasoning central during intense competition, teachers can integrate “reasoning prompts,” such as providing each player or team with prompt cards to be used before or after a move. This encourages deliberate reasoning during gameplay, regardless of the format. Table 3 provides a series of suggested prompts for supporting strategic thinking during gameplay. These prompts align with the eight identified reasoning codes, actively targeting mathematical reasoning by asking players to propose moves, forecast outcomes, convince others, explain choices, clarify actions, seek/offer help, reflect, predict an opponent’s move and connect mathematical ideas. This alignment ensures that the prompts do not simply add conversation but actively target the forms of mathematical reasoning most associated with rich gameplay in the findings. Combining intentional game format selection with explicit teaching of collaborative skills and active facilitation of reasoning allows teachers to make use of both 1v1 and 2v2 structures, fostering individual reasoning alongside teamwork, dialogue, and the co-construction of mathematical ideas.

Table 3. Suggested Teacher Prompts for Supporting Strategic Thinking in Gameplay

Game Format	Example Prompt	Reasoning Code (s)	Purpose
1v1 (One-Against-One Game)	"What would you do if you were me?"	Generating, Predicting	Encourages perspective-taking and anticipatory reasoning
	"What do you think I'm going to do?"	Predicting	Highlights opponent's strategy and anticipation
	"I'll explain my thinking before deciding."	Justifying, Clarifying	Models reasoning and transparency
	"I'll convince you this is the best move for me."	Justifying, Evaluating	Promotes argumentation and critical evaluation
	"Suggest a different move I could have made."	Prompting/Helping, Reflecting	Encourages critique and alternative strategies
	"Explain exactly what you just did."	Clarifying	Builds precision and accountability
2v2 (Paired Game)	*"What are we going to do?"*	*Generating, Predicting*	Fosters joint decision-making
	"How can we figure this out together?	Generating, Clarifying	Encourages shared problem-solving
	"Here's one idea, what do you think?"	Generating, Evaluating	Invites negotiation and co-construction
	"Let's each explain our thinking before deciding."	Justifying, Clarifying	Invites negotiation and co-construction
	"Convince me this is the best move."	Justifying, Evaluating	Encourages persuasion and reasoning
	"Suggest a better option."	Prompting/Helping, Generating	Promotes idea refinement
	"What could we have done differently?"	Reflecting	Supports collective reflection

Conclusion and Limitations

This study offers new insights into how gameplay structures shape student interaction in mathematics classrooms. However, a key limitation is inferring internal thinking and participation from observable behaviour. The analytical framework used in this study assumes that reasoning behaviours can be inferred through students' dialogue and overt actions. However, these also have internal aspects that may not be externally visible or verbalised. Students may think deeply, regulate emotions, or participate nonverbally, yet these internal processes remain uncaptured by a coding scheme focused solely on spoken interaction. This particularly impacts the third research aim concerning student-to-student interaction. While triangulation from teacher interviews, student reflections, and transcripts boosted credibility, it could not fully bridge the gap between observable behaviour and internal experience. Future studies could use think-aloud protocols or video-based self-reflection methods to more fully assess internal processes, particularly metacognitive and affective dimensions.

Future studies could also include pre- and post-reflection data to examine whether students' experiences with 1v1 and 2v2 gameplay influence their attitudes, engagement, and perceived learning with games. Comparing students' expectations with their lived experiences would provide a clearer understanding of how exposure to different formats shapes students' preferences and participation.

In summary, our findings indicate that while 1v1 games support individual strategic thinking and autonomy, the 2v2 format offers a uniquely rich environment for collaborative mathematical reasoning and peer support, fostering shared understanding and distributed problem-solving. However, the advantages of 2v2 gameplay are not inherent; they depend on teacher practice**.** Through intentional facilitation, scaffolding of collaboration, and purposeful questioning, teachers can transform paired gameplay into rich opportunities for mathematical reasoning. Ultimately, collaboration flourishes not through format alone but through the teacher's deliberate orchestration of learning.

Statements and Declarations

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Data Availability Statement: The datasets generated and analysed during the current study are not publicly available due to ethical restrictions, as participant consent did not extend to open data sharing.

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Appendices

Appendix 1. Framework Alignment Table (Construct Mapping)

Our code	Nearest SSMT category (Trakulphadetkrai, 2022)	Nearest Loong et al. (2013) descriptor	Note on fit/mismatch
Generating ideas Proposing a mathematical strategy, move, or action to be taken.	Idea Formulation (Exploration)	Generalizing/ Conjecturing	SSMT: Trakulphadetkrai's framework explicitly has "Idea Formulation (Exploration)" which includes asking peers to generate ideas/solutions and providing them autonomously. Loong et al. (2022): "Generalizing" is a key reasoning action heading in their simplified rubric. They identify conjecturing as a level of "Generalizing," referring to ideas that are often testable claims or hypotheses within a problem-solving context.
Evaluating Expressing support, disagreement, or assessment of an action, strategy, or outcome (one's own or a peer's).	Idea Formulation (Evaluation)	Analyzing	SSMT: Trakulphadetkrai's framework explicitly has "Idea Formulation (Evaluation)" which includes asking peers to evaluate and providing positive or negative evaluations. Loong et al. (2013): "Analysing" is one of the three key reasoning action headings in their simplified rubric.
Justifying Explaining the reasoning behind a decision, move, or strategy, providing a mathematical or strategic rationale to another person.	Justification	Justifying	SSMT: Trakulphadetkrai's framework has a direct talk type named "Justification," which includes asking for and providing justification/reasoning. Loong et al. (2013): "Justifying" is one of the three key reasoning actions headings in their simplified rubric.
Clarifying Making the situation or idea clearer, often for the benefit of others, to	Clarifying	Generalizing/ Explaining	SSMT: Trakulphadetkrai's framework has a direct talk type named "Clarification," which includes asking for and providing clarification. Loong et al. (2013): While not a direct

Our code	Nearest SSMT category (Trakulphadetkrai, 2022)	Nearest Loong et al. (2013) descriptor	Note on fit/mismatch
ensure shared understanding of ideas, game state, rules, or opponent's actions. The act of clarifying predominantly involves ensuring procedural and numerical accuracy.			category, they discuss actions like explaining under their "Generalizing" category. A student clarifying an idea or a move would be engaged in explaining their thinking more clearly.
Predicting Speculating what might happen next in the game, including hopes, fears, guesses about future events, or estimating probabilities.	Speculation / Prediction	Analyzing/ Predicting	SSMT: Trakulphadetkrai's framework includes "Speculation / Prediction" as a talk type. Loong et al. (2013): While not a direct category, they discuss actions like predicting and hypothesizing under their "Analyzing" category.
Reflecting and Self-Talk Looking back on previous actions or decisions, considering what could have been done differently, commenting on past mistakes, or planning future improvements based on prior experience. Constructing or working through a mathematical solution aloud, computational reasoning, or purely internal cognitive processing.	Metacognition/ Self-Talk	Justifying/ Reviewing	SSMT: Trakulphadetkrai's framework explicitly includes "Metacognition," which covers "Self-Talk," which is described as verbalizing one's thinking process, self-reflection and correction. Loong et al. (2013): While not a direct category, they discuss actions like reflecting under their "Justifying" category.
Helping/Prompting	Thinking Facilitation	—	SSMT: Trakulphadetkrai's framework includes "Thinking Facilitation," which

Our code	Nearest SSMT category (Trakulphadetkrai, 2022)	Nearest Loong et al. (2013) descriptor	Note on fit/mismatch
Soliciting a response, input, decision, or action from a peer that constructively advances the shared task or helps/guides a peer to execute a task correctly.			involves asking peer questions to check that they understand something or to help guide others' thinking.
Connecting Making links between mathematical ideas, strategies, or representations.	Making Connections	Generalizing/ Analyzing	SSMT: Trakulphadetkrai's framework has a direct talk type named "Making Connections," which includes asking for and providing clarification. While "Connecting" is not a standalone action in the Loong et al. (2013) rubric, the underlying principle of making connections is integral to several of their reasoning actions. For instance, "Generalizing" involves connecting instances or concepts and applying them.
Off-Topic Talk Making a comment not directly related to the game.	Non- explicitly mathematical	—	SSMT: Trakulphadetkrai's framework categorizes talk as "explicitly mathematical" or "non-explicitly mathematical". Off Topic Talk is considered in their study to be non-explicitly mathematical.
Game Management Coordinating, negotiating, or assigning roles/actions; managing game flow and player behaviour; reporting factual dice rolls or scores; discussing/enforcing rules related to game mechanics.	Non- explicitly mathematical/ Role allocation	—	SSMT: Trakulphadetkrai's framework categorizes procedural talk that assigns, negotiates, or enforces roles as "Role Allocation", including disputes. They code these as non-explicitly mathematical interactions.

Our code	Nearest SSMT category (Trakulphadetkrai, 2022)	Nearest Loong et al. (2013) descriptor	Note on fit/mismatch
Emotional Tone Expressing feelings or emotions related to gameplay, outcomes, or peer actions (joy, frustration, impatience, disagreement and teasing, hope etc.).	—	—	We added this code for the gameplay context.

APPENDIX 2. Games Used in This Study

Game 1: Skip Counting Bingo (Russo & Russo, 2018)

Game Materials and Mathematical Focus	Game Rules (One-Against-One)	Game Rules (Paired)
Materials: · 120-chart gameboard · Game dice: one 6-sided dice (alternatives: 10-, 12-, or 20-sided) · Five counters of the same color for each player Understanding · Recognize that some numbers belong to multiple skip-counting sequences (many factors), while primes have only two. · Understand factors as dice rolls, and multiples as results of repeated addition/multiplication. Fluency: · Develop fluency with skip counting and identify counting patterns. Problem solving: · Identify numbers with many factors to maximize Bingo chances. · Understand that lower numbers are often reached first (e.g., 60 before 120). · Strategically avoid selecting prime numbers or those not in multiple skip-counting patterns. Reasoning:	· Each player chooses five numbers greater than 20 and marks them on the 120-chart, which serves as the gameboard. · The first player rolls the dice, and everyone starts counting by the number on the dice, using the 120-chart to keep track. · Counting continues until one of the player's chosen Bingo numbers is called. That player removes their counter from the gameboard. · The next player rolls the dice, and counting begins again. · Play continues until one player removes all five counters and calls "Bingo!" to win.	· Each pair chooses five numbers greater than 20 and marks them on the 120-chart, which serves as the gameboard. · The dice are rolled to determine which pair will begin. The pair with the highest roll starts and play proceeds clockwise. · The first pair rolls the dice, and everyone counts by the number shown, using the 120-chart to keep track. · Continue counting until one of the pairs' chosen Bingo numbers is called out. That pair removes their counter from the gameboard. · The next pair rolls the dice and counting resumes. · Play continues until one pair removes all five counters and calls "Bingo!" to win.

Game Materials and Mathematical Focus	Game Rules (One-Against-One)	Game Rules (Paired)
· Analyze trade-offs, like 60 being a "better" number than 24 due to more factors, but 24 being landed on earlier.		

Game 2: Doubles Bingo (Russo, 2016)

Game Materials and Mathematical Focus	Game Rules (One-Against-One)	Game Rules (Paired)
Materials: 120-chart gameboard Game dice: one 6-sided dice (alternatives: 10-, 12-, or 20-sided) Five counters of the same colour for each player Understanding: · Understand doubling as adding a number to itself or multiplying by two. · Recognize each number in a doubling sequence is double the previous number. · Distinguish doubling (adding increasing amounts) from skip counting (adding constant amounts). · Identify that doubles are even numbers because two is a factor of all doubles. Fluency: · Develop fluency in doubling and partitioning with place value. Problem solving: · Analyze which doubling sequences can reach selected numbers based on the rolled start	· Each player chooses five numbers greater than 20 and marks them on the 120-chart, which serves as the gameboard. · The first player rolls the dice, and everyone starts doubling from the number rolled, using the 120-chart to keep track. · Doubling continues until one of the player's chosen Bingo numbers is called. That player removes their counter from the gameboard. · The next player rolls the dice, and doubling begins again. · Play continues until one player removes all five counters and calls "Bingo!" to win.	· Each pair chooses five numbers greater than 20 and marks them on the 120-chart, which serves as the gameboard. · The first pair rolls the dice, and everyone starts doubling from the number rolled. · Doubling continues until a pair's chosen Bingo number is called. That pair removes their counter from the gameboard. · The next pair rolls the dice and doubling resumes. · Play continuesuntil one pair removes all five counters and calls "Bingo!" to win.

Game Materials and Mathematical Focus	Game Rules (One-Against-One)	Game Rules (Paired)
value. Reasoning: · Recognize that odd numbers will not appear in doubling sequences. · Understand the largest reachable number depends on the dice used (e.g., maximum 112 with 10-sided dice, 120 with 20-sided dice rolling 15). · Note that even numbers where half is odd (e.g., 66) are excluded from doubling sequences.		

Game 3: Choc-Chip Cookies Game (Russo et al., 2022)

Game Materials and Mathematical Focus	Game Rules (One-Against-One)	Game Rules (Paired)
Materials: Choc-Chip Cookie gameboard. Game dice: one 6-sided dice (alternatives: 10-, 12-, or 20-sided) Understanding: · Understand that the commutative property (e.g., 4x5 vs. 5x4) represent different structures despite producing equal quantities. · Recognize that easily multiplied or skip-counted numbers support efficient calculation. Fluency: · Apply partitioning and known facts to simplify multiplication. · Represent multiplicative	· Each player rolls the game dice to determine how many choc-chips to place on each cookie in a chosen row. · The choc-chips are arranged so the total number can be easily identified without counting individually. The total number of choc-chips used becomes the player's score for that round. The game continues for five rounds, with players filling all rows on the choc-chip cookie gameboard.	· Each pair rolls the game dice to determine how many choc-chips to place on each cookie in a chosen row. · The partners arrange the choc-chips together so the total can be easily identified without counting individually. The total number of choc-chips used becomes the pair's score for that round. · The game continues for five rounds, with all rows completed on the choc-chip cookie gameboard. · The pair with the highest total score after five rounds wins.

Game Materials and Mathematical Focus	Game Rules (One-Against-One)	Game Rules (Paired)
situations using models, moving from concrete (smaller dice) to abstract (larger dice) applications that draw on the distributive property. Problem solving: · Select optimal rows: pair larger dice rolls with rows containing more cookies to maximize score. · Plan ahead and anticipate opponents' moves. · Use landmark numbers (e.g., 10, 15) to simplify calculations. Reasoning: · Understand that all dice outcomes are equally probable. · Strategically assign expected roll ranges to rows to reserve high/low-value rows appropriately.	· The player with the highest total score after five rounds wins.	

Game 4: Reverse Landgrab (Russo & Russo, 2021)

Game Materials and Mathematical Focus	Game Rules (One Against-One)	Game Rules (Paired)
Materials: Grid gameboard Game dice: one 20-sided OR two 10-sided dice (to create a 2-digit number) Understanding: · Distinguish composite numbers (many factors/arrays) from prime numbers (only 1 and itself as factors, forming "skinny" 1xN arrays).	· Each player rolls the dice to generate a number representing an area to claim. · The player draws a rectangle on the grid that corresponds to one of the multiplication facts for that number (e.g., a roll of 12 allows 12×1, 6×2, or 4×3).	· Each pair rolls the dice to generate a number representing an area to claim. · The partners collaborate to draw a rectangle that matches one of the multiplication facts for that number (e.g., a roll of 12 allows 12×1, 6×2, or 4×3). · The rectangle is colored and labelled with the multiplication fact used.

Game Materials and Mathematical Focus	Game Rules (One Against-One)	Game Rules (Paired)
· Understand factors as length and width of rectangles. Fluency: · Develop fluency and flexibility with number facts. · Use arrays to represent multiplicative situations. Problem solving: · Identify all possible rectangles for a given product. Reasoning: · Understand the impact of grid size (e.g., a 12x15 board means a roll of 17 results in a missed turn). · Analyze how the grid size affects possible moves and outcomes.	· The rectangle is colored and labelled with the multiplication fact used.	

Game 5: Three-in-a-row Lucky Numbers (Russo, 2018)

Game Materials and Mathematical Focus	Game Rules (One-Against-One)	Game Rules (Paired)
Materials: 120-chart gameboard. Game dice: one 6-sided and 10-sided (alternatives: two 10-sided, or one 6-sided and one 20-sided die). Understanding: · Recognize that some numbers have many factors (belonging to several counting patterns) while others have very few. · Understand that a factor divides another number with no remainder. · Define a prime number as having	· Each player rolls both dice and uses the numbers rolled to form a multiplication fact. The fact is represented using a model chosen by the teacher (e.g., groups, arrays, or skip counting). · The product is calculated and marked on the chart. · If the number is already taken, it becomes a “lucky number,” allowing the	· Each pair rolls both dice and uses the numbers rolled to form a multiplication fact. · The partners represent the fact together using the teacher’s chosen model (e.g., groups, arrays, or skip counting). The product is calculated and marked on the chart. · If the opposing pair has already marked that number, it becomes a “lucky number,” allowing the team to choose

Game Materials and Mathematical Focus	Game Rules (One-Against-One)	Game Rules (Paired)
only 1 and itself as factors. Fluency: · Develop fluency and flexibility with number facts. Problem solving: · Identify "lucky" prime number candidates (e.g., greater than 7 or ending in 3). · Understand that some numbers (e.g., 16) are rolled more often because they have many factors, while others (e.g., 13) occur less frequently. Reasoning: · Analyze the probability of rolling certain numbers based on their number of factors.	player to choose another number on the chart. · The first player to achieve three rows in any direction wins.	another number on the chart. · The first pair to achieve three sets of three in a row (horizontally, vertically, or diagonally) wins.

APPENDIX 3. Code Book

This codebook outlines the categories used to analyze student dialogue during gameplay. Each code captures a distinct form of reasoning or interaction observed across all games. Illustrative excerpts are included to clarify intent.

Code		Purpose/Definition	Sub-Themes	Illustrative Examples
1	Generating	Proposing or adapting a mathematical move, strategy, or procedural action.	Offering strategies; Stating intentions; Rule innovation	“Should we do 5 × 2 or 1 × 10?” “Let’s save that spot.” “Instead of 9 we can do 90.”
2	Evaluating	Expressing agreement, disagreement, or judgment about a move, strategy, or outcome.	Agreement / disagreement; Corrections / blame; Assessment of performance	“That’s not a good idea.” “You took so long.” “I’m going to win.”
3	Justifying	Explaining or defending a decision using mathematical or strategic reasoning.	Explaining decisions; Mathematical justification; Defending behavior	“It doesn’t work in any timetables.” “We could have gotten higher if we swapped 9 and 10.” “I swear that’s what I rolled.”
4	Clarifying	Making information explicit for shared understanding, ensuring procedural and numerical accuracy.	Stating results; Reiterating numbers; Explaining rules / procedures	“17 and 1 is 18.” “Twenty-eight.” “No, you’re trying to get more land.”
5	Predicting	Anticipating future events, outcomes, or opponent actions.	-	“If you roll a 10, my risk is worthless.” “I think you’re going to win.” “We need 27 to win.”
6	Reflecting	Commenting on previous actions or lessons learned from play.	Reviewing past play; Learning from experience; Meta-commentary on learning	“We should have put the 9 there.” “Next time I’ll play it safer.” “This game really makes me think.”

Code		Purpose/Definition	Sub-Themes	Illustrative Examples
7	Prompting/Helping	Providing or asking for help	-	"Come on, start counting, I'll help." "Where should we put it?"
8	Connecting	Linking mathematical ideas or representations or drawing on prior knowledge.	-	"Thirteen is a prime number." "Double 10 is 20 because 5×2=10."
GM- Game Management		Managing the flow of play, rules, or reporting game state.	Turn-taking; Rules / conduct; Reporting dice rolls; Game-state setup	"Okay, you roll first." "No silly stuff." "Thirteen."
ET- Emotional Tone		Expressing affective responses to gameplay or peer actions.		"Yay!" "He's annoying." "OMG, we got it!"
ST- Self Talk / Metacognition		Thinking aloud or verbalizing internal reasoning.	Calculation; Internal planning; Reflecting on cognition	"1×18 = 18." "Oh, maybe I'll do …" "I'm thinking."
OTT- Off Topic Talk		Utterances unrelated to gameplay.	General commentary; Personal talk; Side remarks	"You know the camera's on." "I like Fridays because my mum goes shopping."

Coding Clarifications and Overlaps

Distinction	**Guideline**
Intent guides coding	Utterances may be multi-coded when they serve more than one clear function.
ST vs Justifying	Self-directed reasoning vs explaining to others.
ET vs Evaluating	Emotion vs analytical judgment.
GM vs Generating	Managing game flow vs proposing strategy.
Clarifying vs Justifying	Making information clear vs explaining *why* something holds.
Short utterances	Context determines function (e.g., "Okay" = GM if procedural; ET if emotive).

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Exploring Middle School Students' Perceptions, Attitudes, and Opinions Toward Artificial Intelligence

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Abstract

The main aim of this study is to examine the perceptions, attitudes, and opinions of seventh and eighth grade middle school students toward artificial intelligence (AI). A mixed-methods approach, combining both quantitative and qualitative data, was employed in the research. The study group consists of a total of 168 students enrolled in the seventh and eighth grades at a middle school located in the Bozüyük district of Bilecik province during the 2024–2025 academic year. Quantitative data were collected using Artificial Intelligence Perception and Attitude Scale. For the qualitative dimension, a semi-structured interview form was used to gain deeper insights into students' views. The analysis of the scale data revealed that students' perceptions and attitudes toward AI were at a moderate level, while their negative perceptions were found to be low. No statistically significant difference was observed based on gender; however, a significant difference favoring seventh-grade students was found when compared to eighth graders. Qualitative findings indicated that students generally held highly positive views toward artificial intelligence. Students emphasized that AI facilitates access to information, improves efficiency, saves time, and contributes to individuals' design and creativity skills. It was also found that students used AI tools in educational contexts for purposes such as completing homework, conducting research, summarizing data, reviewing subjects, and solving problems. On the other hand, some concerns regarding artificial intelligence were also identified. These included the potential disappearance of certain professions, a decline in creativity, threats to data privacy, dependency on AI tools, and reduced opportunities for socialization.

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Introduction

Artificial Intelligence (AI) has emerged as a transformative force in education, offering innovative solutions to enhance both teaching and learning processes. AI technologies in education are not limited to administrative functions; they are actively reshaping classroom experiences through intelligent tutoring systems, adaptive learning platforms, automated assessment tools, and natural language processing-based writing assistants (Luckin et al., 2016). These tools enable more efficient classroom management while also providing individualized support to students.

One of the most prominent benefits of AI in education is its potential to support personalized learning. AI-powered platforms can analyse vast amounts of student data to identify individual learning patterns, strengths, and weaknesses. Based on this analysis, systems can dynamically adjust content, difficulty levels, and instructional approaches to meet students' specific needs, thereby promoting deeper engagement and higher academic performance (Holmes et al., 2019). This form of learning personalization fosters inclusivity and ensures that no student is left behind due to rigid instructional pacing or standardization. Moreover, AI has begun to reshape the role of teachers. Rather than replacing educators, AI augments their capabilities by handling routine tasks such as grading, progress tracking, and even behavior monitoring (Zawacki-Richter et al., 2019). This shift allows teachers to allocate more time to high-impact pedagogical activities, such as mentoring, critical thinking instruction, and emotional support. However, this transformation also demands new competencies from teachers, including digital literacy, data interpretation skills, and ethical awareness related to AI use in schools.

AI tools have also shown a measurable impact on student performance. Studies suggest that students who engage with AI-supported learning environments tend to perform better in both formative and summative assessments due to increased feedback loops and immediate scaffolding (Chassignol et al., 2018). Nevertheless, while the potential is vast, ethical concerns such as data privacy, algorithmic bias, and equity in access remain critical challenges that must be addressed in parallel with technological advancement.

In recent years, there has been increasing interest in understanding how students perceive and respond to technological innovations, particularly artificial intelligence (AI), within educational settings. The integration of artificial intelligence-based tools into educational environments directly impacts the nature of students' relationship with technology. Particularly at the middle school level, students' perceptions and attitudes become decisive in determining the contribution of technological innovations to learning processes. Chen et al. (2020) highlight the importance of considering students' perceptions and attitudes when integrating new technologies such as artificial intelligence into learning processes. Students' perceptions and attitudes toward AI are critical indicators of how effectively these technologies can be integrated into teaching and learning environments. Research has demonstrated that students who hold positive attitudes toward technology tend to exhibit higher motivation, engagement, and willingness to use AI-powered tools in their learning processes (Teo, 2011; Venkatesh et al., 2003). At the middle school level, where cognitive development and digital exposure intersect, perceptions of AI are often shaped by personal experience, media exposure, and socio-cultural factors. Suh and Ahn (2022) found that K-12 students generally hold positive attitudes toward AI applications, especially when they are aware of its educational benefits. Similar findings were reported by Elçiçek (2024), who conducted a study in Turkey showing that students recognize AI as helpful in solving problems and completing assignments, although their AI literacy levels remain low overall.

Demographic variables such as gender, age, and grade level have also been shown to influence attitudes. Chen et al. (2020) reported in their review that male students tend to show slightly more favourable attitudes toward AI than female students, though the gap is narrowing. Moreover, Elçiçek (2024) reported that AI literacy levels vary significantly by gender, with male students showing higher scores in the technical understanding sub-dimension. These findings align with Teo's (2011) work, which emphasized that students' readiness for technology-integrated learning environments is strongly influenced by prior experience with technology. Additionally, ethical concerns begin to surface as students grow older and gain more awareness. Akgun and Greenhow (2022) found that K-12 students are more likely to express critical views about privacy, surveillance, and algorithmic bias associated with AI. Similarly, Suh and Ahn (2022) reported that students raised concerns about AI-related ethical dilemmas, particularly regarding autonomy and data use, suggesting the need for integrated AI ethics education from early school years. Taken together, these findings emphasize the importance of age-appropriate, inclusive AI education that considers both cognitive development and socio-demographic diversity. Understanding how various groups of students perceive and interact with AI is crucial for creating equitable and effective educational strategies.

Understanding how students interact with artificial intelligence (AI) in educational settings requires a strong grasp of the psychological and pedagogical constructs that shape their responses—namely, perception, attitude, and opinion. These constructs not only influence individual behaviour but also mediate how students accept and integrate technology into their learning processes (Schunk, 2020; Venkatesh et al., 2003). Perception refers to the process by which individuals interpret sensory input and assign meaning based on their prior experiences, beliefs, and expectations (Schunk, 2020). In educational contexts, perception significantly influences how students make sense of instructional content and technological tools. A student who perceives AI as a helpful tool is more likely to use it effectively, while those who associate it with surveillance or loss of autonomy may resist its use. Attitude is typically defined as a learned predisposition to respond favourably or unfavourably toward a specific object, idea, or behaviour (Ajzen, 1991). In the domain of educational technology, attitude plays a central role in determining technology acceptance and user intention. According to the Technology Acceptance Model (TAM), perceived usefulness and perceived ease of use are key predictors of user attitude, which in turn influences the behavioural intention to adopt a technology (Venkatesh et al., 2003). Opinion, though closely related to attitude, is considered a consciously held belief or judgment that may not be based on direct experience but is shaped through interpretation and reflection. Students' opinions about AI often include broader concerns—such as ethical implications, societal impact, and future employment—that go beyond immediate classroom experiences. These opinions are particularly relevant when analysing qualitative data in mixed-methods studies.

Collectively, perception, attitude, and opinion form a triadic lens through which student engagement with AI can be understood. These constructs are deeply embedded in the learning process, affecting motivation, autonomy, and behavioural outcomes. Therefore, a clear conceptual understanding of these terms is essential for both interpreting data and designing pedagogical strategies that promote meaningful interaction with AI-based technologies.

Several empirical studies have investigated how students perceive and engage with artificial intelligence (AI) in educational settings, confirming the critical role of psychological constructs such as perception, attitude, and opinion. For example, Suh and Ahn (2022) conducted a validation study with K-12 students in South Korea and found that students generally had positive attitudes toward AI, particularly appreciating its ability to support academic tasks like research and homework. However, the same study also revealed concerns about dependency and creativity loss, highlighting the dual nature of student opinions. In another study, Chen et al. (2020) performed a review across multiple contexts and reported significant gender differences in AI-related attitudes, with males demonstrating higher interest and confidence levels. This supports previous work by Teo (2011), which emphasized the importance of digital familiarity in shaping technology acceptance, especially among young learners. Additionally, Akgun and Greenhow (2022) explored students' understanding of AI in K-12 settings through a synthesis of existing literature. Their analysis suggested that although students were enthusiastic about using AI tools, many held misconceptions about how these systems actually function. The study called for curriculum interventions to increase AI literacy and clarify its ethical and operational boundaries. Further, Elçiçek (2024) examined AI literacy among students in Turkey and found that while students perceived AI as beneficial, they lacked critical awareness of issues such as data privacy and surveillance. These findings align with Akgun and Greenhow (2022), who reported that older students were more likely to express nuanced, ethically informed opinions about AI's broader societal implications. These studies collectively underscore the importance of addressing both the affective (attitudinal) and cognitive (perceptual) dimensions of student engagement with AI. They also highlight the value of mixed method approaches in capturing the complex interplay of factors that shape how students accept and interpret AI in their learning environments.

While previous research has provided valuable insights into students' general attitudes and perceptions toward artificial intelligence, several notable gaps remain—particularly in terms of context, educational level, and methodological design. Most studies have focused either on high school (Akgun & Greenhow, 2022) or university students (Chen et al., 2020), overlooking the middle school population, where students are in a formative stage of cognitive and social development. Furthermore, earlier research has often relied solely on quantitative instruments, such as surveys or standardized scales (Teo, 2011; Suh & Ahn, 2022), which may not fully capture the nuanced and evolving nature of students' thoughts, emotions, and concerns regarding AI.

What sets the present study apart is its specific focus on middle school students (grades 7 and 8) within the Turkish education system, a demographic that has been underrepresented in AI-related educational research (Elçiçek, 2024; Suh & Ahn, 2022). In addition, this study employs a mixed-methods approach, integrating both quantitative data through validated attitude scales and qualitative insights obtained via semi-structured interviews. This triangulated methodology offers a more comprehensive and context-sensitive understanding of how students perceive, engage with, and reflect upon artificial intelligence in real learning environments. Moreover, unlike prior studies that emphasize only the positive dimensions of AI integration, the current research also examines students' critical perspectives—including concerns about privacy, creativity loss, and AI dependency—thus presenting a more balanced and realistic portrayal of youth engagement with emerging technologies. By addressing these methodological and contextual gaps, this study contributes to the global discourse on AI in education and offers practical implications for curriculum designers, educators, and policymakers aiming to implement AI tools in age-appropriate and ethically informed ways.

Aim of the Study

The primary aim of this study is to explore the perceptions, attitudes, and opinions of seventh and eighth-grade middle school students regarding artificial intelligence (AI). In line with this main objective, the study seeks to answer the following sub-questions:

1. To what extent are students' positive and negative perceptions and attitudes toward artificial intelligence statistically significant?
2. Do students' positive and negative attitudes toward artificial intelligence differ significantly according to gender and grade level variables?
3. What are students' general opinions about artificial intelligence, and what are their views concerning its advantages and disadvantages?
4. What are students' expectations regarding education and future prospects related to artificial intelligence?

Method

This section presents detailed information regarding the research design, study group, data collection instruments, data collection and analysis procedures, as well as the strategies employed to ensure the validity and reliability of the study. Furthermore, ethical considerations adhered to throughout the research process are also discussed. Each component is explained to ensure the transparency, rigor, and replicability of the study.

Research Design

This study adopted a mixed-methods research design, integrating both quantitative and qualitative data collection tools to achieve a comprehensive and in-depth understanding of middle school students' perceptions, attitudes, and opinions toward artificial intelligence. Mixed methods allow for the combination of the generalizability and statistical rigor of quantitative approaches with the contextual richness and interpretive depth of qualitative inquiry. This dual strength provides a more holistic perspective on complex educational phenomena (Creswell & Plano Clark, 2018; Karasar, 2005). According to Creswell and Plano Clark (2018), mixed-methods research is defined as a methodological approach that involves the collection, analysis, and integration of both quantitative and qualitative data to better understand a research problem from multiple dimensions. Karasar (2005) similarly describes mixed methods as a framework that allows for the simultaneous use of quantitative and qualitative techniques, enabling researchers to both generalize findings through statistical analysis and generate deeper meaning through contextual exploration. He further emphasizes that such an approach is particularly valuable in educational and social science research, where both breadth and depth of understanding are essential.

In mixed-methods research, the dominance and sequencing of qualitative and quantitative components may vary.

In some studies, the quantitative approach serves as the primary method, while the qualitative part plays a supplementary role; in others, the opposite may occur. There are also designs where both methods are given equal priority. In the current study, an embedded (nested) design—a specific subtype of mixed-methods approach—was employed, as outlined by Yıldırım and Şimşek (2021). This design involves embedding one type of data within another, wherein one method (either qualitative or quantitative) is subordinate but supportive of the dominant method.

In this research, the quantitative component played the dominant role, utilizing a validated Artificial Intelligence Attitude Scale as the primary data collection instrument. To enrich and contextualize the quantitative findings, semi-structured interviews were conducted with a subset of students, offering qualitative insights into students' deeper thoughts, experiences, and concerns regarding artificial intelligence in educational settings. This embedded design allowed for the triangulation of data, strengthening the validity and interpretive power of the study's conclusions.

Study Group / Participants

The participants of this study consisted of seventh and eighth-grade students enrolled at Meliha Ercan Middle School, located in the Bozüyük district of Bilecik province, Turkey, during the 2024–2025 academic year. The selection of the study group was carried out using a combination of purposeful sampling strategies, specifically convenience sampling and criterion sampling methods. The convenience sampling technique was employed primarily due to the fact that the researchers were already working within the same school environment. This method is often preferred in situations where access to participants is limited, and time or logistical constraints exist (Yıldırım & Şimşek, 2021). Convenience sampling provides practical advantages by allowing researchers to work with easily accessible and nearby participants, making data collection more feasible and efficient without compromising the study's integrity. In addition to convenience sampling, the study also utilized criterion sampling, another type of purposeful sampling strategy. Criterion sampling involves identifying participants based on predetermined characteristics or criteria that are central to the research objective (Merriam, 2015). In this study, the primary criteria for participant selection included:

- •Being in the seventh or eighth grade,
- •Having prior experience or basic familiarity with using artificial intelligence tools (e.g., virtual assistants, AI-supported applications),
- •And being at a cognitive developmental stage where opinions and attitudes toward technological concepts are meaningfully formed and expressed.

These criteria were established to ensure that the participants were both developmentally appropriate and contextually relevant for investigating perceptions and attitudes toward AI in education. By selecting students who met these conditions, the study aimed to capture more accurate, reflective, and diverse insights into the ways adolescents understand and interact with artificial intelligence in their learning environments. The combination of convenience and criterion sampling thus enabled the researchers to conduct a study that was not only logistically practical but also methodologically rigorous, aligning with the principles of purposeful sampling in qualitative and mixed-methods research.

Data Collection Instruments

To investigate the perceptions, attitudes, and opinions of seventh and eighth-grade middle school students toward artificial intelligence, two primary data collection tools were employed in this study: the Artificial Intelligence Perception and Attitude Scale (YAZAT-24) and a semi-structured interview form.

Artificial Intelligence Perception and Attitude Scale (YAZAT-24)

The YAZAT-24 was developed by Dinler (2025) to measure students' positive and negative perceptions and attitudes toward artificial intelligence. The scale development process followed rigorous psychometric protocols to ensure validity and reliability. Initially, an extensive review of contemporary literature and existing scales focusing on AI-related attitudes and perceptions was conducted to generate a preliminary item pool. This item pool was refined through expert evaluations involving professionals in education, psychology, and educational technology, resulting in a 50-item draft version of the scale.

A pilot study was carried out with a large sample of 1,600 students. The data were analyzed in two stages using both Exploratory Factor Analysis (EFA) and Confirmatory Factor Analysis (CFA) on a subset of 855 participants. EFA results revealed a Kaiser-Meyer-Olkin (KMO) value of .94 and a Bartlett's Test of Sphericity of 19028.027 ($p < .001$), indicating suitability for factor analysis. The EFA indicated a four-factor structure explaining a cumulative variance of 75.17% across sub-dimensions: Positive Perception (46.90%), Negative Perception (63%), Media Production Attitude (70.20%), and ChatGPT Usage Attitude.

The four-factor structure was further validated using first- and second-order CFA. The first-order CFA showed factor loadings ranging from .72 to .98, with acceptable model fit indices: $\chi^2/df = 9.59$, RMSEA = .10, CFI = .95, TLI = .94, and WRMR = 2.07. The second-order CFA also confirmed the structure with factor loadings between .72 and .99 and improved fit indices: $\chi^2/df = 5.32$, RMSEA = .07, CFI = .97, TLI = .97, and WRMR = 1.37. These results indicated a statistically acceptable model-data fit. The internal consistency of the scale was evaluated using Cronbach's Alpha, calculated via SPSS 23. The reliability coefficients for the subscales were $\alpha = .96$ for Positive Perception, $\alpha = .92$ for Negative Perception, $\alpha = .94$ for Media Production Attitude, and $\alpha = .90$ for ChatGPT Usage Attitude. The overall reliability of the scale was found to be $\alpha = .96$. According to Kayış (2014), a Cronbach's Alpha value of .80 or above is considered indicative of high internal consistency. Therefore, the scale demonstrates strong psychometric properties suitable for use in this study. In the current sample, the recalculated Cronbach's Alpha was found to be $\alpha = .67$, which, although lower, is still within acceptable range for social science research.

Semi-Structured Interview Form

To complement the quantitative findings, a semi-structured interview form was developed by the researchers to collect qualitative data. This method allows for both standardized responses and in-depth exploration of participants' thoughts and experiences (Büyüköztürk et al., 2016).

In preparation for the interviews, the researchers followed the steps recommended by Adıgüzel (2019) for designing semi-structured interviews. First, interview questions were developed in alignment with the theoretical framework of the study, focusing on students' general perspectives on AI, perceived advantages and disadvantages, and future expectations regarding AI in education. Next, the draft interview questions were subjected to expert review. A structured feedback form was created, including four evaluation categories: "Appropriate," "Not Appropriate," "Appropriate with Revisions," and an open field for comments. The form was shared with four experts holding doctoral degrees or advanced expertise in educational sciences. Based on their feedback, necessary revisions were made to ensure content validity and clarity of the interview items. The finalized interview form was used in the qualitative component of the research to gain deeper insight into students' reflections, language, and emotional responses related to AI.

Data Collection and Analysis

Following the receipt of necessary institutional and ethical permissions, data collection procedures were conducted in two stages: quantitative and qualitative. The Artificial Intelligence Perception and Attitude Scale (YAZAT-24) was administered to all participants in the study group to gather quantitative data. Before completing the scale, students were asked whether any items or questions were unclear, and researchers were available to clarify if needed. On average, students completed the instrument in approximately 20 to 25 minutes under the supervision of the researchers, ensuring consistency and data quality during administration. Qualitative data were collected through a semi-structured interview form, which was developed in alignment with the study's theoretical framework. Interviews were conducted with a purposefully selected subgroup of 17 students who had prior interest or experience related to artificial intelligence. This criterion ensured that participants could provide informed and reflective insights. Each interview lasted approximately 15 minutes, and responses were audio-recorded and later transcribed for analysis.

To analyse the quantitative data, the researchers utilized IBM SPSS Statistics 27. Independent samples t-tests were conducted to examine whether students' positive and negative attitudes toward artificial intelligence differed significantly based on gender and grade level, in line with the sub-questions of the study. The qualitative data were analysed using the content analysis technique, which is widely used to systematically categorize and interpret textual information in qualitative research (Yıldırım & Şimşek, 2021). This process involved four major stages:

1. Transcription and familiarization – All interview data were transcribed verbatim and reviewed line by line.
2. Initial coding – Researchers identified and labelled meaningful units of text.
3. Categorization – Codes were grouped into themes that broadly represented students' thoughts and experiences.
4. Interpretation – Themes were analysed and discussed in relation to the study's objectives.

To ensure trustworthiness and transparency, direct quotations from student responses were included in the findings section. These excerpts were selected to illustrate recurring themes, add depth to the analysis, and support the interpretations made by the researchers. In accordance with ethical research standards, participants' real names were not disclosed. Instead, pseudonyms were used in the form of coded identifiers such as S1-M, S2-M for male students and S1-F, S2-F for female students. In this coding system, "S" stands for Student, while "M" and "F" indicate Male and Female, respectively. Alignment between the study variables, data collection instruments, and analysis techniques is presented clearly in Table 1 to provide a structured overview of the research design and methodology.

Table 1. Measurement Tools, Variables Measured, and Analysis Methods Used in the Study

Measurement Tool	Variable Measured	Analysis Method
Artificial Intelligence Perception and Attitude Scale (YAZAT-24)	Students' Perceptions and Attitudes Toward Artificial Intelligence	Independent Samples t-Test
Semi-Structured Interview Form	Student Opinions on Artificial Intelligence	Content Analysis

Validity, Reliability, and Trustworthiness of the Study

To ensure the credibility and trustworthiness of the study, various strategies were employed across both quantitative and qualitative phases. In line with internal validity standards, the research design incorporated methodological triangulation, including the use of both quantitative instruments and qualitative data collection tools. This integration of data sources enhanced the depth and breadth of the findings and contributed to the robustness of the interpretations. During the qualitative data collection process, member checking was actively implemented to ensure that participants' statements were accurately represented. After interviews were conducted, students were given the opportunity to confirm or clarify their responses, helping to prevent potential misinterpretation or bias in the analysis. This process strengthened the credibility of the findings by validating the authenticity of participants' voices (Lincoln & Guba, 1985).

In addition, expert validation was utilized during the development of the semi-structured interview form. Feedback was obtained from four experts with academic qualifications in educational sciences, who evaluated the interview items in terms of clarity, relevance, and content coverage. Their insights contributed to the content validity of the qualitative instrument by ensuring alignment with the study's research questions and theoretical framework. To address the criterion of transferability, thick descriptions were provided throughout the presentation of findings. Comprehensive information about the research design, participant characteristics, data collection tools, and procedures was offered in the methodology section.

Furthermore, data were visualized through tables and supported by direct quotations from students, offering readers rich contextual understanding that allows for potential application of results in similar educational settings. Finally, dependability and confirmability were addressed through clear documentation of coding procedures, systematic analysis strategies, and transparent decision-making during data interpretation. The coding and theme development process was grounded in the content analysis framework outlined by Yıldırım and Şimşek (2021), which includes multiple stages such as transcription, initial coding, theme generation, and interpretation. Collectively, these strategies demonstrate a rigorous approach to ensuring that the study's conclusions are both valid and reliable, and that they reflect the authentic perspectives of participants in a transparent and ethically sound manner.

Ethical Considerations

Throughout the research process, strict adherence to ethical principles was ensured, and the following measures were taken to protect the rights, safety, and dignity of all participants:

- Prior to the implementation of the data collection process, official permission was obtained from the Ministry of National Education of Turkey to conduct the research in the designated school. This approval was granted after finalizing the appropriate research design, developing the qualitative interview protocol, and selecting the measurement instruments to be used in the study.
- All student participants were informed about the purpose and scope of the study, and their voluntary participation was emphasized. Informed consent procedures were followed in accordance with ethical research standards, and parental consent forms were distributed and collected for all minors involved in the research. Additionally, permission to use the Artificial Intelligence Perception and Attitude Scale (YAZAT-24) was formally obtained from the developer of the instrument.
- To maintain participant confidentiality and protect personal identities, pseudonyms were used throughout the study. Students' real names were not recorded or reported at any stage. Instead, each participant was assigned a coded identifier (e.g., S1-M, S2-F), allowing the researchers to refer to individual contributions while safeguarding privacy. These identifiers also facilitated transparent reporting of qualitative findings without compromising anonymity.

All data were stored securely and used solely for research purposes. The ethical guidelines followed were in accordance with the standards set by international codes such as the American Psychological Association (APA) Ethical Guidelines and the Declaration of Helsinki, particularly regarding voluntary participation, informed consent, and confidentiality.

Findings

This section presents the findings of the study, which aimed to explore middle school students' perceptions, attitudes, and opinions toward artificial intelligence. The results are organized in accordance with the research sub-questions and include both the quantitative analysis of the data collected through the Artificial Intelligence Perception and Attitude Scale (YAZAT-24), and the qualitative findings obtained through content analysis of the student interviews. Both data sets are interpreted to provide a comprehensive understanding of how students perceive and evaluate AI in educational contexts.

Findings Related to Middle School Students' Perceptions and Attitudes Toward Artificial Intelligence

The quantitative findings regarding middle school students' perceptions and attitudes toward artificial intelligence are presented in Table 2. As shown in the table, middle school students demonstrated a moderate level of positive perception, ChatGPT usage attitude, and overall scores regarding artificial intelligence. However, their scores in the negative perception dimension were found to be low. The findings related to students' perceptions and attitudes toward artificial intelligence based on gender and grade level are presented in Table 3.

Table 2. Mean and Standard Deviation Scores for Middle School Students' Perceptions and Attitudes Toward Artificial Intelligence

Dimension	**N**	**X̄**	**Sd**	**Level**
Positive perception	168	57.38	.85	Moderate
Negative perception	168	27.01	.97	Low
Attitude Toward Using Chat-GPT	168	18.35	.54	Moderate
Total	168	102.75	1.23	Moderate

Table 3. Findings Related to Middle School Students' Perceptions and Attitudes Toward Artificial Intelligence According to Gender and Grade Level

Variable		**N**	**X̄**	**Sd**	**p**
Gender	Girl	93	102.4	17.8	.76
	Boy	75	103.1	13.5	
Grade	7th grades	72	109.66	15.87	.001*
	8th grades	96	97.56	14.15	

As shown in Table 3, when examining the total scores of students' perceptions and attitudes toward artificial intelligence, female students had a mean score of 102.4, while male students had a mean score of 103.1. The results indicated no statistically significant difference between the groups based on gender. However, when analysed by grade level, it was found that seventh-grade students had a higher mean score (M = 109.66) compared to eighth-grade students (M = 97.56). This difference was found to be statistically significant, suggesting that grade level plays an important role in shaping students' perceptions and attitudes toward artificial intelligence.

The students' responses to the question "What does artificial intelligence mean to you?", which was asked to explore their general opinions about AI, eleven students described artificial intelligence primarily as a tool for accessing and expressing information. These students emphasized that AI systems help them retrieve knowledge quickly and efficiently, particularly when conducting research or completing homework assignments. One student, for instance, remarked that they could "easily learn anything [they] want" using AI and even receive help with generating content, such as writing a paragraph on the benefits of oranges. Such reflections reveal that students perceive AI as a facilitator of autonomous learning and digital literacy. Seven participants associated artificial intelligence with convenience and efficiency, specifically highlighting its time-saving benefits. These students viewed AI as a support mechanism that assists them in managing their academic responsibilities more effectively. One female student explained that AI allows her to "easily access nearly everything" in both the digital and physical world, adding that it simplifies daily tasks and provides support in completing schoolwork.

In contrast, a smaller group offered more conceptual or futuristic interpretations. Two students saw artificial intelligence as a symbol of the future, referring to it as a powerful innovation that will influence "every area of life." Meanwhile, one student associated AI with superior intelligence, noting its capacity for analytical thinking and problem-solving, and another highlighted its creative potential, especially in design and production tasks. Overall, these findings indicate that most students regard artificial intelligence not only as a practical tool in educational contexts but also as a transformative technology with far-reaching implications for the future.

An integrated analysis of both the quantitative and qualitative findings reveals a coherent and mutually reinforcing outcome. The data suggest that middle school students generally maintain a moderately positive perception and attitude toward artificial intelligence. Quantitative results demonstrated moderate levels of positive perception and ChatGPT usage, while negative perceptions were found to be low. These numerical patterns are mirrored in the qualitative responses, where students frequently expressed that artificial intelligence helps them access information more easily, complete assignments faster, and manage learning tasks more efficiently. Interviewed students often described AI as a supportive presence in their academic lives, citing examples such as writing assistance, summarizing content, or retrieving facts instantly. This practical and efficiency-focused appreciation reflects the attitudes captured through the scale. Furthermore, the lack of statistically significant differences between genders, alongside the observed grade-level differences, is supported by qualitative evidence in which younger students tended to view AI more enthusiastically than their older peers. Taken together, the data indicate that students do not perceive AI as a source of anxiety or resistance. Instead, they regard it as a useful, manageable, and supportive tool that enhances their learning experiences and helps them feel more competent and autonomous in educational contexts.

As part of the exploration of students' general opinions about artificial intelligence, their responses to the question regarding the use of AI in daily life are presented in Figure 1.

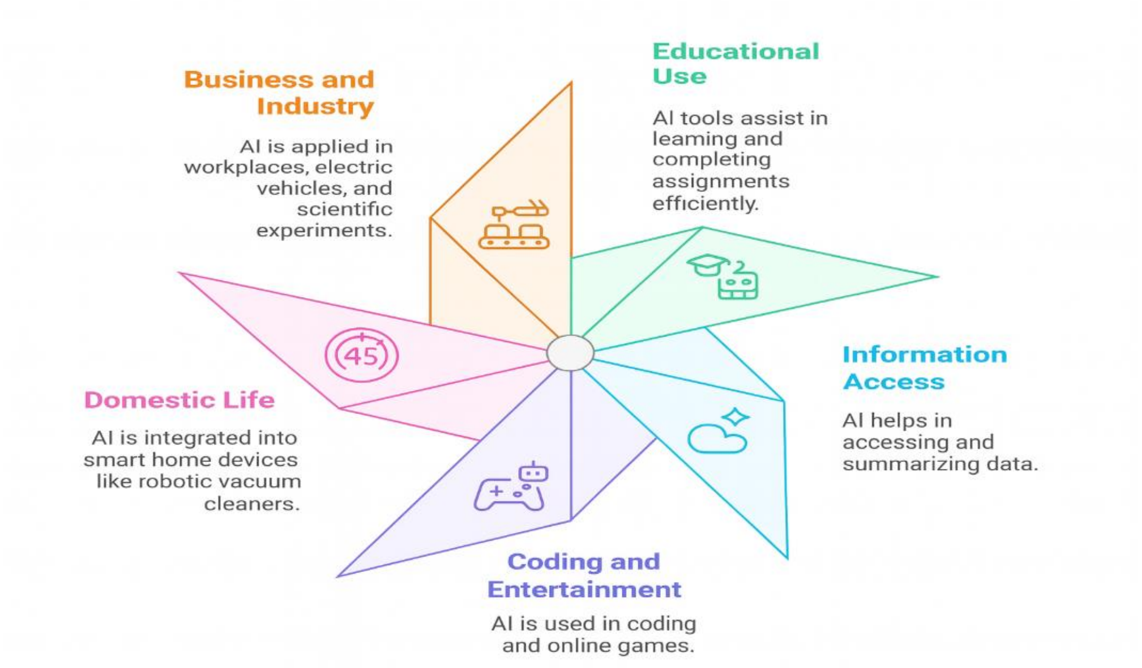

Figure 1. Students' Responses to the Question on the Use of Artificial Intelligence in Daily Life

As illustrated in Figure 1, fourteen students reported that artificial intelligence is particularly useful in learning and educational processes, especially in conducting research for assignments. They emphasized that AI tools help them complete homework more efficiently and serve as reliable academic assistants. In addition to educational use, five students mentioned that AI is beneficial in accessing information and summarizing data in everyday contexts. Other responses reflected more diverse applications. One student referred to the use of AI in coding and digital entertainment, especially through online games. Another mentioned smart home devices, such as robotic vacuum cleaners, as examples of AI integration in domestic life. Additional comments included references to business and industrial applications, such as calculations in workplaces and the use of AI in electric vehicles, robotics, and scientific experimentation. For instance, S1-F noted that AI is helpful for entertainment (like computer games), makes housework easier with devices like robotic cleaners, and supports studying and homework tasks. She also added that it assists with workplace calculations and much more. Similarly, S5-F highlighted that electric vehicles, such as Tesla, use AI for sensory functions, and that AI can facilitate dangerous or complex scientific experiments through intelligent robotics. Another participant, S7-M, pointed out that AI allows users to easily access information they don't know, especially when trying to understand topics they are curious or confused about. These responses indicate that students recognize the multi-functional role of AI, not only in academic settings but also in daily practical contexts, ranging from education to entertainment, technology, and domestic life.

As part of students' general opinions on artificial intelligence, their responses to the question regarding which AI tools they use, the majority of interviewed students (fourteen out of seventeen) reported using ChatGPT primarily for research purposes and completing assignments. This suggests that ChatGPT is widely perceived as a practical educational tool among middle school students. Additionally, three students mentioned using Copilot as a conversational AI tool, mainly for informal dialogue and entertainment. A smaller group of students, specifically two participants, indicated that they used AI tools such as Picsart AI and Ideogram for generating images and visual content. Only one student stated that they do not use any artificial intelligence tools at all. Several student statements further illustrate these patterns. For instance, S4-M explained that he uses ChatGPT for academic tasks such as homework, Copilot for casual conversations, and Picsart AI for creating images and visuals. Similarly, S8-M shared that he relies on ChatGPT not only for completing school assignments but also for satisfying everyday curiosities. He also noted using Picsart AI to create visuals and edit photographs.

These findings suggest that middle school students are not only familiar with multiple AI tools but are also able to differentiate their functional roles—from academic productivity to creative expression and personal assistance. This versatility in usage underscores the growing integration of artificial intelligence into students' daily academic and technological routines. As part of students' general opinions regarding artificial intelligence, their responses to the question about the use of AI tools in educational processes, fourteen out of seventeen students stated that artificial intelligence tools contribute positively to teaching and learning processes, primarily because of their ability to provide easy and fast access to information. Students reported using AI to support various academic tasks, such as completing homework, reviewing lessons, and solving practice questions. These applications were seen as enhancing their efficiency and understanding in subjects like mathematics and language.

For instance, S2-F mentioned that AI has a positive impact on her academic performance and that she already uses it regularly in daily life. She explained that she turns to AI when she cannot solve a math problem or when she encounters a difficult language question, although she only asks for help with the parts she finds truly challenging. Similarly, S6-M highlighted that AI significantly contributes to his learning, especially in mathematics. He shared that he often asks AI about problems he does not understand or uses it to clarify points during study sessions. However, two students reported that they do not find AI effective in educational settings. They explained that assignments completed with the help of AI are often easily distinguishable from those done independently, raising concerns about authenticity and academic integrity. For example, S4-F noted that although AI can answer almost any question due to its large knowledge base, it may sometimes provide incorrect information. She also emphasized that when AI is used for assignments, teachers can easily detect the difference between AI-generated content and student-created work. Only one student, S1-M, stated that he does not use AI tools in his educational activities at all. He believed that relying on artificial intelligence in schoolwork could hinder his personal development by reducing opportunities for independent thinking and learning. These findings reflect a general consensus that AI tools can be beneficial in supporting students' academic efforts. However, they also highlight a minority of students who express critical concerns related to overreliance, reduced originality, and the potential negative impact on learning autonomy.

The students' responses to the question regarding their concerns about artificial intelligence and its potential harm are presented in Figure 2.

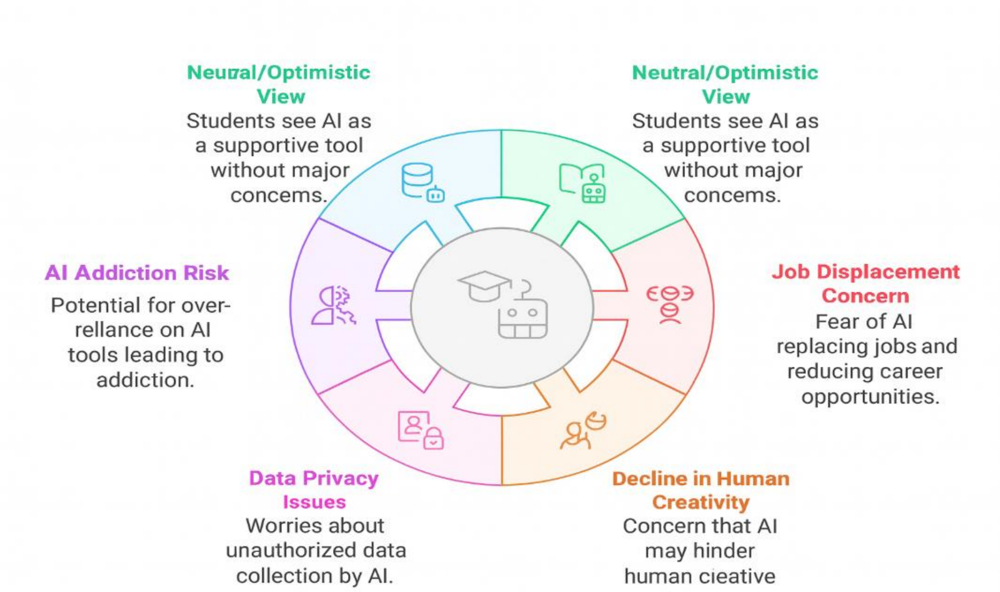

Figure 2. Students' Responses to the Question About Concerns and Perceived Harms of Artificial Intelligence

As seen in Figure 2, more than half of the students (ten out of seventeen) reported no significant concerns about artificial intelligence and stated that they do not consider it a threat to humanity. These students emphasized that the outcomes of using AI depend largely on how responsibly individuals choose to use it. For example, S1-M explained that he is not worried about AI because "how good or bad it becomes depends on how we use it," adding that if used efficiently, AI can offer many benefits. Similarly, S2-F expressed confidence in AI, saying that it makes life easier and helps people access information quickly and effectively. Nevertheless, several students voiced critical concerns about the possible negative consequences of AI in the long term. A number of participants highlighted the risk of job displacement, arguing that as AI becomes more advanced, the need for human labor in certain professions may diminish. Others were worried about a decline in human creativity, as AI tools become capable of generating ideas and solutions with minimal human input. S5-F pointed out that "AI could be harmful in some cases," particularly in terms of fostering dependency. She added that such risks can be mitigated by setting clear boundaries and limits on AI use. Likewise, S7-M noted that overreliance on AI might "cause people to lose touch with real-life social interactions" and reduce human-to-human communication over time. Concerns about data privacy were also mentioned, with a few students expressing unease about the possibility of AI tools collecting personal or sensitive information without consent. S4-F remarked that while she values the convenience of AI, she is cautious about sharing too much information through digital platforms, as it could be misused or exploited. In summary, while the majority of students held optimistic and pragmatic perspectives on AI, a smaller group demonstrated critical awareness of its potential social, emotional, and ethical drawbacks. These nuanced responses reflect a growing consciousness among young learners about both the opportunities and challenges posed by artificial intelligence in everyday life.

Several students indicated that they had encountered artificial intelligence tools during Information and Communication Technology (ICT) classes, though often only in a limited or introductory capacity. Most participants emphasized the need for more in-depth coverage of AI concepts within the formal curriculum. For example, S8-M shared that AI tools were mentioned briefly in fifth and sixth grade but that the lessons did not provide enough depth. He explained, "We only talked about AI a little bit in ICT class, but I think it wasn't enough. We need more time for AI, because it's the technology of the future, and we should be learning to use it." Similarly, S1-F added, "In class, we mostly learn about basic computer skills, but we barely touch on AI. I think we should learn more, especially how to use tools like ChatGPT or image generators."

Several students also referenced the use of AI tools in project-based extracurricular settings, particularly within eTwinning and TÜBİTAK initiatives. These projects provided more practical engagement with artificial intelligence in a creative and collaborative context. S6-F recalled her experience with an eTwinning project: "We created visual content and videos using AI tools. It was really fun and made our project more interesting." Similarly, S7-M described how his group used AI to develop a product prototype in a TÜBİTAK science fair project, adding, "AI helped us generate ideas and improve our designs." S9-F emphasized the motivational effect of using AI in school projects: "When we use AI in group activities, it feels like we're working with real-world tools. It makes the project more exciting and realistic."

These insights suggest that while classroom integration of AI remains minimal, students are increasingly exposed to AI applications through project-based, interdisciplinary learning, which they find both engaging and meaningful. Students shared diverse views when asked whether they would consider a career involving artificial intelligence. A majority of those who expressed interest envisioned themselves in technology-related fields, especially in coding, software development, and computer engineering. S3-M expressed a clear goal, saying, "I want to become a computer engineer and work with AI. I've always liked technology and robots, and I want to build smart systems." S4-F echoed this ambition: "I want to be a software engineer. Since I was young, I've been interested in AI and how it thinks like a human. I want to create programs that can do that." S10-M added, "I like programming, and I want to make games and AI systems that can play with humans. That would be amazing."
Some students linked their future career aspirations to STEM fields that intersect with AI, such as architecture, engineering, space exploration, and design.

S5-M explained, "I want to be a space engineer, and AI will help with building intelligent systems for rockets or satellites." S9-F mentioned an interest in architecture: "I think AI can help us design smarter cities and buildings. I'd like to study that." In contrast, a few students shared that they did not plan to pursue AI-related careers, either due to lack of interest or different personal goals. S2-F stated, "I'm not into technology that much. I'd rather be a doctor and help people directly." S11-M added, "AI is cool, but I don't want to work with computers. I want to do something outdoors like be an environmental scientist." Overall, the findings show that AI inspires many students to dream of future careers in cutting-edge technology fields yet also reveals that some maintain a preference for human-centred or nature-focused professions. The responses reflect a broad spectrum of aspirations, with AI serving as both a motivator and a boundary, depending on students' interests and perceived identities.

Discussion, Conclusion, and Recommendations

The findings of this study revealed that middle school students demonstrated moderate levels of positive perception and attitudes toward artificial intelligence (AI), especially in dimensions related to ChatGPT usage, while their negative perception levels remained low. This suggests that efforts to increase students' awareness of AI's core principles, applications, and ethical dimensions generally yield positive outcomes. Moreover, exposure to emerging tools such as ChatGPT appears to shape students' views of AI as a useful and assistive educational tool. Supporting this, Oruç, Korkmaz, and Kurt (2024) argued that AI applications in education enhance academic achievement and provide instructional opportunities tailored to individual needs. This claim aligns with students' positive views on the role of AI in supporting access to information, time efficiency, and productivity. However, the same study also emphasized certain risks such as security and privacy concerns, which were echoed in the current research by a subset of students.

The study also found no significant differences based on gender in students' perceptions of AI, though grade level did play a significant role, with seventh-grade students showing more favourable attitudes than eighth-grade students. These results suggest that while gender may not influence students' views on AI, developmental and educational stages might. This is consistent with Eker and Halıcı Gürbuz (2024), who found that gender and demographic variables had limited influence on perceptions of AI, whereas Akbay and Yıldırır (2024) reported that middle school students tend to view AI more optimistically compared to high school students, whose perspectives are shaped by more human-cantered metaphors. In alignment with this, younger students tend to be more open and enthusiastic toward new technologies like AI due to their association with innovation and playfulness, whereas older students adopt a more critical and analytical stance. Aksakal, Emre, and Özbek (2024), in contrast, identified gender as a significant factor in shaping AI attitudes among primary teachers, showing that contextual variables can yield different outcomes.

The current study also showed that students viewed AI tools as beneficial in tasks such as homework completion, research, summarization, review activities, and problem-solving. These views resonate with findings from Zawacki-Richter et al. (2019), who reported that AI in higher education enabled faster access to learning resources and personalized feedback, improving productivity and engagement. Holmes, Bialik, and Fadel (2019) similarly emphasized the value of AI in developing creativity and design-oriented thinking, especially in problem-solving exercises. Nevertheless, some scholars have taken a more cautious stance. Selwyn (2019) emphasized that the increasing use of AI in education may threaten the human dimension of learning by reducing opportunities for critical thinking and social interaction. Williamson (2017) also warned that the use of AI might push education toward a metric-based, algorithmically governed model, where students' autonomy could be undermined. Students in this study also reported frequent use of AI technologies not only in academic settings but also in their daily lives, such as coding, online games, smart appliances, and commercial tools. This is consistent with Dwivedi et al. (2021), who noted that smart devices and AI-based recommendation systems are rapidly shaping consumer behaviour and daily decision-making.

While many students expressed strongly positive views about AI—largely due to its ability to support learning, simplify daily tasks, and offer meaningful solutions—some also voiced concerns. These included the elimination of certain professions, the diminishing of creativity, invasion of privacy, dependency, and reduced social interaction. literature concerns were raised by a minority of students; they reflect broader themes found in the literature. Frey and Osborne (2017), for instance, highlighted the risk of job displacement due to automation, confirming students' anxieties about the future workforce. Therefore, despite students' generally optimistic outlook on AI, this research demonstrates that they also maintain a critical awareness of its potential risks. To ensure that the opportunities provided by AI in both educational and personal contexts are ethically and productively leveraged, it is crucial to foster ethical awareness, digital literacy, and human-guided implementation strategies. Educational environments must balance technological advancement with reflective and ethically grounded practices, preventing overdependence and promoting responsible AI use. Luckin et al. (2016) emphasize that educators should guide students through AI experiences in ways that preserve critical thinking and human creativity.

In conclusion, while artificial intelligence offers promising benefits for personalized learning, creative support, and task efficiency, it is imperative that these technologies are positioned within ethical, pedagogical, and developmentally supportive frameworks, ensuring that AI remains a tool that enhances rather than replaces the human dimension of education. In light of the study's findings, several important recommendations can be proposed for the effective and ethical integration of artificial intelligence in middle school education. First and foremost, artificial intelligence should be more comprehensively embedded into the school curriculum, particularly within Information and Communication Technology (ICT) courses. This integration should move beyond surface-level discussions and offer hands-on opportunities for students to interact with AI tools in meaningful ways. In addition, given that some students expressed concerns related to data privacy, algorithmic bias, and overdependence, it is recommended that digital citizenship and AI ethics be included in educational content to develop students' critical digital literacy. Teacher training is another essential area, as educators must be equipped not only with technical knowledge but also with pedagogical skills to use AI effectively while maintaining ethical sensitivity. Schools should also support project-based learning initiatives, such as eTwinning and TÜBİTAK programs, which provide interdisciplinary and practical applications of AI.

Furthermore, career guidance and awareness campaigns are necessary to help students explore how AI relates not only to technology professions but also to areas such as healthcare, architecture, environmental science, and art. To promote healthy learning habits, it is important to guide students toward a balanced use of AI tools, ensuring that these technologies enhance, rather than hinder, original thinking and independent problem-solving. Finally, educational policymakers should establish clear frameworks and regulatory guidelines to safeguard student data, ensure responsible AI use, and foster equitable access to AI-enhanced learning environments. These combined efforts will help maximize the benefits of AI in education while minimizing its potential risks.

Statements and Declarations

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Blended Learning in Mathematics Education: A Bibliometric Analysis of Research Trends and Patterns

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Abstract

Blended learning has become a prominent instructional approach in mathematics education, offering flexible and interactive strategies that enhance student engagement and learning effectiveness. Given its growing importance, a comprehensive bibliometric analysis is needed to clarify current research trends, influential contributors, and key themes. This study analyzed 295 Scopus-indexed publications from 1999 to 2025, employing OpenRefine, biblioMagika®, and VOSviewer for data processing and visualization. Findings highlight a steady increase in blended learning research, peaking at 58 publications in 2023. Leading contributing countries include Indonesia and the United States, while Universitas Pendidikan Indonesia is identified as the most influential institution. Thematic analysis identifies blended learning, flipped classroom, and mathematics education as dominant research clusters. These clusters underscore the importance of digital integration and innovative pedagogies for enhancing student competencies and academic outcomes. Future research should investigate underexplored pedagogical methods, integrate emerging technologies, and explicitly focus on the development of higher-order thinking skills. Addressing these aspects can substantially improve blended learning practices, enhance mathematical understanding, and better equip students with the essential skills required to meet contemporary educational demands.

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Introduction

Blended learning has the potential to transform teaching and learning by offering flexible, continuous, and efficient learning opportunities. The necessity for changing conventional educational practices particularly during the pandemic has accelerated the adoption of this approach. Educational institutions around the world have shifted from face-to-face instruction to blended learning modes to ensure educational continuity (Ashraf et al., 2021). Recognizing blended learning's capability to support uninterrupted learning, many institutions have continued implementing this approach even after the pandemic (Van der Westhuizen & Hlatshwayo, 2023). With its capacity to combine the strengths of traditional and digital pedagogies, this not only demonstrates the adaptability of blended learning during global disruptions but also affirms its viability as a long-term educational solution.

In mathematics education, blended learning has emerged as a significant trend in technological innovation (Suripah et al., 2025). This approach offers innovative solutions to ongoing pedagogical challenges such as low student engagement and difficulty in understanding abstract concepts. For instance, the implementation of blended learning such as the flipped classroom model promoting student autonomy and collaborative learning through independent online content delivery and utilizing class time for mathematical problem-solving activities and deeper discussions (Güler et al., 2023). On the other hand, station rotation model which integrates face-to-face sessions, computer-based instruction and independent practice enhanced students' engagement and on-task behavior in mathematics learning (Johnson et al., 2024). This approach promoted active participation and collaboration that improved student achievement and conceptual understanding.

Technology integration also plays a crucial role in optimizing the effectiveness of blended learning. Technologies such as interactive digital tools, learning platforms, virtual simulations, and multimedia resources provide visually rich and interactive environments (Cirneanu & Moldoveanu, 2024). This is highly beneficial in mathematics classrooms as they help students grasp challenging mathematical concepts through practical and engaging activities (Suripah et al., 2025) thereby enhancing understanding and knowledge retention. Additionally, learning through these technologies allows teachers to develop personalized instruction suited to different student learning styles (Wang et al., 2024).

In addition to technology integration, the implementation of blended learning also depends on the pedagogical approaches employed. Pedagogical strategies such as project-based and problem-based learning within blended learning enable students to deeply engage with mathematical content through authentic tasks and problem-solving scenarios (Amin et al., 2021; Sari et al., 2022). Grounded in constructivist theories, these student-centered approaches emphasize on collaborative interactions and active knowledge construction. Furthermore, the integration of gamification into blended learning also creates interactive and engaging mathematics classrooms (Bedebayeva et al., 2025). Thus, combining blended learning with strong pedagogical methods can enhance student autonomy, conceptual understanding, and engagement, providing a more meaningful and effective mathematics education experience.

In brief, blended learning has substantial potential to significantly enhance mathematics education by creating interactive and engaging learning environments beyond traditional instructional methods. As educational institutions worldwide address the evolving demands of 21st-century education, the role of blended learning as an essential approach for improving learner engagement and educational outcomes becomes increasingly clear. Nevertheless, successful implementation relies on robust technological infrastructure and effective teaching practice (Bizami et al., 2023). This bibliometric analysis will examine the current landscape of blended learning research in mathematics education and its future directions, drawing on influential studies that have shaped the understanding of this field.

Literature Review

Emerged in the early 2000s, blended learning has become widely adopted in education today (Ghimire, 2022). Garrison & Kanuka (2004) and Graham (2006) define blended learning as combining traditional instruction with online methods through effective instructional design. Despite challenges posed by COVID-19, blended learning has demonstrated significant potential at school and higher education (Topping et al., 2022) and is expected to shape future educational practices (Bozkurt et al., 2020). It effectively addresses limitations of traditional face-to-face learning such as location, rigid schedules, and time constraints (Cronje, 2022), as well as online learning challenges including limited interaction, low participation, and dropout rates (Khaldi et al., 2023). Ultimately, blended learning represents an adaptable educational strategy suited to various contexts significantly enhancing teaching effectiveness and student outcomes across educational levels.

In mathematics education, traditional lecture-based methods often inadequately address issues related to low student engagement and difficulty in grasping concepts (Nanda & Rani, 2025) thus negatively impacting students' understanding and motivation. However, blended learning strategies have appeared as promising solutions by actively involving students in their learning. For instance, empirical research by Esperanza et al. (2023) demonstrated the effective use of the flipped classroom improved classroom communication and allowing students to progress at their own pace.

Similarly, Egara and Mosimege (2024) also found that students who learned through flipped classroom achieved better performance and interest compared to those taught using traditional methods. This models which delivers instructional content online prior to face-to-face classes, enhances conceptual understanding and promotes greater engagement with mathematical content. Meanwhile, Latif et al. (2024) applied the station rotation model where the students engaged with video lessons and online quizzes found that opportunities for peer collaboration encouraged active participation thus indicating that combining digital tools with group work can enhance engagement in mathematics learning.

The integration of technology in blended learning is essential for improving teaching effectiveness and supports dynamic instructional methods. In mathematics education, interactive platforms and digital simulations enable students to actively explore and visualize mathematical concepts. Supported with findings by Nasrullah et al. (2025), the incorporation of Edmodo platform and GeoGebra software in the blended learning classroom provided students with a more engaging learning experience and enhanced problem-solving skills compared to the control class where such technological tools were not utilized thus limiting students' opportunities for exploration.

Moreover, technological tools also facilitate real-time assessment, immediate feedback and customized learning pathways that cater to students' individual needs and cognitive styles (Wang et al., 2024). For instance, research by Attard & Holmes (2022) had found that teachers preferred using individual video responses and Learning Management System (LMS) platforms to actively communicate with students beyond school hours. These methods provided accessible, timely, and personalized feedback thereby extending mathematical conversations and supporting the development of students' mathematical thinking.

The combination of pedagogical strategies within blended learning environments further enriches instructional effectiveness in mathematics education. For instance, research by Fitrah et al. (2025) has highlighted the effectiveness of combining project-based learning with flipped classroom. This approach encourages project collaboration and supports self-directed learning using video materials thus allowing students to understand concepts before attending face-to-face sessions. This integrated approach enhances students' computational abilities and equips them to tackle real-world problems, positively impacting broader STEM learning contexts.

Furthermore, Amin et al. (2021) found that the structured approach of blended problem-based learning allows students to actively engage in the analysis and interpretation of findings both independently and collaboratively through online and face-to-face discussions. In addition, Zhao et al. (2021) initiate that gamified flipped learning approach improves student mathematics performance by increasing their engagement and providing peer interaction opportunities. The flipped classroom enables students to prepare and explore concepts independently before class while gamification elements foster deeper engagement and participation thereby boosting students' motivation and self-efficacy.

Given its increasing significance demonstrated by previous empirical research, bibliometric analysis is essential to comprehensively understand the impact and evolving trends of blended learning in mathematics education (Donthu et al., 2021). In this area, Samosir et al. (2023) mapped publications from 2008 to 2023 using keywords such as “blended learning” and “mathematics,” whereas Özdemir (2024) conducted a bibliometric analysis focusing on the flipped classroom model from 2014 to 2023. Meanwhile, Xueli et al. (2025) examined publication patterns from 2004 to 2024 using a broader range of keyword selections. Although these studies establish a foundation for understanding the literature, further bibliometric analysis is still needed through a comprehensive mapping study that covers a longer publication window, employs an inclusive and systematically developed set of search terms to enable broader thematic insights, and clearly reports the data refinement process.

Addressing these identified gaps, this research reviews literature published from 1999 to 2025, providing a comprehensive analysis covering over 25 years of scholarly work. Given that blended learning gained momentum in the early 2000s, initiating the analysis from 1999 establishes an appropriate baseline to understand the evolution of the field and highlight recent developments. Furthermore, accurate and reliable bibliometric outcomes significantly depend on effective data cleaning and harmonization (Ahmi, 2023). Accordingly, this study addresses this methodological need by systematically refining bibliographic data to ensure accuracy and consistency.

Research Questions

This study presents a bibliometric analysis by addressing four research questions (RQs):

(1) What is the current state of research on blended learning in mathematics education?
(2) What publication trends can be identified in blended learning studies within mathematics education?
(3) Who are the productive authors, institutions, and countries contributing to blended learning research in mathematics education?
(4) What core research themes underpin blended learning in mathematics education?

Methodology

This study employed bibliographic data retrieved from the Scopus database on 10 July 2025. Scopus was chosen as the primary source due to its extensive coverage of peer-reviewed publications, stringent indexing criteria, and global academic scope, which collectively provide robust metadata suitable for bibliometric analysis. The metadata including citations, author affiliations, publication details, and indexed keywords, facilitated a thorough and precise bibliometric analysis. The datasets such as document and source types, languages, subject, publication trends, authorship, institutional, geographical, and prevalent keywords, enabling a comprehensive analysis of blended learning literature within mathematics education.

Search Strategy

The review adopted the modified PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines for conducting systematic research reviews (Page et al., 2021). The search query (“blended learn*” OR “blended course” OR “blended teach*” OR “hybrid learning” OR “blended education” OR “blended e-learning” OR “blended instruction” OR “B-learning” OR “flipped classroom”) AND (“Mathematics Education” OR “Mathematic*” OR “Math*”) was applied in the Scopus database. Correspondingly, subject-specific filters were applied.

This study research scope and coverage were based on the search field, source type, and document types to eliminate irrelevant literature, resulting in 1745 initial documents (see Figure 1). After reviewing the abstracts of these documents, additional exclusions were performed based on topical relevance. Following this filtration process, 275 documents relevant to blended learning in mathematics education were retained for the final analysis.

Figure 1 illustrates the detailed screening steps applied to select relevant studies for this bibliometric analysis. Initially, 1745 documents were identified from the Scopus database. Using automation tools, 782 records were removed as they did not meet the eligibility criteria. These included documents not classified as articles or proceedings and studies as well as titles and abstracts were unrelated to Social Science and Mathematics. As a result, 963 reports remained for further review. However, 644 of these reports could not be retrieved for additional evaluation. After thoroughly assessing the eligibility of the remaining 319 reports, 24 were excluded for being either non-English or unpublished in final form.

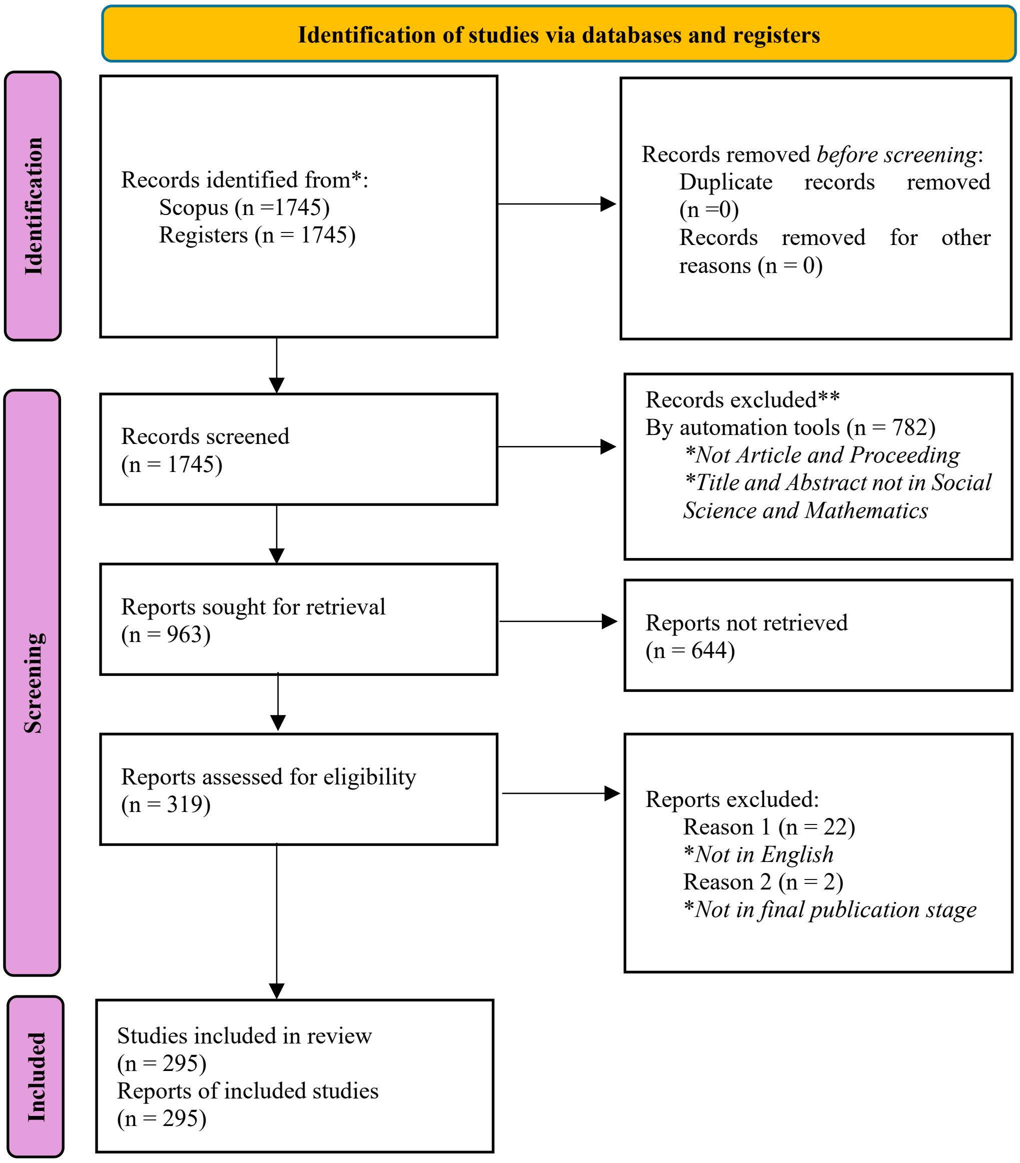

Figure 1. Flow Diagram of The Search Strategy (Page et al., 2021)

To ensure data quality and relevance, systematic inclusion and exclusion criteria were employed. Inclusion criteria were strictly limited to articles and proceedings related explicitly to blended learning in mathematics education indexed in Scopus (1999 to 2025), written in English and categorized under Social Science and Mathematics. Exclusion criteria eliminated non-English articles and proceedings, non-academic documents such as editorials, book chapters, incomplete metadata entries, and those unrelated to mathematics education. After applying these detailed screening steps, 295 relevant studies were finalized and included in the bibliometric analysis. This careful and transparent screening approach ensures reliability and accuracy in capturing the scholarly landscape of blended learning in mathematics education.

Data Cleaning, Harmonization, and Analysis

Data cleaning and harmonization are essential steps in ensuring accurate and reliable bibliometric analysis outcomes. Initially, bibliographic records extracted from the Scopus database in CSV format underwent refinement using OpenRefine to standardize author names, affiliations, and keywords. Advanced data preparation and harmonization were further conducted using biblioMagika® (Ahmi, 2024), generating indicators such as publication counts, number of authors, citation total and averages, and bibliometric indexes (h-index, g-index, m-index, Citation Sum within the h-Core). Missing or incomplete data identified through this process were manually corrected to enhance data integrity, ensuring clarity, consistency, and accuracy.

Subsequently, a structured approach was employed to examine current research focusing on important aspects such as document types, source titles, languages, subject areas, and citation metrics. Findings were categorized by publication year, authors, institutions, and countries, thus identifying major contributors and emerging trends. Additionally, thematic mapping and co-occurrence network analyses were performed using author keywords to visualize thematic clusters and reveal underlying research patterns and connections among various subfields. These analytical and visualization approaches provided comprehensive insights into the blended learning landscape in mathematics education research.

Tools

This study utilized multiple specialized software tools to conduct a systematic bibliometric analysis. Initially, Microsoft Excel was employed to organize and prepare the raw bibliometric data retrieved from Scopus, facilitating efficient sorting and structuring processes. The metadata was then standardized and harmonized using biblioMagika®, addressing inconsistencies in author names, affiliations, and country details. OpenRefine was used to enhance the clarity and consistency of author keywords. Following data preparation, VOSviewer was applied to generate visual maps illustrating keyword patterns, thematic clusters, and citation relationships. Lastly, Mendeley was employed as a reference management tool, ensuring efficient citation organization throughout the study.

Results

The following results section provides a thorough analysis of the current blended learning research in mathematics education. This analysis systematically addresses each research question, offering detailed insights into the bibliometric landscape and delivering a comprehensive overview of blended learning studies in the context of mathematics education.

Current State of Research

To address the first research question, the authors mapped the current state of research by analyzing the distribution of publications across various bibliometric indicators, including total publication output, citation metrics, and author contributions (see Table 1). These indicators enable an assessment of productivity, scholarly influence and collaboration trends in the research domain over time. Covering the period from 1999 to 2025, the dataset comprises a total of 295 publications spanning 27 citable years, underscoring sustained scholarly engagement and continuous growth within the field. These publications were collectively authored by 895 contributing authors, highlighting extensive academic collaboration. Of these outputs, 254 papers have been cited, demonstrating notable visibility and acknowledgment within the academic community.

Table 1. Citation Metric

Main Information	Data
Publication Years	1999 - 2025
Total Publications	295
Citable Year	27
Number of Contributing Authors	895
Number of Cited Papers	254
Total Citations	3,837
Citation per Paper	13.01
Citation per Cited Paper	15.11
Citation per Year	147.58
Citation per Author	4.29
Author per Paper	3.03
Citation Sum within h-Core	3,088
h-index	28
g-index	49
m-index	1.037

Source: Generated by the author(s) using biblioMagika® (Ahmi, 2024)

In terms of academic influence, the research corpus has amassed 3,837 total citations, translating to an average of 13.01 citations per paper. The average citations per cited paper stands at 15.11, further emphasizing the ongoing scholarly relevance of cited publications. The annual citation rate averages at 147.58, reflecting steady and robust academic interest and engagement across multiple decades. At an individual contribution level, each author averages 4.29 citations, while the average number of authors per paper is 3.03, suggesting meaningful collaborative and interdisciplinary interactions among researchers.

The citation sum within the h-core is notably high at 3,088, indicating that the core set of highly cited papers significantly influences the scholarly dialogue and the direction of the field. Further bibliometric indicators reinforce the robustness and depth of the research landscape. The h-index of 28 indicates that at least 28 papers have each garnered a minimum of 28 citations, underscoring a strong balance between productivity and scholarly impact. Similarly, the g-index of 49 highlights that top publications continue to accrue citations consistently. Additionally, the m-index of 1.037 points to a steady increase in scholarly influence over time. Collectively, these metrics clearly demonstrate that blended learning research in mathematics education represents an active, influential, and collaborative scholarly field. This body of literature has significantly contributed to the broader educational landscape, informing both theory and practice in mathematics education.

Publication Trends

To address the second research question, the authors examined publication trends in blended learning studies within mathematics education. The earliest recorded publication in the dataset appeared in 1999, marking the onset of academic interest in blended learning within mathematics education. The data in Figure 2 and Table 2 indicate that the field exhibited gradual growth initially. The most significant increase in publication output occurred between 2016 and 2023. This clear upward trajectory highlights sustained and robust scholarly attention to the field. The annual publication data identify several notable milestones in research productivity, particularly during the years 2020 (42 publications), 2022 (46 publications) and 2023 (58 publications) with 2023 marking the highest recorded output. Parallel to the rise in publication counts, citation metrics have also shown significant peaks. The highest total citation count was observed in 2020 with 715 citations, followed by substantial citations in 2022 with 568 citations and 2021 with 494 citations. These citation peaks underline the considerable scholarly influence and recognition these recent publications have garnered within the academic community. While the dataset for 2023 indicates sustained academic productivity with 58 publications and 327 citations, the observed decline in citation counts compared to previous peak years may suggest a natural temporal lag in citation accumulation or potentially reflect an emerging shift towards new research themes and methodologies within the field. Nevertheless, the overall scholarly interest and engagement remain robust.

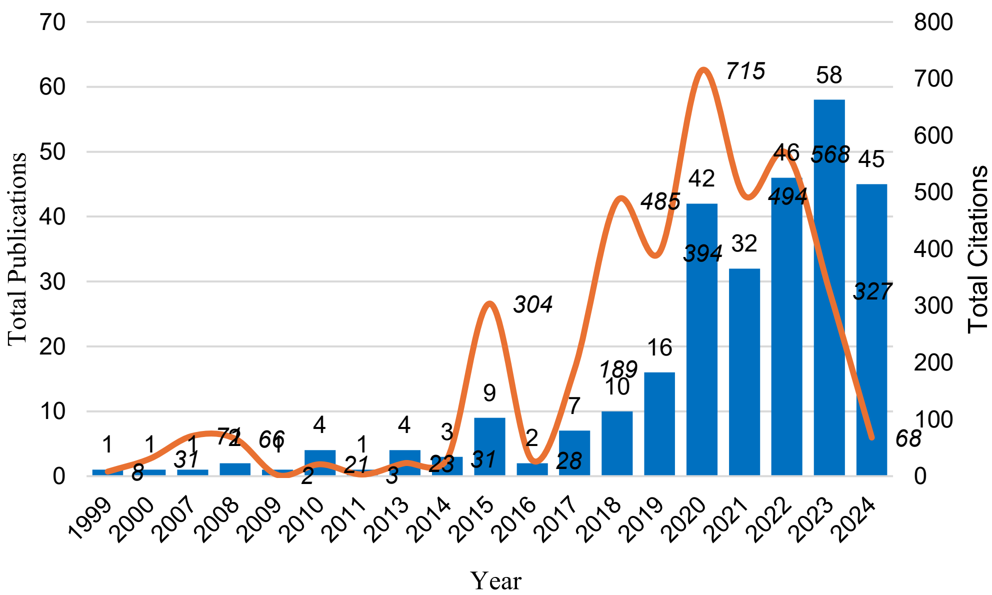

Figure 2. Total Publications and Citations by Year (Excluding the Year 2025, as Data is Only Available Up to 10 July 2025)

The consistent growth in publication numbers is accompanied by intensified scholarly collaboration, as evidenced by the increasing number of contributing authors each year. This trend demonstrates the strengthening of a global academic community actively engaged in interdisciplinary studies that combine mathematics education with instructional design, educational technology and innovative pedagogical approaches. Bibliometric indicators including the h-index (28), g-index (49) and m-index (1.037) reinforce the strong trajectory and increasing academic influence of research in this field. In summary, the analysis underscores blended learning in mathematics education as a thriving area of scholarly inquiry, characterized by increasing publication output, strong collaborative networks, and significant academic impact. The fluctuations observed in recent citation trends highlight the dynamic nature of scholarly dissemination and emphasize the importance of ongoing monitoring and analysis to fully capture emerging research trends and priorities in this evolving field.

Table 2. Publication by Year

Year	TP	NCA	NCP	TC	C/P	C/CP	*h-index*	*g-index*	*m-index*
1999	1	4	1	8	8.00	8.00	1	1	0.037
2000	1	3	1	31	31.00	31.00	1	1	0.038
2007	1	2	1	71	71.00	71.00	1	1	0.053
2008	2	3	2	66	33.00	33.00	2	2	0.111
2009	1	5	1	2	2.00	2.00	1	1	0.059
2010	4	12	4	21	5.25	5.25	3	4	0.188
2011	1	4	1	3	3.00	3.00	1	1	0.067
2013	4	13	3	23	5.75	7.67	2	4	0.154
2014	3	8	2	31	10.33	15.50	2	3	0.167
2015	9	28	8	304	33.78	38.00	6	9	0.545
2016	2	4	2	28	14.00	14.00	2	2	0.200
2017	7	16	6	189	27.00	31.50	5	7	0.556
2018	10	32	8	485	48.50	60.63	7	10	0.875
2019	16	55	15	394	24.63	26.27	9	16	1.286
2020	42	119	42	715	17.02	17.02	16	25	2.667
2021	32	107	32	494	15.44	15.44	14	20	2.800
2022	46	131	44	568	12.35	12.91	13	21	3.250
2023	58	182	50	327	5.64	6.54	9	14	3.000
2024	45	129	26	68	1.51	2.62	4	6	2.000
Grand Total	285	857	249	3828	13.43	15.37	28	49	1.037

Notes: TP = total number of publications; NCA = number of contributing authors; NCP = number of cited publications; TC = total citations; C/P = average citations per publication; C/CP = average citations per cited publication; h = h-index; g = g-index; m = m-index.

**Excluding the year 2025, as data is only available up to 10 July 2025*

Productive Authors, Institutions, and Countries

To address the third research question, the authors identified productive authors, institutions, and countries actively contributing to blended learning research in mathematics education. Table 3 highlights the most productive authors contributing significantly to this field. Leading this group are David González-Gómez and Jin Su Jeong, both from Universidad de Extremadura who authored four highly cited publications with a total of 84 citations, averaging approximately 21 citations per publication, indicating their substantial impact and scholarly recognition within this research community. Additionally, other contributing authors include Zsolt Lavicza, Helge Fredriksen, and Dadang Juandi also made four publications respectively.

Table 3. Top 5 Most Productive Authors

Full Name	Current Affiliation	Country	TP	NCP	TC	C/P	C/CP	*h*	*g*	*m*
González-Gómez, David	Universidad de Extremadura	Spain	4	4	84	21.00	21.00	4	4	0.667
Jeong, Jin Su	Universidad de Extremadura	Spain	4	4	84	21.00	21.00	4	4	0.667
Lavicza, Zsolt	Johannes Kepler University	Austria	4	4	62	15.50	15.50	3	4	0.500
Fredriksen, Helge	The Arctic University of Norway	Norway	4	3	44	11.00	14.67	3	4	0.500
Juandi, Dadang	Universitas Pendidikan Indonesia	Indonesia	4	4	20	5.00	5.00	3	4	0.750

Notes: TP = total number of publications; NCP = number of cited publications; TC = total citations; C/P = average citations per publication; C/CP = average citations per cited publication; h = h-index; g = g-index; m = index.

Further bibliometric indicators such as h-index, g-index, and m-index enrich our understanding of these scholars' impact. For example, González-Gómez and Jeong each hold an h-index and g-index of 4, along with an m-index of 0.667 confirming their steady and sustained influence over time. This analysis highlights productive scholars whose contributions significantly influence the discourse and development of blended learning approaches in mathematics education. The insights identify key researchers actively shaping the academic conversation and directing future research trajectories in this vibrant educational field.

Next, Table 4 highlights the institutions that have actively shaped research on blended learning in mathematics education, emphasizing those with at least four scholarly publications. Universitas Pendidikan Indonesia leads notably with a total of seven publications, followed by Universidad de Extremadura, Johannes Kepler University, Universidad Nacional Autónoma de México, De La Salle University, and Open University UK, each contributing four publications. In terms of citations, Universidad de Extremadura from Spain received highest total citation (84 citations) with average of 21 citations per publication, underlining its significant impact per research output. Regarding bibliometric indices, Universitas Pendidikan Indonesia notably leads with an h-index of 5 and a g-index of 6, reflecting consistent impact and scholarly recognition. In summary, these institutions highlight a dynamic research community, paving the way for continued innovation and impactful future research.

Table 4. Most Productive Institutions with a Minimum of Four (4) Publications

Institution Name	Country	TP	NCP	TC	C/P	C/CP	*h*	*g*
Universitas Pendidikan Indonesia	Indonesia	7	7	40	5.71	5.71	5	6
Universidad de Extremadura	Spain	4	4	84	21.00	21.00	4	4
Johannes Kepler University	Austria	4	4	62	15.50	15.50	3	4
Universidad Nacional Autónoma de México	Mexico	4	4	26	6.50	6.50	3	4
De La Salle University	Philippines	4	3	25	6.25	8.33	3	4
Open University UK	United Kingdom	4	3	4	1.00	1.33	1	2

Notes: TP = total number of publications; NCP = number of cited publications; TC = total citations; C/P = average citations per publication; C/CP = average citations per cited publication; h = h-index; g = g-index; m = index.

Further analysis reveals countries significantly contributing to this field. Figure 3 and Table 5 summarizes research productivity at the country level, highlighting nations contributing ten or more publications.

Table 5. Countries that Contributed Ten (10) or More Publications

Country	TP	NCA	NCP	TC	C/P	C/CP	*h*	*g*
Indonesia	38	124	32	330	8.68	10.31	10	18
United States	37	116	33	644	17.41	19.52	15	25
Spain	24	72	22	425	17.71	19.32	10	20
China	18	38	14	99	5.50	7.07	6	9
United Kingdom	14	41	13	286	20.43	22.00	9	14
Germany	14	32	13	237	16.93	18.23	6	14
South Africa	11	26	9	187	17.00	20.78	6	11
Malaysia	10	36	10	76	7.60	7.60	4	8
Russian Federation	10	35	10	85	8.50	8.50	5	9
Norway	10	17	9	297	29.70	33.00	7	10

Notes: TP = total number of publications; NCP = number of cited publications; TC = total citations; C/P = average citations per publication; C/CP = average citations per cited publication; h = h-index; g = g-index; m = index

Indonesia emerges as the leading contributor publishing a total of 38 articles, achieving a substantial impact with 330 citations and an h-index of 10 reflecting a consistent and influential presence within the international research community. This performance indicates not only productivity but also considerable scholarly engagement and recognition. The United States closely follows with 37 publications yet notably leads in terms of citation impact with 644 total citations. Moreover, it exhibits impressive citation metrics with an average of 17.41 citations per publication and 19.52 citations per cited publication underlining the significant global influence and academic recognition of its research contributions. These metrics are further supported by an h-index of 15 emphasizing strong academic quality and sustained scholarly relevance. Other active countries include Spain (24 publications), China (18 publications), the United Kingdom and Germany (14 publications each), South Africa (11 publications), and Malaysia, the Russian Federation, and Norway (10 publications each). These countries also have solid citation averages and bibliometric indices indicating their active role and scholarly recognition. Overall, these insights reflect the diverse and collaborative global landscape in blended learning research in mathematics education. These countries' contributions collectively shape academic discourse, enrich educational practices and highlight significant trends guiding current and future research within evolving fields.

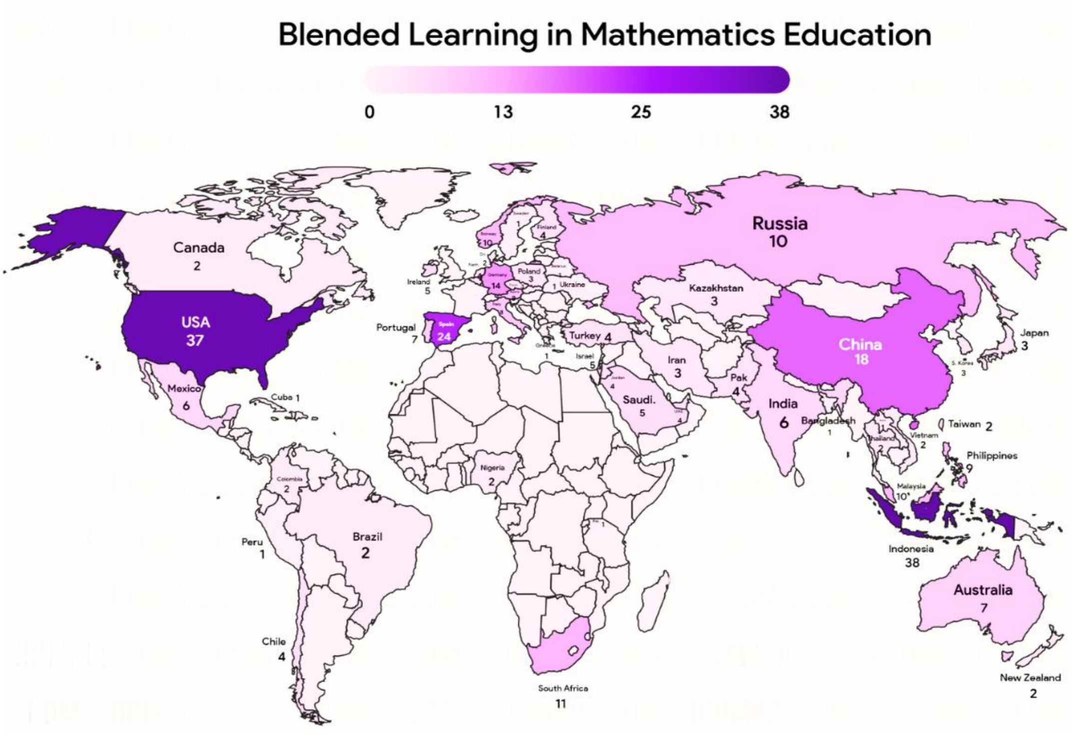

Figure 3. Visualization of Global Distribution of Blended Learning in Mathematics Education Research Publications

Co-Occurrence Analysis

The fourth research question guided the thematic analysis to identify core research themes and their interconnections. The co-occurrence network of author keywords in Figure 4 highlights research themes appearing at least five times, providing insights into key focus areas in blended learning research. In this network, each node's size indicates keyword prominence while the proximity and connections among nodes represent thematic relatedness. A closer examination reveals distinct thematic clusters, each representing an important direction in blended learning integration into mathematics education. The terms "blended learning", "flipped classroom" and "mathematics education" notably appear as dominant themes, clearly illustrating their central role in the scholarly discourse on mathematics education within blended environments.

A red cluster is centered on the concept of "blended learning" closely associated with keywords such as “online learning”, “distance learning”, “hybrid learning”, and “e-learning”. This cluster emphasizes the increasing significance of digital and hybrid educational strategies underscoring the importance of online platforms and technology-supported approaches. The presence of “pandemic” and “COVID-19” particularly highlights how recent global disruptions have accelerated the adoption of blended learning thus reinforcing its crucial role in maintaining educational continuity and addressing emerging challenges within education contexts. Another substantial thematic area represented by the green cluster revolves around “flipped classroom” closely linked with keywords such as “active learning”, “attitudes”, and “education”. This cluster strongly highlights student-centered instructional approaches designed to actively engage learners and foster positive attitudes toward mathematics. The presence of “gamification” and “project-based learning” further suggests an emphasis on interactive, engaging pedagogies that promote deeper learner autonomy and academic achievement. The yellow cluster encompasses themes centered on “mathematics education” closely associated with keywords such as “educational technology” and “technology”. This cluster underscores the strategic implementation of digital tools and technological innovation aimed at enhancing students' mathematical understanding and supporting effective teaching practices.

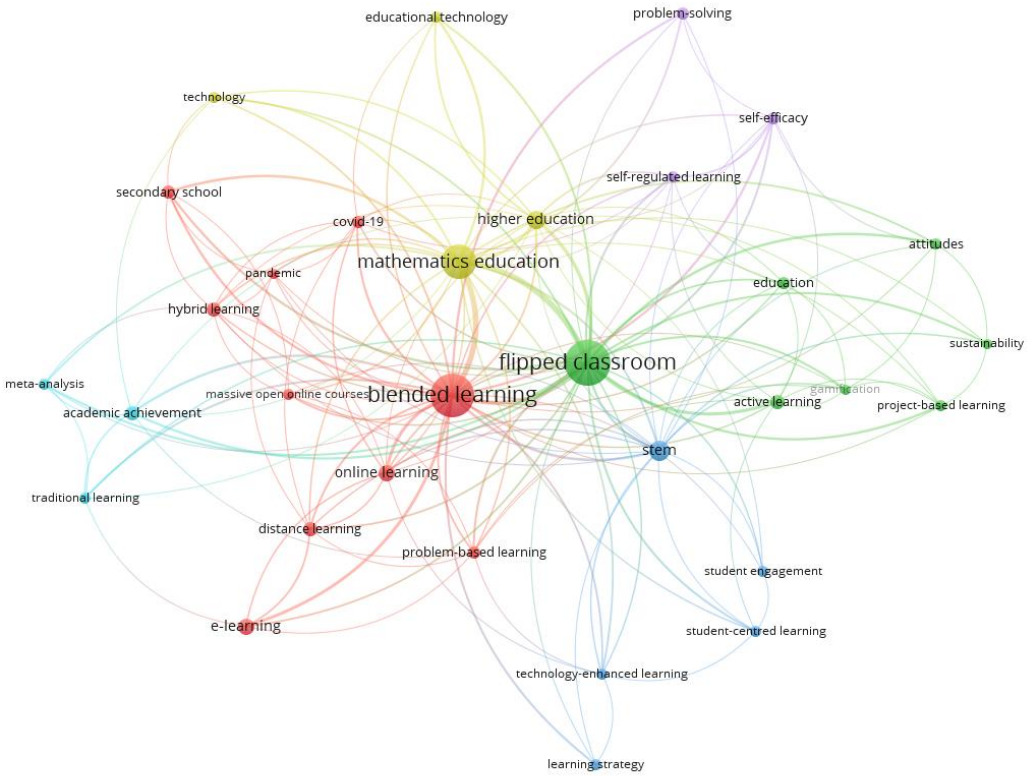

Figure 4. Co-Occurrence Network of the Author's Keywords with At Least Five Occurrences

Additionally, the blue cluster highlights the role of “STEM” education and is closely linked with “student engagement”, “student-centered learning”, “technology-enhanced learning”, and “learning strategy”. This thematic grouping emphasizes the importance of interdisciplinary integration, highlighting current educational policies and practices that prioritize the connection between mathematics and other STEM disciplines. This cluster also strongly indicates a growing research interest in innovative pedagogical approaches that leverage technology to create engaging, student-focused, and sustainable learning environments. Moreover, the purple cluster emphasizes learner competencies highlighted by keyword of “self-efficacy” and “problem-solving". This cluster indicates growing scholarly attention towards understanding how blended learning environments can enhance self-confidence and strengthen critical problem-solving skills which are crucial competencies for thriving in the 21st century. Collectively, the co-occurrence analysis highlights that research on blended learning in mathematics education is strongly connected to pedagogical strategies such as “project-based learning”, “problem-based learning”, “gamification”. The prominence of these themes within the network suggests their vital role in promoting effective instructional practices and reflects an ongoing commitment to engaging students actively in their own learning processes, fostering deeper mathematical reasoning and applied problem-solving skills.

Discussion

This study presents a comprehensive bibliometric analysis exploring the current landscape of blended learning research in mathematics education from 1999 to 2025 with 295 publications indexed in Scopus. The findings indicate significant scholarly growth, highlighting blended learning as a prominent instructional approach particularly within the field of mathematics education. The analysis shows a consistent upward trend in publications with the highest peak in 2023 by 58 publications reflecting rising global interest in blended learning approaches. This increase in publication numbers corresponds with the rise of educational technologies and blended learning practices particularly accelerated during the pandemic. The substantial citation peaks in 2020 with 715 citations underscore the foundational impact of key studies during periods of educational disruption, signifying the vital role blended learning has played in ensuring educational continuity and adaptation to new learning environments (Ashraf et al., 2021).

In examining prominent scholars, authors such as David González-Gómez and Jin Su Jeong have significantly shaped current educational practices in this field by their consistent scholarly contribution. Prominent institution which is Universitas Pendidikan Indonesia have emerged as key players reinforcing institutional commitments to integrating innovative blended learning approaches. These contributions reflect their growing visibility and academic engagement within the community. On an international level, countries including Indonesia and the United States lead research contributions reflecting a global recognition of blended learning's effectiveness in diverse educational contexts. Adoption of technology in education during the Fourth Industrial Revolution may led to greater implementation and research on blended learning in mathematics education (Naidoo & Reddy, 2023).

The co-occurrence analysis further identified important research themes within blended learning in mathematics education. Blended learning's as a central theme underscores its vital role in shaping modern educational practices especially during global disruptions. This highlights the adaptability and practicality of blended learning methods for ensuring educational continuity in challenging contexts (Jailani et al., 2025). The emphasis on flipped classrooms and active learning signifies an important pedagogical shift towards student-centered strategies that prioritize student autonomy and conceptual understanding. This reflects a broader pedagogical transformation from traditional teaching methods towards student-centered approaches aimed to fostering critical thinking and active learning capabilities (Nuryadin et al., 2023). Additionally, the integration of STEM education within blended learning underscores the importance of interdisciplinary instructional methods, aligning with contemporary educational priorities aimed at equipping students to face real-world challenges (Gong et al., 2024).

Furthermore, the focus on technology-enhanced learning emphasizes the critical role of digital tools in providing interactive and personalized mathematics instruction. Selecting suitable technologies is essential to support dynamic mathematics instruction and actively engage students in exploring abstract concepts (Suripah et al., 2025). As effective technology integration aligned with instructional objectives will promotes student participation, facilitates real-time assessment and personalized feedback that extends mathematical discussions beyond classroom boundaries. However, despite significant attention to digital integration, comprehensive research remains necessary to critically evaluate specific technologies effectiveness in blended learning environments (Angawi & Tasir, 2024).

The findings from the co-occurrence analysis also indicate a clear relationship between blended learning and pedagogical strategies such as project-based, problem-based, and gamification within mathematics education. As effective blended learning requires thoughtful planning, teachers must choose and integrate appropriate instructional methods based on their teaching goals, course content, and student characteristics (Yu et al., 2025). The blended project-based learning facilitates students' creative learning and product development without limitations of time and place. This approach enables students to solve problems through investigations and experiments, supported by the flexibility of space and time provided by blended learning (Suyantiningsih et al., 2023). Meanwhile, blended problem-based learning provides interactive learning environment that encourages active engagement and critical thinking as students solve problems involving mathematical concepts (Nasrullah et al., 2025). Additionally, the emergence of gamification as a significant theme indicates a growing emphasis on more engaging and interactive pedagogies within mathematics classrooms. Gamification, which integrates game-like elements into learning, makes mathematics education more enjoyable, positively influencing students' attitudes and motivation (Zhao et al., 2021). These interconnected pedagogical approaches within the blended learning framework significantly enhance student learning outcomes and experiences.

Overall, this bibliometric analysis highlights the potential of blended learning to enhance mathematics education through active learning and effective technology integration. However, several areas still require deeper exploration. Although pedagogical strategies like project-based, problem-based and gamification are widely discussed, other approaches such as task-based, role-playing, inquiry-based and case-based learning had great potential (Yu et al., 2025) but remain understudied. Future research could explore how these methods support learner autonomy and conceptual understanding in mathematics education. Additionally, although advanced technologies such as artificial intelligence and augmented reality are gaining attention in mathematics (Li & Zaki, 2024), their application within blended mathematics instruction remains limited. Further investigation of these emerging technologies could deepen our understanding of their instructional value and influence on learning outcomes. Lastly, while blended learning has been shown to improve students' problem-solving skills, there is a noticeable lack of focus on fostering higher-order thinking skills such as creativity and critical thinking. These competencies are essential for mathematics education in the 21st century and warrant more targeted research.

Conclusion and Future Research

This bibliometric analysis provides a comprehensive overview of the research landscape related to blended learning in mathematics education covering 295 publications from 1999 to 2025. Findings indicate a steady increase in scholarly interest particularly from 2016 onwards, driven significantly by the growing global demand for flexible educational solutions. Leading institution which is Universitas Pendidikan Indonesia stand out prominently with the highest total publication reflecting their pivotal roles in shaping blended learning research. Significant scholarly contributions from countries including Indonesia and the United States further underscore the global acceptance and application of blended learning methodologies in mathematics education. The co-occurrence analysis identifies core research themes such as blended learning, flipped classrooms, and mathematics education. These themes highlight the critical role of digital integration and innovative pedagogies in enhancing students' real-world competencies and academic achievement within blended mathematics instruction. Despite these insights, further research is needed to explore underrepresented pedagogical strategies within blended learning contexts. Moreover, deeper exploration into emerging technologies could significantly enhance instructional effectiveness. Future studies should explicitly address strategies for developing higher-order cognitive skills, preparing students to effectively meet 21st-century educational demands. Ultimately, this bibliometric analysis offers a solid foundation for advancing blended learning approaches in mathematics education by offering valuable insights for educators, researchers, and policymakers.

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The Role of Prompt Writing in AI-Supported Teaching: Views of Prospective Science Teachers

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Abstract

Central to the efficacy of AI-driven applications is the quality of prompts the input commands or texts that guide AI systems in generating accurate and meaningful responses. This study investigates science pre-service teachers' perceptions of the prompt writing process within AI tools. Utilizing a qualitative case study approach, data were gathered from 32 science pre-service teachers in their second, third, and fourth academic years through an open-ended questionnaire designed by the researchers. Content analysis was independently performed by two coders, with inter-coder reliability measures ensuring consistency. The findings indicate that participants regard prompt writing as crucial for language and expression, scientific rigor, and user engagement, though its contribution to fostering creativity and critical thinking was viewed as limited. Additionally, respondents highlighted the significance of factors such as topic selection, clarity of objectives, and precise language in constructing effective prompts. Challenges were identified both on the user side including language proficiency and articulation and on the AI side, particularly regarding scientific accuracy and maintaining focus on intended goals. Based on these results, the study recommends the design of targeted educational interventions and AI tool enhancements that address both pedagogical and technological competencies to facilitate more effective prompt generation.

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Introduction

Artificial intelligence (AI) is rapidly transforming numerous fields by enabling technological systems to perform human-like cognitive functions. Drawing upon interdisciplinary approaches such as machine learning, deep learning, natural language processing, and computer vision, AI has become particularly prominent in tasks including data analysis, problem solving, decision making, and forecasting. The integration of these advancements into education offers significant opportunities to personalize instruction, enhance learning efficiency, and strengthen interactions between teachers and students. AI-supported educational applications facilitate the creation of pedagogically differentiated and more effective learning environments by providing tailored solutions that address individual learner needs. Recent research highlights the critical role of prompt engineering in enhancing educational outcomes through generative AI tools (Chen et al., 2024).

Empirical studies suggest that AI technologies can effectively support personalized learning, increase knowledge acquisition, and bolster students' motivation via smart learning tools (Ahmad et al., 2022; Hwang et al., 2020). However, realizing these benefits sustainably and inclusively requires comprehensive consideration of the evolving roles and digital competencies of teachers. In particular, understanding how teachers' pedagogical approaches, ethical sensibilities, and technological literacies develop within AI-enhanced learning environments is essential (Markauskaite et al., 2022). Teachers play a pivotal role in designing meaningful learning experiences that deepen students' understanding and foster their capabilities (Ng et al., 2023). Despite this, many teachers lack sufficient digital preparedness to effectively integrate AI-supported educational applications into their teaching practices (Ally, 2019). Specifically, they often do not possess the technological expertise required to analyze data or to program AI tools for automatic assignment generation and feedback provision (Seo et al., 2021). Therefore, fostering digital literacy among teachers and students is imperative for the successful integration of modern technologies into education (Pihir et al., 2018). Moreover, AI empowers students to engage with information technology for program design and system development, thereby enhancing educational quality and skill acquisition (Zhou, 2023). Nevertheless, compared to other sectors, the adoption of AI in educational settings remains limited (Luckin & Cukurova, 2019). This limitation stems primarily from the underutilization of AI's potential in education (Luckin et al., 2022) and insufficient recognition of teachers' roles in embedding AI within learning environments (Seufert et al., 2021).

The Use of AI in Education and Prompt Writing

AI-enhanced learning denotes the application of innovative technologies to improve teaching and learning processes (Zhou, 2023). These technologies not only facilitate learning conditions but also promote students' cognitive development, adaptability, and problem-solving skills (Chen et al., 2020). The widespread adoption of AI tools based on natural language processing such as ChatGPT, Copilot, and Gemini necessitates users' ability to communicate effectively with these systems. Research has demonstrated that large language models (LLMs) can enrich educational experiences by supporting adaptive, personalized, and self-directed learning methodologies (Knoth et al., 2024; Ruwe & Mayweg-Paus, 2023; Zhu et al., 2023). Additionally, these tools provide timely feedback, enhance accessibility to information, improve student performance and motivation, and contribute to teaching quality (Alves de Castro, 2023; Su & Yang, 2023). Within this context, prompt writing the craft of formulating inputs to AI systems has emerged as a critical determinant of the quality of user–AI interaction (Geroimenko, 2025). A prompt, defined as the instruction or command given to an AI system, directly shapes the quality of the output received (Liu et al., 2023).

Effective use of AI in education depends heavily on the quality of user-generated prompts, which serve as guiding texts, commands, or questions for AI tasks (Lo, 2023). Well-constructed prompts enable AI systems to produce outputs that are meaningful, coherent, and pedagogically valuable (Aktaş, 2025). According to Giray (2023), prompt writing encompasses four fundamental components.

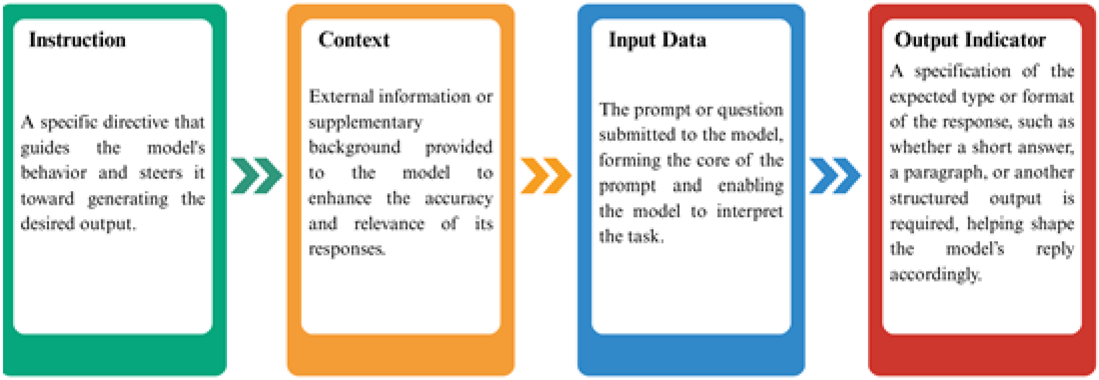

Figure 1. Prompt Writing Encompasses Four Fundamental Components Giray (2023)

Understanding these elements is essential for effective communication with AI models. Careful prompt construction guides AI behavior and enhances response quality, thereby maximizing educational utility (Jiao et al., 2023).

The Importance of Writing the Right Prompt

In educational settings, both teachers and students require not only access to technological tools but also the ability to craft meaningful prompts to utilize AI-based applications effectively. This competence enhances the pedagogical functionality of AI tools and supports higher-order cognitive processes such as critical thinking, inquiry, and knowledge structuring (Kim et al., 2021). Effective prompt writing entails clear, goal-oriented, context-rich, and structured communication (Zhou, 2023).

The process should be considered through the lens of Technological Pedagogical Content Knowledge (TPACK), as contemporary educators must integrate technological understanding with pedagogical and content expertise (Mishra & Koehler, 2006). Prompt writing facilitates more effective teacher–student interactions with AI, offering opportunities for monitoring, evaluating, and personalizing learning. Teacher candidates' proficiency in prompt writing contributes both to their technological literacy and adoption of innovative teaching practices. This underscores the vital role of prompt engineering in optimizing AI for educational purposes (Chen et al., 2024). Incorporating prompt engineering activities into teacher education is therefore critical to developing candidates'

AI literacy and digital pedagogical skills. This is particularly important in science education, where critical thinking, problem solving, and scientific inquiry are prioritized, necessitating the integration of technology with these core skills.

Purpose and Significance of the Study

This study aims to examine science teacher candidates' perceptions of the prompt writing process in AI tools using qualitative methods. It seeks to identify the challenges encountered, perceptions held, and areas for improvement in prompt creation. The findings intend to inform both teacher education programs and the design of AI-supported instructional applications.

Effective communication with AI tools and maximizing their educational potential depend on teacher candidates' digital and pedagogical competencies. This highlights the need to embed AI literacy within teacher training curricula to prepare candidates for the effective use of AI in teaching (Kim et al., 2025). AI tools can create responsive learning environments that consider not only what students learn but also how they learn and experience learning (Zhou, 2023). Furthermore, students contribute to emerging fields such as learning analytics, quality assessment of educational resources, and the development of skills aligned with labor market demands (Huang, 2021). Given the pivotal role prospective teachers will play in educational contexts, their proficiency with AI technologies is essential for delivering high-quality instruction. Accordingly, it is critical to comprehensively examine how teacher candidates utilize AI in practice and to bridge the gap between professional development offerings and actual teacher needs (Tan et al., 2025). Exploring science teacher candidates' perspectives on prompt writing will provide valuable insights for updating teacher education and improving AI-based teaching materials.

Method

Research Design

This research used the case study method, which is one of the qualitative research methods. A case study is a research method that evaluates a current phenomenon within its own real-life context and examines events/situations in a multifaceted, systematic, and in-depth manner (Yıldırım & Şimşek, 2018). With its ability to customize instructional materials and pedagogical approaches, artificial intelligence holds promise for supporting students who struggle to adapt to conventional classroom environments by addressing their unique learning needs (Rakap, 2024). The incorporation of advanced language models like GPT into educational contexts represents more than a superficial improvement; it has the potential to serve as a foundational element of contemporary pedagogical and learning frameworks (Walter, 2024). Despite the increasing integration of AI tools in education, the prompt engineering practices of pre-service teachers an essential element in effective AI use remain under-researched. In this study, a case study was chosen to reveal in detail the issues that science teacher candidates pay attention to when writing prompts in AI applications, the problems they encounter, and their suggestions for improving the prompt writing process.

Participants

The research group consisted of 32 pre-service science teachers studying at a university in the Central Anatolia region of Turkey. The research was conducted during the fall semester of the 2024-2025 academic years. Participants were informed about the study and their participation was based on voluntary consent. Demographic information about the pre-service teachers who participated in the research is presented in Table 1.

Table 1. Demographic Information of Pre-service Science Teachers

Demographic information	Variable	f	%
Gender	Female	22	68.75
	Male	10	31.25
AI Frequency of Use	Rarely	5	16.63
	Moderately	20	62.50
	Frequently	7	21.88
AI Purpose of Use	Homework	23	41.07
	Research	14	25.00
	Other	19	33.93
Total		32	100.0

Data Collection Tool

An open-ended interview form prepared by researchers was used to collect data. Two (2) different field experts were consulted to ensure the validity of the open-ended interview form. The final version of the form was created after the necessary corrections were made. The open-ended interview form consists of two sections. The first section contains questions aimed at determining the demographic information of the teachers. The second section contains five (5) different questions prepared in line with the purpose of the research. At the beginning of the form, it was stated to the pre-service teachers that ethical rules would be adhered to and that participation was based on voluntary participation.

Data Analysis

The data were analyzed using inductive content analysis, a qualitative approach that facilitates the systematic identification of themes and patterns within textual data. Content analysis enables researchers to code qualitative information in a structured manner by categorizing it into themes and sub-themes, thereby revealing meaningful relationships within the data set (Cohen, Manion, & Morrison, 2007; Fraenkel, Wallen, & Hyun, 2012; Yıldırım & Şimşek, 2018). To ensure analytical rigor, each transcript was independently reviewed by two researchers to gain a holistic understanding of participants' responses. Through iterative reading and open coding, recurring expressions and semantic patterns were identified. These initial codes were then grouped into sub-themes and overarching categories through a process of abstraction. Inter-coder reliability was assessed using the formula proposed by Miles and Huberman (1994): Reliability = Consensus / (Consensus + Disagreement). The agreement between the two coders yielded a reliability coefficient of 94.0%, which exceeds the commonly accepted threshold of 80% for qualitative research. Discrepancies in coding were subsequently resolved through collaborative discussion until full consensus was reached, thereby enhancing the trustworthiness and consistency of the coding process. This analytic approach ensured that the findings emerged inductively from the data rather than being imposed by predetermined categories, allowing for a nuanced understanding of participants' perspectives on prompt writing within AI-supported educational settings.

Results

This section presents the findings obtained in the study. The study first aimed to evaluate the importance of prompt writing in artificial intelligence applications from the perspective of pre-service teachers. The findings are presented in Figure 1.

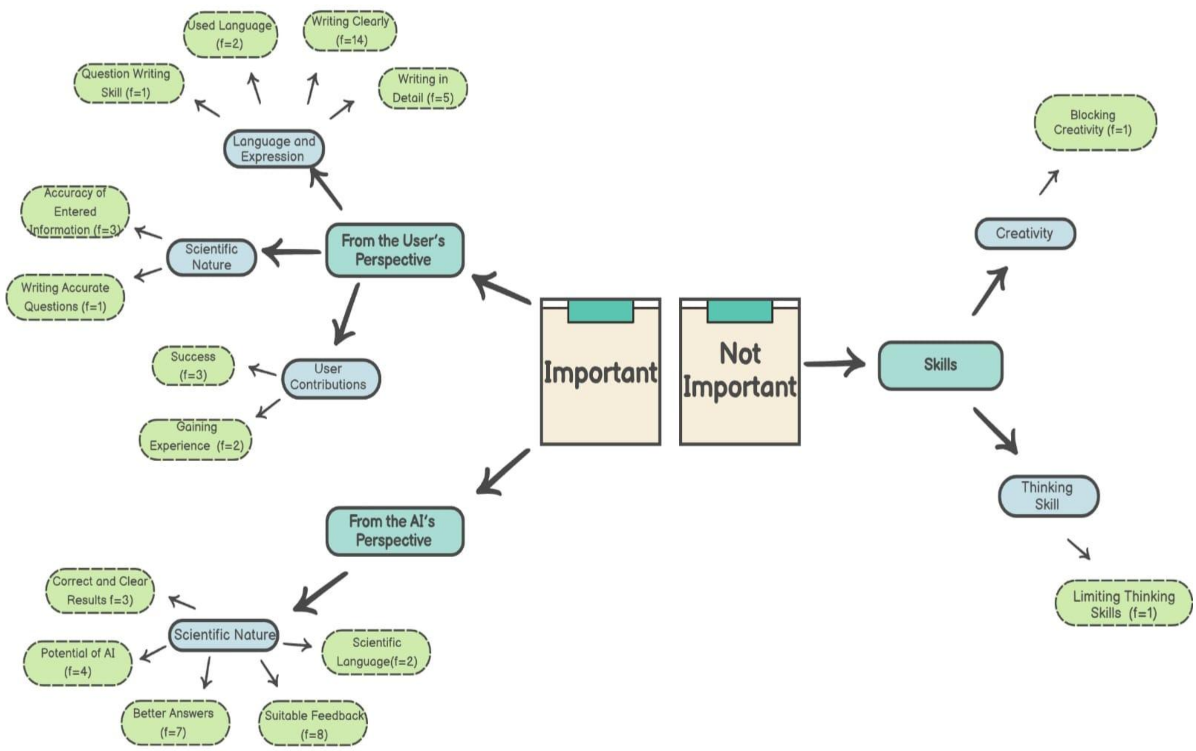

Figure 2. Pre-Service Teachers' Evaluation of The Importance of Prompt Writing

An analysis of the findings presented in Figure 2 reveals that pre-service teachers evaluated the importance of prompt writing in AI applications under two main categories: important and not important. Within the not important category, two key themes emerged: creativity and thinking skills. In contrast, the important category was divided into two overarching themes: user-related and AI-related perspectives. Participants emphasized that, during their interactions with AI tools, certain factors such as clarity of expression, scientific rigor, and user benefit were particularly significant. Regarding language and expression, participants stressed the importance of posing clear, comprehensible, and grammatically accurate prompts. In this context, the sub-themes of clear expression (f=14), detailed writing (f=5), language use (f=2), and question formulation skills (f=1) were frequently noted.

From a scientific perspective, participants underlined the necessity for providing accurate and academically sound input to AI systems. Sub-themes such as accuracy of information (f =3) and formulating accurate questions (f=1) were identified in this regard. In terms of user-related benefits, participants reported gains such as academic success (f=3) and increased experience (f=2), suggesting that AI use contributes positively to learning processes. From the AI perspective, participants evaluated the quality and scientific appropriateness of feedback received from the system. The most frequently emphasized theme here was scientific reliability. Participants stressed that AI responses should be both scientifically accurate and easily understood. Sub-themes such as appropriate feedback (f=8), more effective answers (f=7), AI potential (f=4), accurate and clear results (f=3), and scientific language (f=2) were identified within this dimension. Within the not important category, a minority of participants expressed concerns about the potential impact of AI use on individual skills. Specifically, some suggested that excessive reliance on AI could limit critical thinking (f=1) or creativity (f=1). These concerns highlight possible negative effects of AI on personal productivity and cognitive independence. Sample participant responses are provided below:

T-2: Yes, I believe so. Because AI has a scientific language, but it lacks actual intelligence. That's why we need to formulate the questions ourselves. T-14: Yes. The more detailed our prompt is, the more accurate and specific the response we receive from AI. T-21: Yes. Sometimes AI helps with topics I am unfamiliar with. However, relying on it all the time is not ideal it may limit our thinking and creativity. T-28: Important. Because we should fully utilize the potential of AI.

The second focus of the study was to evaluate the elements that pre-service teachers consider important when writing prompts in AI-based applications. The findings related to this objective are presented in Figure 3.

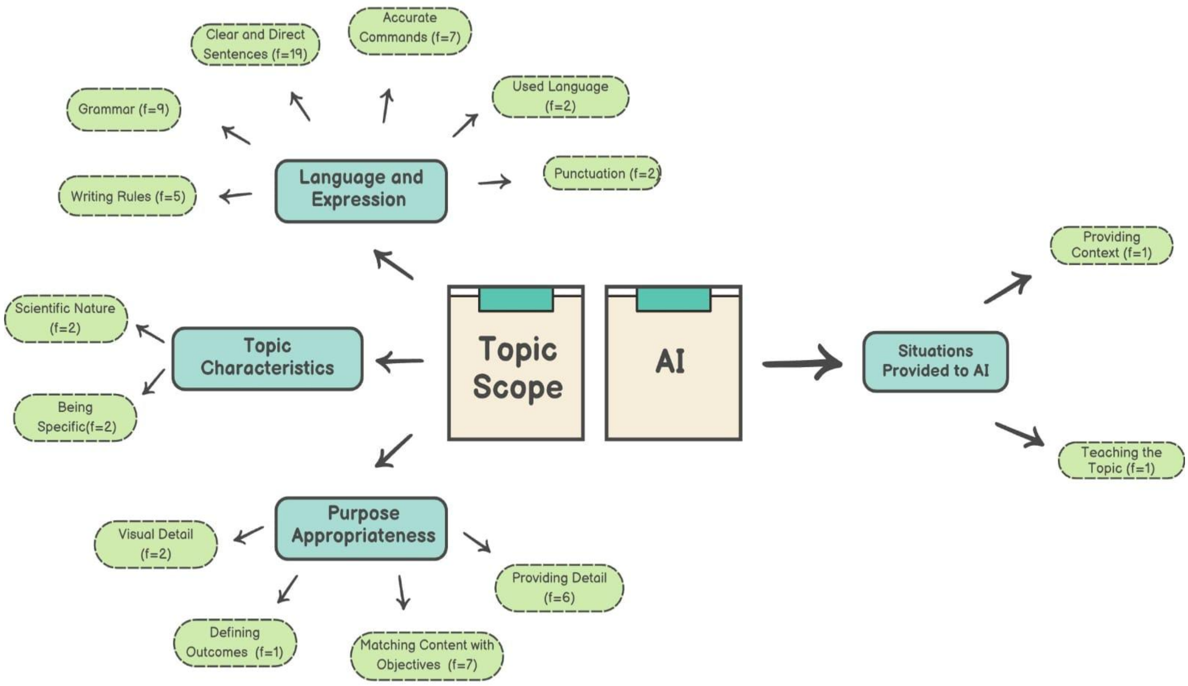

Figure 3. Key Considerations in Prompt Writing

An examination of the findings presented in Figure 3 reveals that pre-service teachers evaluated the critical elements of prompt writing in AI-based applications under two main categories: content scope and AI-related factors. Within these categories, four overarching themes and several sub-themes were identified: language and expression, the nature of the selected topic, goal alignment, and contextual input provided to the AI. Participants frequently emphasized the linguistic structure and format of the inputs submitted to the AI. In particular, the need for clarity, accuracy, and grammatical correctness was repeatedly highlighted. The most frequently cited sub-theme was using clear and unambiguous sentences (f=14), followed by generating accurate commands (f=7) and grammar (f=9). In addition, technical aspects such as spelling rules (f=5), language used (f=2), and punctuation (f=2) were also noted by participants. These findings indicate that the quality of AI-generated responses is highly dependent on the linguistic precision of the user-provided input. With respect to the nature of the topic, participants emphasized that the characteristics of the query submitted to the AI significantly influence the relevance and specificity of the responses. The sub-themes scientific rigor (f=2) and specificity (f=2) suggest that narrowly defined and focused topics enhance AI performance. Another frequently mentioned theme was the alignment between the prompt content and the intended outcome. In this regard, defining the topic and objective (f=7) and providing sufficient detail (f=6) were the most prominent sub-themes. Less frequently mentioned but noteworthy considerations included visual detail inclusion (f=2) and identifying learning outcomes (f=1), highlighting the multifaceted nature of prompt design. These findings collectively underscore the importance of clearly articulating the intended purpose when interacting with AI tools to generate high-quality outputs. A number of participants also noted the need for supplementary explanation and contextualization to enhance AI performance. Sub-themes such as providing background context (f = 1) and teaching the topic to the AI (f=1) reflect the necessity of equipping AI with sufficient prior information and user guidance for optimal results. Selected participant responses are presented below:

> *T-4: Prompts should follow grammar rules (e.g., subject–predicate agreement) and be tailored to the expected response. T-22: To conduct an effective search, we need to structure our query properly for the AI. That's why attention to writing conventions is essential. T-25: Writing for accurate content; visual detail for suitable imagery; learning objective for research alignment; punctuation to avoid sentence-level errors. T-26: Writing, punctuation, font size, and layout matter. A well-structured page is more visually appealing and easier to process.*

The study also aimed to examine the challenges experienced by pre-service teachers during the prompt writing process in AI-based applications. The findings related to this objective are presented in Figure 4. An analysis of the findings in Figure 4 reveals that the challenges pre-service teachers faced during prompt writing in AI applications were categorized into two groups: challenging and not challenging. The majority of participants reported that the difficulties they experienced were primarily user-related. Within the domain of language and expression, the most frequently cited challenge was lack of clarity in articulation (f=7). Other issues included incomplete statements (f=1), inability to provide detailed information (f=5), difficulty in formulating appropriate questions (f=1), and inability to construct coherent sentences (f=1). These findings suggest that the way participants expressed themselves directly influenced the quality and relevance of the responses generated by the AI. In terms of language use, participants noted difficulties such as inability to articulate prompts verbally (f=5) and struggles with command formulation (f = 3), indicating challenges in verbal expression and directive language skills. Under the theme of other issues, several cognitive and procedural limitations were identified, including failure to state the intended goal (f=3), lack of contextualization (f=2), ethical concerns (f=1), inability to maintain chronological order (f=1), and deficiency in critical thinking skills (f=1). These results suggest that participants experienced difficulties not only in linguistic aspects but also in cognitive and ethical dimensions of prompt construction.

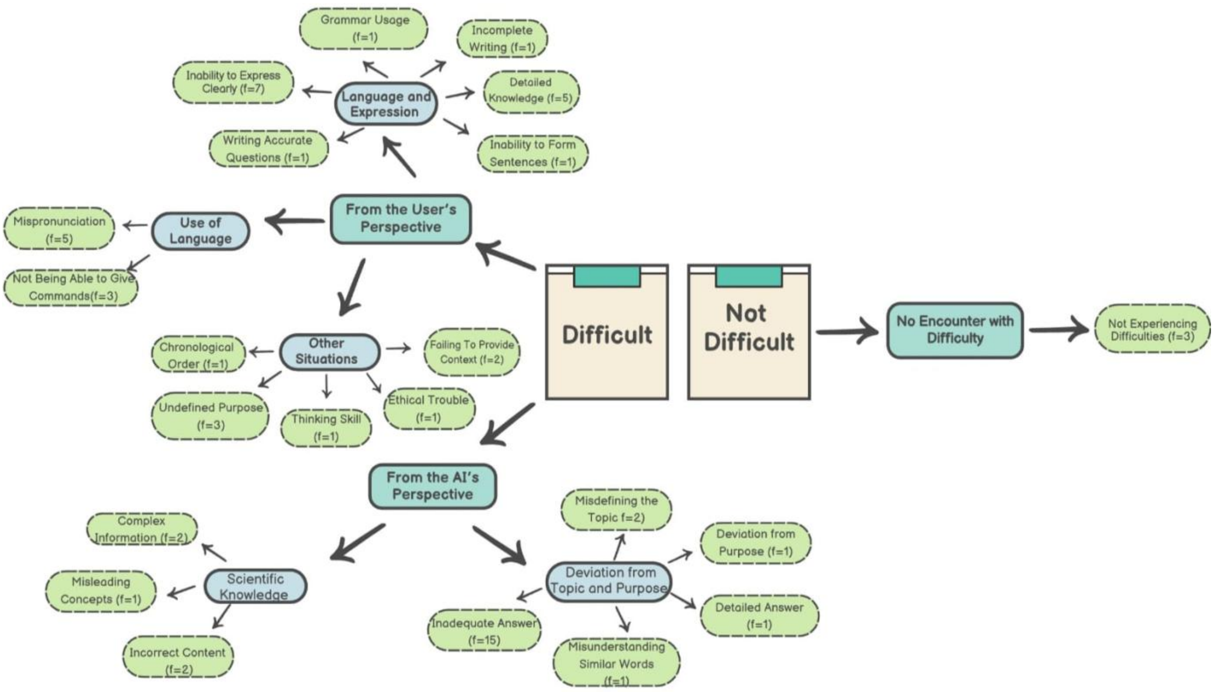

Figure 4. Challenges Encountered During the Prompt Writing Process

From the AI-related perspective, some challenges were linked to the limitations of the AI system itself. Within the theme of scientific information, participants reported issues such as overly complex information presentation (f=2), conceptual inaccuracies (f=1), and incorrect content (f=2), all of which point to concerns regarding the accuracy and reliability of AI-generated responses. Another dominant theme was misalignment with topic and objective, with inadequate responses (f=15) being the most frequently reported sub-theme. Other related problems included misidentification of the topic (f=2), misinterpretation of similar words (f=1), lack of detail in responses (f=1), and deviation from the intended purpose (f=1). These findings indicate that AI outputs may suffer not only from linguistic deficiencies but also from semantic and contextual shortcomings. A smaller group of participants reported no challenges during their use of AI. These responses were grouped under the code absence of difficulty (f = 3), indicating that the user experience may vary considerably depending on individual profiles and usage contexts. Sample participant responses are provided below:

> *T-3: The most difficult challenge I faced was the AI misinterpreting similar words. T-5: I didn't encounter any major issues. When the AI didn't organize the information as I expected, I just provided more details. T-6: Lack of thinking skills and difficulty in forming sentences were challenges. T-7: There were times I couldn't reach the exact result I wanted; sometimes the responses were overly complex. T-11: Occasionally, the AI provides vague or incomplete feedback; sometimes there are conceptual errors in its responses. T-18: Either the answer is incorrect, or the question is misunderstood, and sometimes it gives the same response despite varied inputs. T-19: When I write prompts about topics I know little*

about, the words I use tend to mislead the AI.

The fourth aim of this study was to examine the challenges encountered by pre-service science teachers in the prompt writing process within AI applications. The results of this analysis are presented in Figure 5.

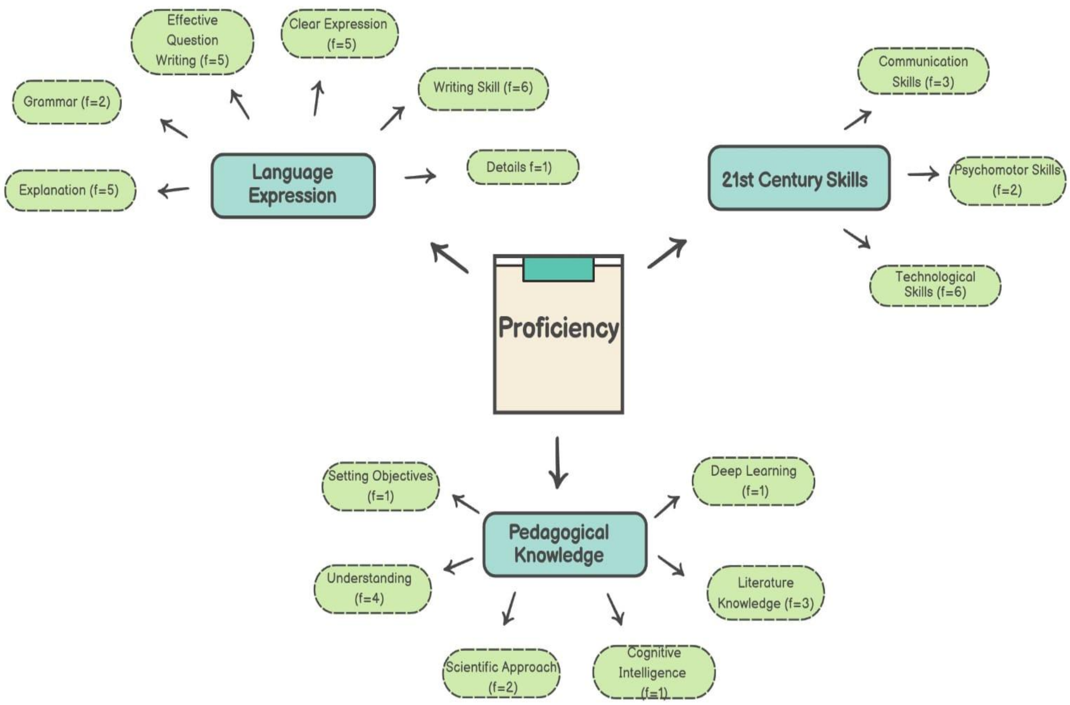

Figure 5. Skill Development to Enhance the Prompt Writing Process

An examination of the findings presented in Figure 5 reveals that the skill and knowledge levels possessed by teacher candidates play a critical role in their interactions with artificial intelligence (AI). The findings are categorized under two main headings: skills and others. Within these categories, four primary themes “language and expression,” “21st-century skills,” “knowledge,” and “others” along with several sub-themes, have emerged. Participants emphasized that the quality of outputs obtained from AI is largely determined by their own linguistic competencies. Among the most frequently highlighted sub-themes were writing skills (f=6), technological skills (f=6), effective question formulation and writing (f=5), clarity of expression (f=5), and explanation (f=5). Additionally, issues such as grammatical accuracy (f=2) and insufficient detail (f=1) were also noted. Within the scope of 21st-century skills, user-related competencies such as technological skills (f=5), communication skills (f=3), goal-setting (f=3), scientific approach (f=2), and psychomotor skills (f=2) were identified as decisive factors in the AI usage process. Furthermore, under the “others” category, higher-order thinking skills including comprehension (f=4), reading (f=3), deep learning (f=1), and procedural intelligence (f=1) were emphasized as important. Regarding the theme of knowledge, participants expressed the need for formal instruction (f=6) and the integration of curiosity driven information into AI systems (f=1). The prevalence of calls for instructional interventions underlines teacher candidates’ perception of a knowledge gap in AI-based applications, which they expect to be directly addressed through education. Overall, the findings suggest that teacher candidates need to develop multifaceted competencies linguistic, technological, cognitive, and pedagogical to use AI effectively.

Selected exemplar statements from the participants are presented below:

> *T-4: Strategic thinking, deep learning, and procedural intelligence should be developed to be more adaptive and constructive. T-16: Training on AI usage can be provided to education faculty students to foster effective prompt writing skills and AI utilization. T-18: Skills such as questioning, self-expression, comprehension, and understanding need to be developed, since obtaining the desired information from AI begins with asking the right questions. T-24: Proficiency in using Turkish effectively should be improved. One must recognize that the interlocutor's understanding may differ from their own; therefore, expressing oneself as clearly and plainly as possible is essential. T-26: I have no opinion. T-27: Effectively using AI-supported educational tools. T-31: AI support should be incorporated into the curriculum to enhance effective utilization.*

Finally, the study aimed to evaluate pre-service science teachers' recommendations for enhancing the efficiency of prompt writing in artificial intelligence applications. The findings obtained are presented in Figure 6.

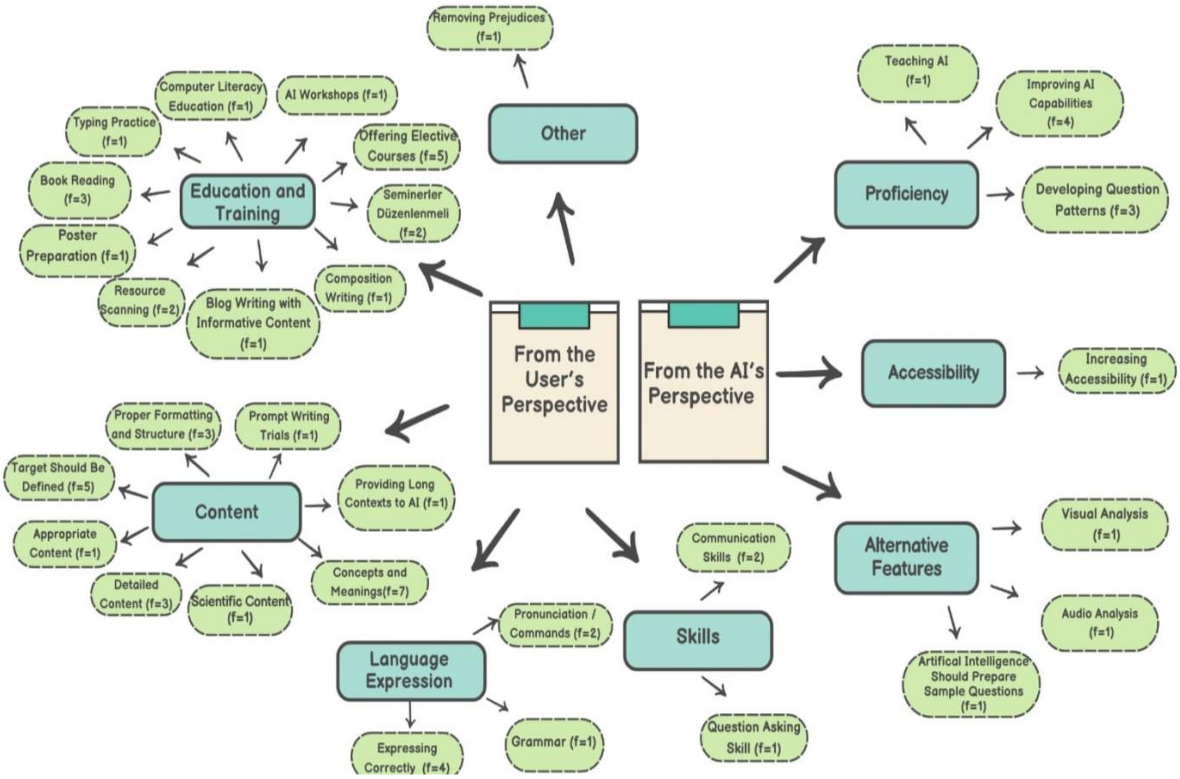

Figure 6. Recommendations for Enhancing the Effectiveness of Prompt Writing in AI Applications

An analysis of the findings presented in Figure 5 indicates that the experiences encountered in using artificial intelligence are evaluated by pre-service science teachers within two categories: "user-related" and "artificial intelligence-related." Challenges experienced from the user perspective are grouped under the themes of education and training, language and expression, content, skills, and others. Within the education and training theme, the most frequently reported problem was inadequate responses (f=15), while issues such as lack of clarity regarding the objective (f=3), deviation from the objective (f=1), misdefinition of the topic (f=2), inability to provide detailed responses (f=1), misunderstanding of similar words (f=1), inability to follow chronological order (f=1), lack of contextualization (f=2), ethical concerns (f=1), and deficits in critical thinking skills (f=1) emerged as both content-related and cognitive-level challenges. Regarding the content theme, difficulties related to linguistic competencies were observed, including insufficient detail (f=5), incorrect content (f=2), incomplete writing (f=2), unclear explanations (f=2), misconceptions (f=1), complex information (f=2), grammatical usage (f=1), and sentence formation problems (f=1). Additionally, the language and expression theme revealed problems such as inaccurate expression (f=4) and lack of pronunciation/command clarity (f=2). Under the skills theme, inadequacies in question-asking skills (f=1) and communication skills (f=2) highlighted interaction difficulties faced by users. The “others” category drew attention to individual deficiencies affecting the process, such as correct question formulation (f=1), which could not be classified directly under other themes. From the perspective of artificial intelligence, the themes identified include competence, accessibility, and alternative features. Under the competence theme, participants indicated that AI is open to development, emphasizing that AI can be improved (f=4), should enhance its question patterns (f=3), and can be taught (f=1). Within the accessibility theme, suggestions were made to increase accessibility (f=1). The alternative features theme revealed expectations for AI to provide not only written responses but also multimodal support, including recommendations such as visual analysis (f=1), voice analysis (f=1), and example question provision (f=1). Taken together, these findings suggest that teacher candidates experience various challenges in AI use stemming from both their own competencies and the technological limitations of the tools, while simultaneously demonstrating an awareness of the system’s potential for improvement. Selected participant statements are presented below:

> *T-1: Organizing seminars, offering elective courses, or preparing informational blog posts would be effective on this matter. T-5: If we want, for example, a summary of a piece of information from AI, providing it first with detailed information to summarize yields more efficient results. Therefore, AI should learn from us and interpret accordingly. T-8: Questions posed to AI should be scientifically robust. T-9: AI workshops are important because detailed learning can take place. Composition writing is essential since the more fluent and detailed our inputs to AI, the better the responses we receive. T-12: We must pay attention to spelling and punctuation and write sentences properly. T-22: Providing AI with appropriate content is crucial because writing the requested expression accurately is an important task. T-30: Objectives should be clearly defined and stated.*

Discussion

This study offers significant insights into pre-service science teachers’ perceptions and experiences regarding the prompt writing process within AI-supported educational settings. The findings highlight that participants view prompt quality as a critical skill for engaging effectively with AI tools. The first major result reveals that the majority of candidates acknowledge the importance of prompt writing, evaluated from two primary perspectives: that of the user and that of the AI system. This aligns with previous research by Zhou (2023) and Huang (2025), who emphasized the necessity of effective human AI interaction to maximize educational outcomes. Participants indicated the need to develop multidimensional competencies linguistic, cognitive, pedagogical, and technological to communicate effectively with AI systems. Moreover, the prompt writing process was perceived not simply as a technical task, but as one requiring higher-order skills such as critical thinking, inquiry, and content creation. Consistent with this, Woo et al. (2024) found that university students’ prompt writing abilities and AI self-efficacy significantly improved through structured interventions. Additionally, a comprehensive literature review by Sahoo et al. (2024) demonstrated that the quality of AI outputs largely depends on the clarity, scope, and contextual framing of user inputs. Thus, prompt writing is better understood as a holistic process that integrates cognitive reasoning, question generation, and narrative construction. Supporting this view, Chen et al. (2020) reported that employing AI tools with well-designed techniques enhances students' cognitive flexibility, adaptability, and problem-solving capacities.

Findings related to the key elements of effective prompt writing indicate that participants emphasized the use of clear and comprehensible language, adherence to writing conventions, and the necessity of specificity in relation to the subject matter. These findings align with studies such as Chen et al. (2024), which underscore the impact of prompt quality on the relevance and accuracy of AI-generated outputs. Participants' awareness of concepts like "topic–purpose alignment" and "providing prior knowledge" further highlights the importance of pedagogical design thinking in human–AI interactions. Notably, instances in which participants struggled to clearly articulate their questions, inadequately specified their intentions, or received unsatisfactory AI responses point to competency gaps not only in technological proficiency but also in cognitive and linguistic dimensions. Laupichler et al. (2022) conceptualize AI literacy as more than the mere technical use of tools; it encompasses a multidimensional skill set involving critical evaluation, analysis of outputs, and the cultivation of ethical awareness. These findings suggest that teacher education programs should go beyond simply introducing digital tools and instead foster the ability to interact with such technologies critically, reflectively, and responsibly.

The challenges reported by participants indicate that prompt writing is not merely a technical task but a complex, multidimensional process encompassing cognitive, linguistic, and ethical considerations. Among the most frequently cited difficulties were the inability to articulate queries clearly and the failure to define objectives explicitly—both of which suggest limitations in cognitive load management and metacognitive awareness. These findings align with prior research indicating that effective interaction with artificial intelligence is closely tied to individuals' cognitive competencies (Tan et al., 2025). Giray (2023) also emphasized that inadequately constructed prompts can lead to various issues in AI outputs, such as inaccuracies and ambiguity. Consequently, prompt engineering is increasingly recognized as a vital skill for both students and graduates entering AI-integrated professional environments (Lee & Palmer, 2025; Raftery, 2023).

Pre-service science teachers highlight the necessity for structured training in areas such as written communication, technological proficiency, strategic thinking, and question formulation to develop effective prompt-writing skills in AI tools. As artificial intelligence becomes increasingly embedded in educational settings, the ability to engage with and guide AI processes is emerging as a key competency for contemporary educators (Foster & Piacentini, 2023). Lee and Palmer (2025) argue that prompt engineering should be regarded as a core competency rather than an optional skill at the higher education level. Moreover, integrating GenAI into creative curricula can enhance students' understanding of how such tools influence the quality and innovation of AI-generated outputs. In this regard, prompt design is not merely a technical skill but also a pedagogical element that should be embedded into teacher education programs. Indeed, a review of recent studies suggests that prompt engineering is increasingly conceptualized as a developing skill set that must be explicitly taught (Aaron et al., 2024; Zawacki-Richter, 2024).

Another noteworthy insight from participants is their recognition of AI's open-ended nature, along with suggestions for improving its responsiveness—such as incorporating multimodal outputs like visual or auditory feedback. This perspective illustrates that pre-service teachers view AI not only as a utilitarian tool but also as a technology open to critical reflection and iterative enhancement (Southworth et al., 2023). In doing so, they position themselves not as passive users but as active stakeholders capable of reshaping AI-enhanced learning environments.

Pre-service science teachers underscore the necessity of structured training in key areas such as written communication skills, technological proficiency, strategic thinking, and question formulation to improve the effectiveness of prompt writing in AI tools. As artificial intelligence becomes increasingly integrated into educational settings, the capacity to interact efficiently with these tools and to effectively manage this process has emerged as a critical contemporary competency for teachers (Foster & Piacentini, 2023). Lee and Palmer (2025) further contend that prompt engineering should be considered a core competency within higher education curricula rather than an elective. Additionally, a thoughtfully designed curriculum that instructs students on how to incorporate generative AI (GenAI) into creative processes can enhance their understanding of the impact AI-generated outputs have on both quality and innovation. Within this context, prompt design is regarded not merely as a technical skill but as a pedagogical component that must be integrated into teacher education programs.

A comprehensive review of the literature indicates that prompt engineering is increasingly recognized as an essential and emerging skill set that should be integrated into student curricula (Aaron et al., 2024; Zawacki-Richter, 2024). Moreover, participants in this study demonstrated an acute awareness of the evolving nature of artificial intelligence and advocated for system enhancements, including improved feedback mechanisms and the incorporation of multiple response modalities, such as visual and auditory analyses. This outlook suggests that pre-service teachers regard AI not merely as a tool for user interaction but as a dynamic technology open to critical evaluation and continuous improvement (Southworth et al., 2023). Accordingly, pre-service teachers move beyond passive users to become active agents capable of transforming AI-supported educational environments.

Conclusion

This study examined the perspectives of pre-service science teachers on prompt writing within AI-supported instructional processes, revealing important insights related to both individual competencies and systemic requirements. The findings suggest that teacher candidates need to cultivate multidimensional skills including linguistic, cognitive, pedagogical, and technological competencies to engage effectively with artificial intelligence. Moreover, prompt writing is identified not merely as a technical activity but as a complex process that entails higher-order skills such as critical thinking, inquiry, and content creation.

Recommendations

Based on these results, it is recommended that teacher education curricula be revised to incorporate structured courses and practical experiences focusing on AI literacy, effective question formulation, critical thinking, and ethical awareness. Additionally, the development of comprehensive guidance materials on classroom integration of AI applications and the establishment of hands on training opportunities such as workshops and laboratory sessions tailored to instructional technology courses are essential. This study further emphasizes that pre-service teachers should move beyond passive use of AI tools to assume active roles as content creators, critical interrogators, and developers. These findings highlight the urgent need to realign teacher education programs with the evolving demands of the digital era.

Limitations of the Study

This study is limited to the perspectives of pre-service science teachers enrolled at a single university, and therefore, the findings may not be generalizable to other disciplines or socio-cultural contexts. While the structured interview form used for data collection provided valuable qualitative insights, it may have restricted the depth and richness of participants' experiences. Furthermore, the AI tools utilized in the study likely varied in terms of model architecture, language capabilities, and response algorithms, potentially affecting the consistency of user experiences. Considering the rapid pace of AI technological advancements, the relevance and applicability of these findings may be time-sensitive. Accordingly, future research is encouraged to include more diverse participant samples, employ multiple data collection methods, and focus on specific AI platforms to enhance generalizability and validity.

Statements and Declarations

Ethics Approval and Consent to Participate: All of the procedures performed in studies involving human participants were in accordance with the ethical standards and the Helsinki Declaration and its later amendments or comparable ethical standards.

Informed Consent: Informed consent was obtained from all participants (prospective science teachers) prior to data collection.

Statement Regarding Research Involving Human Participants and/or Animals: This research involved human participants (prospective science teachers). All procedures were conducted in accordance with ethical standards, and written informed consent was obtained from all participants.

Consent to Participate: All participants provided written consent to participate in the study.

Consent to Publish: Consent to publish the findings of the study was obtained from all participants.

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Authors' Contributions: All authors contributed to the data collection, analysis, and writing of the paper. All authors read and approved the final manuscript.

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Availability of Data and Materials: The datasets generated and analyzed during the current study are available from the corresponding author on reasonable request.

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Nature on the Use of AI Tools and Academic Achievement in Mathematics

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Abstract

This study investigates the nature of AI tool use and its relationship to the academic achievement of senior high school STEM students in Mathematics. Guided by a quantitative descriptive-correlational design, the research surveyed students to examine their extent of AI use in completing tasks and administered an achievement test to measure performance. Results revealed that students primarily used AI tools as a scaffold to enhance independent learning and reinforce mastery of mathematical concepts, rather than solely as a crutch for task completion. Analysis showed that scaffolded use exhibited a weak positive correlation with achievement, while crutch-based use displayed a weak negative correlation. However, both relationships were found to be not significant. These findings indicate that AI tools, when used strategically, may support student learning, but overreliance could hinder problem-solving and critical thinking. The study underscores the importance of promoting responsible and balanced AI use in mathematics classrooms, ensuring that technology serves as a supplement rather than a substitute for cognitive engagement. Recommendations are offered for educators to integrate AI in ways that reinforce higher-order skills and for future researchers to examine its long-term influence on learning outcomes.

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Introduction

In the rapidly evolving landscape of education, technological advancements have significantly influenced teaching and learning practices. Among these advancements, artificial intelligence (AI) tools have emerged as prominent resources, reshaping how students approach academic tasks. AI tools, such as mathematical solvers, tutoring platforms, and content generators, provide opportunities for personalized learning and increased efficiency in task completion. However, their widespread accessibility raises concerns about the student's dependency on AI tools and the potential implications for academic development.

In the context of Senior High School STEM (Science, Technology, Engineering, and Mathematics) students, Mathematics is a core subject that fosters critical and problem-solving skills essential for their academic and professional pursuits. Activities in this subject such as homework, performance tasks, or even reviewing in preparation for the exams require higher-order thinking, conceptual understanding, and application of learned concepts. While AI tools offer support in addressing complex problems, an overreliance on AI tools may hinder students' ability to develop independent critical thinking and problem- solving skills.

AI tools such as Photomath, Wolfram Alpha, and ChatGPT have become popular among students for their ability to break down complex equations and provide step-by-step solutions. These tools are particularly useful for students who struggle with abstract mathematical concepts as they offer personalized support and immediate feedback. Research has shown that AI tools, when effectively implemented, can provide personalized learning experiences, helping students understand complex mathematical concepts at their own pace (Liu & Liao, 2020). These tools allow students to visualize problems, break them into manageable steps, and receive instant solutions and explanations, making mathematics more accessible and less intimidating. In this way, AI can potentially improve student engagement and learning outcomes by offering support tailored to individual needs (Baker & Siemens, 2014).

However, concerns have emerged about overreliance. Limniou and Smith (2021) argue that while AI enhances efficiency, excessive use reduces independent problem-solving and critical thinking. Fischer, Lundin, and Lindberg (2020) similarly caution that dependency may weaken higher-order reasoning, even though AI improves personalization and engagement internationally. In the Philippines, adoption is still developing. Sarmiento (2020) notes that limited access, internet connectivity issues, and lack of teacher training hinder widespread use. Department of Education CAR (2020) adds that private and urban schools benefit more than rural ones, creating uneven opportunities. Nonetheless, the National Economic and Development Authority (2017) stresses that AI can help strengthen STEM education to prepare students for future demands.

At the local level, Baguio City schools are beginning to adopt AI tools. VanLehn (2019) explains that intelligent tutors can provide targeted support to help students master mathematics. Bucad (2021) warns that students who depend too much on AI risk losing abstract reasoning skills. Similarly, Sarmiento (2020) emphasizes that excessive use discourages independent problem-solving. Gomez and de Guzman (2021) observe that adoption remains inconsistent, limited by accessibility and teacher readiness.

The National Council of Teachers of Mathematics (2024) underscores AI's contribution in helping students break down and understand complex mathematical concepts. Opesemowo (2024) highlights advancements in adaptive assessment and real-time feedback, which adjust to student weaknesses. Xu and Ouyang (2022), however, argue that AI must be balanced with traditional instruction to preserve cognitive skills. Kelley et al. (2024) warn that students who rely too heavily on AI develop only surface-level understanding. Wang et al. (2024) note a clear distinction between scaffolded use, which supports independent reasoning, and crutch-based use, which bypasses it.

Similar dependency issues are found in other disciplines. Chen et al. (2020) reveal that students using AI-based grammar checkers in language learning struggle to detect errors independently. In medicine, Topol (2019) points out that AI enhances diagnostics, but Reddy, Fox, and Purohit (2021) warn that overdependence can weaken diagnostic reasoning. In arts, McCarthy (2022) and Jones and Brown (2023) discuss how AI-generated works raise issues of originality, authorship, and devaluation of creativity. In engineering, Zou (2024) explains that AI enhances design and predictive analytics but stresses the need for integration with industry to build practical and innovative skills.

Overall, Bucad (2021) and Sarmiento (2020) stress the risks of dependency in mathematics education. Xu and Ouyang (2022) found in China that students relying heavily on AI retained fewer concepts than those who used it only as a supplement. These findings show that while AI can be a scaffold for learning, it also risks becoming a crutch. Although research exists internationally and nationally, few studies focus on Senior High School STEM students in Baguio City. This study therefore addresses the gap by exploring whether AI tools support or hinder the development of critical thinking and academic achievement in mathematics.

Conceptual Framework

The integration of AI tools has reshaped education, especially in mathematics, where problem-solving and conceptual understanding are central. This study is anchored on the idea that students' use of AI tools, either as scaffolds that enhance learning or as crutches that replace independent thinking, affects their academic achievement in General Mathematics under the STEM strand. Academic achievement, as defined by Airasian (2005), refers to the attainment of learning outcomes measured through grades, test scores, and assessments. In this study, it is represented by students' scores in an achievement test on Calculus and Statistics, based on DepEd's K to 12 grading standards.

AI tools are digital technologies that simulate human intelligence to assist learning. These include AI-based platforms, calculators, problem solvers, and tutoring applications. Their use is classified into scaffolded AI, where tools enhance understanding and problem-solving and crutch-based AI, where tools substitute for reasoning. The extent of use is measured by frequency: never, rarely, sometimes, and always.

In the Philippines, Dizon and Reyes (2023) observed that students switch between scaffolded and crutch-based use depending on task difficulty. Capinding (2023) and Santos and Cruz (2024) reported that many Filipino learners use Photomath mainly to verify answers or deepen understanding, suggesting scaffolded use. Shearman (2024), Holmes et al. (2019), and Lin, Huang, and Lu (2023) emphasize that strategic AI integration strengthens critical thinking and problem-solving. Martinez and Zhao (2022) and Kroeger & Brown (2021) also confirm AI's effectiveness when reinforcing not replacing the learning process. On the other hand, Al-Zahrani (2024), and Akinwalere and Ivanov (2022) caution that excessive dependence undermines retention and higher-order skills.

Bancoro (2024) found no significant correlation between AI use and performance among Negros Oriental State University students, despite moderate availability. Nguyen and Duong (2023) and Raza et al. (2023) reported similar findings, noting that AI improves convenience but has limited academic impact unless paired with active engagement. The Digital Education Council (2024) adds that in the Philippines, AI's benefits depend largely on teacher guidance and student study habits.

Broader studies echo these mixed results. Dong et al. (2025) and Vieriu and Petrea (2025) concluded that AI's academic effects are small and context-dependent. Adewale et al. (2024), in a systematic review, found that while AI supports open and distance learning, significant gains in achievement are rare without strong cognitive engagement. These insights shape this study's framework: AI tools can support mathematics learning when used as scaffolds, but crutch-based use risks diminishing achievement. Thus, the study considers nature of AI use (scaffold vs. crutch) and extent of AI use (frequency) as independent variables, academic achievement as the dependent variable, and critical thinking and problem-solving skills as intervening variables.

Schematic Illustration of the Study

The study employs a systems model to illustrate the interaction of variables. The independent variables are the nature (scaffolded or crutch-based, measured via Likert scale) and extent (never, rarely, sometimes, always) of AI tool use. The dependent variable is academic achievement, assessed through a Calculus and Statistics test aligned with DepEd standards. The intervening variables are critical thinking and problem-solving skills, measured through test performance and a self-reported survey of analytical reasoning.

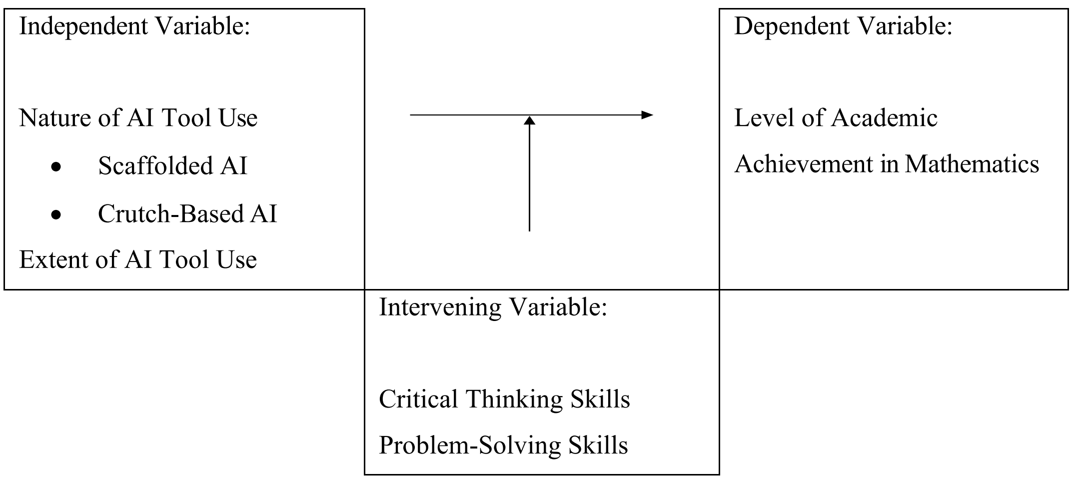

Figure 1. Paradigm of the Study

Statement of the Problem

The study aimed to examine the relationship between the nature and extent of artificial intelligence tool use and the academic achievement of STEM students in Mathematics. Specifically, the study sought to address the following objectives:

1. What is the nature of students' use of AI tools in their learning engagement in Mathematics?
2. What extent do students use AI tools to complete mathematics tasks?
3. What is the effect of the nature of AI tools used in the mathematics achievement of the student?
4. What is the effect of the extent use of AI tools in the mathematics achievement of the students?

Methodology

Research Design

This study employed a quantitative descriptive-correlational design to examine the relationship between the nature and extent of AI tool use and students' mathematics achievement. The design enabled the analysis of test scores in Calculus and Statistics alongside self-reported AI usage patterns, without inferring cause-and-effect. Descriptive analysis determined the nature and extent of AI use and levels of achievement, while correlational analysis assessed possible relationships between AI tool reliance and academic outcomes.

Population and Locale of the Study

The study was conducted at the University of Baguio, Philippines, among Senior High School STEM students enrolled in General Mathematics in the academic year 2024–2025. Using multi-stage random sampling, one section was allocated for reliability testing and 554 students were eligible. Cochran's formula determined a sample size of 228, though 202 valid responses were retained after data cleaning. This ensured statistical sufficiency and representation. The breakdown of the sample size is presented in Table 1.

Table 1. Number of Sample of Respondents

Section	Total number of students	Randomly selected sections	Proportional Sample respondents
A	43		
B	43	B	39
C	44	C	40
D	44		
E	41		
F	42	F	38
G	42	G	38
H	44		
I	43		

Section	Total number of students	Randomly selected sections	Proportional Sample respondents
J	43		
K	42	K	38
L	44		
M	39	M	35
Overall	554		228

Data Collection Instrumentation

Data were collected using a researcher-made survey questionnaire and a mathematics achievement test. The survey included demographic questions, Likert-scale items to assess nature (scaffold vs. crutch) and extent (never, rarely, sometimes, always) of AI tool use, and a checklist of AI platforms and their perceived benefits. The achievement test, validated by three mathematics teachers, covered Calculus, Statistics, and Probability, measuring problem-solving skills and conceptual understanding. It obtained a validity score of 0.76 and high reliability (Cronbach's $\alpha = 0.91$).

Data Collection Procedure

The data collection process began with securing approval from the University of Baguio's administration and obtaining informed consent from student participants. To ensure validity, the instruments were reviewed by a Mathematics teacher, followed by pilot testing: the Likert-scale questionnaire with Grade 11 STEM students and the achievement test with Grade 12 STEM students. Reliability was established through Cronbach's Alpha for the Likert scale and item analysis, including the difficulty index, for the achievement test. Necessary revisions were made based on the results.

The finalized instruments were administered to the selected Grade 11 STEM students during their free periods. Responses were then encoded and analyzed using Microsoft Excel. Descriptive statistics (mean and standard deviation), the t-test for independent samples, and Pearson's correlation coefficient were applied to examine the relationship between AI tool use and mathematics achievement. The findings were summarized, and recommendations were formulated to guide the integration of AI tools in Mathematics education.

Data Analysis

The collected data were systematically analyzed using descriptive and inferential statistics to address the study objectives. For SOP 1, the nature of AI tool use was described through frequency and percentage distribution of survey responses. For SOP 2, the extent of AI tool use was determined using means and standard deviations, with responses categorized into always, sometimes, rarely, or never, based on a four-point scale.

For SOP 3, mathematics achievement was analyzed by calculating frequency of students within each level of academic achievement. Raw scores from the achievement test were converted to numerical grades based on

DepEd grading standards (Department of Education, 2012) to align interpretations with national benchmarks. The classification was shown in Table 3.

Table 2. Categorization of the Extent Use of AI tools

Point	Scale Range	Interpretation	Scaffolded AI Use (support-based)	Crutch-based AI Use (over-reliance)
4	3.25- 4.00	Always *Uses AI in nearly every task*	Highly Strategic Use of AI- AI is used as an enhancement to learn, supporting understanding while maintaining problem-solving independence.	Highly Over-Reliant on AI- AI is relied upon excessively, often replacing independent thinking in problem-solving.
3	2.50- 3.24	Sometimes *Uses AI tools periodically*	Moderate AI Use- AI is used as a supplementary tool, enhancing but not replacing traditional problem-solving.	Moderate Over-Reliance on AI- AI use begins to replace independent problem-solving in more challenging tasks.
2	1.75- 2.49	Rarely *Uses AI tools occasionally*	Limited AI Use- AI is used only when needed for complex topics, ensuring conceptual understanding.	Limited Over- Reliance on AI- AI is used occasionally but primarily for quick answers rather than learning.
1	1.00- 1.74	Never *Do not use AI tools*	No AI Use- Fully relies on traditional learning methods but remains open to AI if needed.	Not Dependent on AI- Avoids AI use entirely, possibly due to lack of access or distrust in AI tools.

Table 3. Score Ranges and Corresponding Academic Achievement Levels

Actual Score	Numerical Grade	Level of Academic Achievement
50	100	Advanced (A)
49	98	
48	97	
47	96	
46	95	
45	93	
44	92	
43	91	
42	90	
41	88	Proficient (P)
40	87	
39	86	
38	85	

Actual Score	Numerical Grade	Level of Academic Achievement
37	83	Approaching Proficient (AP)
36	82	
35	81	
34	80	
33	78	Developing (D)
32	77	
31	76	
30	75	
29 and below	Below 75	Beginning (B)

The t-test for two independent samples were used to determine the effect of the nature of AI tools use and mathematics achievement following the interpretation in Table 4. For SOP 4, the effect between the extent of AI tools use and mathematics achievement was examined by analyzing their means. Pearson's correlation coefficient was applied to assess the strength and direction of these relationships. Interpretation of the correlation strength followed Wahyuni & Purwanto (2020), using the scale in Table 4.

Table 4**.** Level of Effect on the Nature and Extent of AI Tools in Mathematics Achievement

Range (±)	Level	Description
0.80-1.00	Very Strong	AI tools significantly enhance mathematics achievement when relationship is statistically significant.
0.60-0.79	Strong	AI tools contribute positively to learning, but only if statistically significant.
0.40-0.59	Moderate	AI tools provide moderate support in learning, if statistically significant.
0.20-0.39	Weak	AI tools have a weak but notable effect if statistically significant.
0.00-0.19	Very Weak or No Significant Effect	AI tools have little to no meaningful effect on mathematics achievement, not statistically significant.

Item analysis of the achievement test was conducted using the difficulty index, with average-level items retained and revisions made to overly easy or difficult items. Reliability was assessed through Cronbach's alpha for both the Likert-scale questionnaire and the achievement test, while content validity was established through expert review. Results were presented in tables with descriptive and inferential statistics to illustrate the findings clearly.

Research Ethics

Ethical standards were strictly observed throughout the conduct of the study. Prior to data collection, formal approval was secured from the administration of the University of Baguio. Participants were informed of the study's objectives, procedures, and their rights, including the freedom to withdraw at any point without penalty. Informed consent forms were distributed, ensuring voluntary participation. To safeguard participants' welfare, all responses were treated with strict confidentiality. No identifying information was disclosed, and data were encoded and stored securely. Anonymity was maintained in reporting, ensuring that results reflected group trends rather than individual performance. The safety and well-being of student participants were prioritized by conducting the survey and tests during their free periods to minimize disruption and stress. Furthermore, the instruments underwent expert validation and pilot testing to ensure fairness, accuracy, and appropriateness. The research adhered to established ethical principles, protecting participants' rights while ensuring the integrity of the findings.

Results

Nature on the Use of AI Tools in Mathematics of Senior High School STEM Students

Table 5 shows the frequency distribution of the nature of using AI tools among senior high school STEM students in Mathematics. The nature of using AI tools among senior high school STEM students in Mathematics is scaffolded. Result shows that about 180 students, or 89.11% use scaffolded AI, while only 22 students , or 10.89% used crutch- based AI.

Table 5. Nature of Students' Use of AI Tools in Mathematics

Nature on Use of AI Tools	Frequency (f)	Percentage (%)
1. Scaffolded AI	180	89.11
2. Crutch-based AI	22	10.89
Total	202	100

Extent of AI Tool Usage in Completing Mathematics Task

Table 6 presents the extent of AI tool use in completing mathematics tasks. The overall mean was 2.10, was interpreted as rarely. Scaffolded AI had a composite mean of 2. 40 and interpreted as rarely, while cutch-based AI obtained a composite mean of 1.80 and also interpreted as rarely.

Table 6. Extent of AI Tools Use in Completing Mathematics Task

Extent on Use of AI Tools as Scaffolded AI	N=202	
In learning Calculus and Statistics, I use AI tools …	M	DE
1. when I struggle to understand a concept, but I still try to solve problems on my own first.	2.41	R
2. to check if my answers are correct after solving problems independently.	2.60	S
3. to explore different methods for solving a problem and compare which one works best for me.	2.40	R
4. to help me visualize and break down complex Calculus and Statistics concepts into simpler steps.	2.51	S
5. to practice solving problems so I can perform better in assessments like quizzes, major exams, and performance tasks.	2.48	R

Extent on Use of AI Tools as Scaffolded AI	N=202	
6. because it boosts my confidence in solving Calculus and Statistics problems.	1.78	R
7. as a guide to deepen my understanding of mathematical concepts.	2.65	S
8. to improve my problem-solving skills rather than just obtaining the correct answer.	2.36	R
Composite Mean	2.40	R
Extent on Use of AI Tools as Crutch-Based AI		
1. as my first option whenever I encounter a difficult problem, without trying to solve it myself.	1.97	R
2. to get instant solutions without attempting to understand the process.	1.71	N
3. to quickly generate answers rather than solving the problem myself.	1.73	N
4. because I find it difficult to solve math problems without AI assistance.	1.84	R
5. because it allows me to complete tasks faster, even if I don't fully understand the concepts.	1.81	R
6. because I feel dependent on AI tools to answer math-related questions like assignments and performance tasks.	1.66	N
7. because I consider AI tools essential for my success in Mathematics.	1.86	R
Composite Mean	1.80	R
Overall Mean	2.10	R

Legend: N= sample size. M= mean. DE= descriptive equivalent. 2.50-3.24= Sometimes (S). 1.75-2.49= Rarely (R). 1.00- 1.74= Never (N)

Effect of the Nature of AI Tools Use in Mathematics Achievement of Student

Table 7 presents the effect of the nature of AI tool use on students' mathematics achievement. Scaffolded AI users obtained a mean score of 77.88, while crutch-based AI users obtained 77.32. Both fall under the developing level. The computed t-value of 0.570 with a p-value of 0.569 indicates no statistically significant difference.

Table 7. Effect of the Nature of AI Tools on Mathematics Achievement

Nature of Use	Level of Mathematics Achievement						t	p
	P	AP	D	B	Mean	DE		
Scaffolded AI	3	36	56	85	77.88	D	0.570	0.569
Crutch-based AI	-	4	8	10	77.32	D		

Legend: P = proficient. AP = approaching proficiency. D = developing. B = beginning. DE = descriptive equivalent. t = t-test for two independent samples. p = probability (Sig.) value.

Effect of the Extent Use of AI Tools on Mathematics Achievement of Students

Table 8 shows the relationship between the extent of AI tool use and mathematics achievement. The overall Pearson correlation coefficient of 0.009 with a p-value of 0.895 suggests a very weak positive relationship that is not statistically significant.

Table 8. Effect of Extent Use of AI Tools in Mathematics Achievement

	Extent of Use					
	Scaffolded AI		Crutch-based AI		Overall	
Mathematics	r	p	r	p	r	p
Achievement	0.045	0.529	-0.036	0.611	0.009	0.895

Legend: r = Pearson correlation coefficient. p = probability (Sig.) value. r (±0.000 - ± 0.199) = very weak or no relationship thus, very weak or not significant. p (> 0.05) = not statistically significant.

Discussion

The results show that most students use AI as a scaffolded, support-based tool, integrating it into their tasks after exerting independent effort. For example, in Calculus, a student solved a limit problem step-by-step before checking with AI, while in Statistics, another student constructed a frequency distribution and histogram manually before refining the graph with AI. In these cases, AI served as confirmation and visualization aid rather than the primary solver, fostering independence similar to how a teacher provides temporary guidance. In contrast, crutch-based AI use was observed in only 22 students (10.89%), who relied on AI for immediate solutions without attempting the task first. For instance, pasting an entire math problem into AI and copying the answer. While this ensures timely submission, it undermines problem-solving and reasoning, limiting deeper learning. Some students also exhibited situational switching, shifting between scaffolded and crutch-based use depending on academic pressure or time constraints.

These findings align with prior studies. Dizon and Reyes (2023) noted Filipino students alternate between AI for deeper understanding and convenience depending on task complexity and pressure. Shearman (2024) and Holmes et al. (2019) highlighted that scaffolded AI fosters critical thinking and comprehension, while Lin, Huang, and Lu (2023) emphasized its role in strengthening conceptual understanding. Similarly, Kroeger & Brown (2021) and Martinez and Zhao (2022) concluded that AI is most beneficial when reinforcing, not replacing, learning. However, literature also warns against overdependence. Al-Zahrani (2024) and the Digital Education Council (2024) cautioned that reliance on AI may weaken critical thinking, and Akinwalere and Ivanov (2022) stressed that it can hinder long-term retention of mathematical knowledge. Overall, the study reveals a promising trend of constructive AI use, where most students employ AI as a scaffold for learning rather than a shortcut. This underscores the importance of teachers promoting scaffolded AI integration in classrooms modeling reflective use, encouraging critical thinking, and helping students avoid overdependence, especially under pressure.

The extent to which students use AI tools to complete mathematics tasks in Calculus and Statistics, as gleaned from Table 6 imply that, in general, students do not heavily rely on AI tools in their daily mathematics tasks. Their use of AI is occasional, situational, and often depends on topic difficulty. For scaffolded AI use, the composite means of 2.40 (rarely) suggests that students are beginning to integrate AI tools cautiously, using them mainly to deepen conceptual understanding. For example, students may consult ChatGPT or Photomath to clarify complex topics like limits or use Gauthmath to check answers after independently solving Statistics problems. Others turn to visualization tools such as Desmos or GeoGebra to make abstract concepts more tangible. These practices reflect initiative and responsibility, showing that students view AI as a support system rather than a substitute. However, other scaffolded uses such as test preparation, exploring alternative methods, or boosting confidence remained less frequent, possibly due to unfamiliarity or uncertainty about whether such tools are permitted. By contrast, crutch-based AI use yielded a lower composite mean of 1.80 (rarely), with several items falling under the “never” category. This indicates a strong avoidance of misusing AI for shortcuts. Most students attempt problems manually before turning to AI, valuing long-term learning over immediate task completion. While some admitted to occasional dependency during deadlines or heavy workloads, the overall pattern reflects a desire for independence.

These findings parallel both international and local trends. Holmes, Bialik, and Fadel (2019) emphasized that AI is most effective when used to support deeper learning rather than as a shortcut. Similarly, Al-Zahrani (2024) and Tchounikine (2020) highlighted that AI enhances conceptual understanding when learners engage critically but yields limited benefits with passive use. Locally, Capinding (2023) observed that Filipino students mainly use AI apps like Photomath to verify solutions after independent attempts, while Santos and Cruz (2024) noted a cautious, supplement-oriented approach among Filipino learners. Taken together, these results affirm that students both in the Philippines and internationally tend to use AI responsibly as a scaffold to learning rather than as a crutch for shortcuts. This suggests a growing awareness of AI’s potential as a supportive educational tool, while also underscoring the need for teacher guidance to help students maximize its benefits for critical thinking and problem-solving.

Table 7 presents the effect of the nature of AI tool use on students’ mathematics achievement depending on the nature of AI tools use. Both mean scores fall under the developing level, indicating that students demonstrated only partial mastery of mathematical competencies, particularly in Calculus and Statistics topics such as limits and probability distributions. At this level, students can perform tasks with some guidance but still struggle with consistency, independence, and procedural fluency. While scaffolded AI appears to help students review procedures, explore methods, and verify answers, it does not necessarily ensure deeper understanding or accuracy.

Among the 180 students who used AI as a scaffold, the majority were classified as developing (56) and beginning (85), with only 36 in approaching proficient and 3 in proficient. This distribution suggests that while students attempt to apply concepts, their understanding often remains shallow, as reflected in incomplete solutions and frequent inaccuracies in the achievement test. Some exhibited passive AI use, weakening retention and limiting conceptual clarity. Nevertheless, the small group of proficient students demonstrated the potential of scaffolded AI, showing accurate computations, complete solutions, and strong analytical skills on evidence that AI can serve as a meaningful supplementary tool when used responsibly. By contrast, the 22 students who used AI primarily as a crutch showed lower performance: 10 were at the beginning level, 8 developing, and 4 approaching proficient, with none reaching the proficient category. Many of these students relied on AI for direct answers through tools such as Photomath or GeoGebra, bypassing the problem-solving process. This over-reliance likely explains their weak performance on multi-step problems and frequent conceptual errors.

The computed t-value ($t = 0.570$, $p = 0.569$) indicates no statistically significant difference between scaffolded and crutch-based groups. This suggests that the nature of AI use alone does not significantly affect mathematics achievement. One explanation lies in the specific test topics on limits, probability distributions, and histograms which are cognitively demanding and require deeper conceptual understanding. Even scaffolded use may fall short without consistent practice, teacher feedback, and active engagement.

These findings align with existing literature. Tchounikine (2020) emphasized that AI promotes deeper understanding when used as scaffolding, while Holmes et al. (2019) found that strategic AI use enhances performance through cognitive engagement. However, similar to this study's results, both highlight that AI alone is insufficient without sustained learning efforts. The Digital Education Council (2024) likewise noted that AI access improves opportunities but has no significant effect on achievement without teacher intervention. Locally, Bancoro (2024) also reported no significant relationship between AI usage and academic achievement among Business Administration students. International studies by Nguyen and Duong (2023) and Raza et al. (2023) further support this, showing that while AI offers convenience and reduces workload, academic outcomes improve only when paired with active learning strategies and critical engagement. Overall, the findings reveal that AI tools, whether scaffolded or crutch-based, are not sole determinants of mathematics achievement. Their impact depends on how students are guided to use them. Scaffolded AI offers a more constructive framework, but its benefits must be reinforced through well-designed instruction, active practice, and teacher support. AI tools can serve as valuable allies in mathematics education, but they cannot replace the foundational elements of effective teaching, student effort, and critical thinking.

Table 8 shows the effect of the extent of AI tool use on the mathematics achievement of students. The overall Pearson correlation coefficient of 0.009 with a p-value of 0.895 indicates a very weak positive relationship that is not statistically significant. The results suggest that the frequency of AI tool use does not have a meaningful or consistent connection to mathematics achievement. Students' scores neither reliably increased nor decreased in relation to their AI use, indicating that mere frequency of use is not a determinant of success.

For students using AI tools as a scaffold, the Pearson correlation coefficient was $r = 0.045$ with $p = 0.529$, reflecting a very weak positive but non-significant relationship. This implies a slight tendency for performance to improve with scaffolded use, yet not strong or reliable enough to confirm any real effect. Although scaffolded use aligns with more strategic behaviors such as verifying steps or supporting conceptual understanding, this did not consistently translate into higher achievement scores. Conversely, students who relied on AI tools in a crutch-based manner had $r = -0.036$ with $p = 0.611$, a very weak negative and non-significant relationship. This indicates a slight tendency for performance to decline as crutch-based use increased, but again without statistical confirmation. Thus, while shortcut-based reliance on AI may appear detrimental, it does not alone strongly predict lower performance.

Analysis of achievement test responses provides further nuance. Students reporting scaffolded AI use, typically in the "sometimes" category, often showed greater independence in solving problems and, in some cases, produced complete and accurate solutions. By contrast, crutch-based users more frequently left items blank or made procedural errors, indicating over-reliance and limited conceptual engagement. This reinforces the idea that the quality and purpose of AI use, rather than its frequency, matter most for learning outcomes.

These results are consistent with prior research. Bancoro (2024) likewise found no significant relationship between AI use and academic performance among Business Administration students at Negros Oriental State University (r = 0.0404, p = 0.4916). A meta-analysis by Dong et al. (2025) also reported that AI integration often produces small and statistically insignificant effects on achievement. Similarly, Vieriu and Petrea (2025) observed wide variation in AI's impact, with no consistent academic benefits, while Adewale et al. (2024) concluded that AI adoption in open and distance learning showed mixed outcomes, with some applications aiding achievement and others showing no effect.

Taken together, these findings indicate that AI tools, regardless of frequency of use, are not inherently linked to academic success. Instead, their educational value depends on how purposefully and critically they are integrated into learning. While scaffolded AI use appears to foster more independent engagement, crutch-based reliance may undermine problem-solving confidence. This underscores the need for guided, reflective, and goal-oriented use of AI in mathematics education to maximize meaningful learning outcomes.

Conclusion

Based on the findings of the study, the following conclusions were drawn. First, the scaffolded nature of AI tool use demonstrates that students primarily utilized these technologies to deconstruct complex mathematical problems into simpler concepts and to follow step-by-step processes that facilitate their comprehension of mathematical tasks. This indicates a positive engagement with AI tools as supports for learning rather than as shortcuts. Second, students did not exhibit heavy reliance on AI tools in their mathematics classes; rather, they employed them selectively, particularly when confronted with difficult mathematical concepts. This purposeful use reflects that students sought to verify their answers and strengthen their understanding while still maintaining independent problem-solving skills, thereby avoiding excessive dependence on technology. Third, the study revealed that the nature of AI tool use did not have a direct effect on academic achievement, suggesting that the supportive or task-based use of AI tools does not automatically translate into improved performance in mathematics. Lastly, the extent of AI tool uses likewise did not demonstrate a significant correlation with higher academic achievement, indicating that the quality of students' engagement, critical thinking, and active learning strategies may play a more critical role in influencing mathematics performance than the frequency of AI tool utilization.

Recommendations

Accordingly, anchored on the conclusions drawn, several recommendations are forwarded. First, teachers may intentionally integrate scaffolded AI into mathematics instruction in a manner that complements traditional teaching strategies. This integration should be implemented through carefully designed learning activities that promote conceptual understanding and strengthen problem-solving skills, thereby ensuring that AI is utilized to deepen learning rather than to merely accomplish tasks. Second, schools may consider establishing an AI-assisted

Mathematics Laboratory class, where students can solve mathematical problems with the aid of AI tools. Such a laboratory may be structured to provide a supportive learning environment that enhances mathematics performance, promotes guided and responsible AI use, and fosters the development of critical thinking and independent learning among students.

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Examining the Readiness of Science Teachers for Online Education with a Decision Tree

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Abstract

In this study, the preparedness of science teachers for online education was examined. The research, which used the survey method, involved 306 science teachers working in institutions affiliated with the Ministry of National Education during the 2023-2024 academic year. The "Preparedness for Online Teaching Survey" was used as the data collection tool, and descriptive statistical techniques along with the CHAID algorithm, a decision tree algorithm used for classification analysis, were employed for data analysis. According to the research results, it was found that the participants' competence and attitudes towards technology use in online teaching, as well as their perceptions of online teaching, social connections, and student participation, were positive (at the agree level). It was observed that as the frequency of using video conferencing and EBA (Educational Information Network) increased, the participants' perceptions of online teaching became more positive. Furthermore, the use of teaching methods and techniques such as direct instruction, educational games, question-answer, drama, discussion, and case studies positively affected their perceptions of online teaching.

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Introduction

Science studies natural phenomena encountered in everyday life. Science is not only concerned with numerical data, but also with scientific processes, methods, and skills, and because it covers most events that occur in everyday life, it is a comprehensive field of study that everyone, not just students, needs to understand (Maryanti, et al., 2023). In this age of information, rather than simply imparting scientific knowledge to students, they should be taught the skills to access information. This is achieved by developing students' higher-level scientific skills. Instead of equipping students with rote knowledge, they can be taught mental process skills such as learning through understanding and being able to generate solutions to problems. The importance of a good science education is crucial for students to acquire these skills.

Understanding and being aware of the impact of science and technology on society is part of the definition of scientific literacy (Laugksch, 2000), and scientific literacy is a new requirement for producing knowledgeable and autonomous citizens in post-industrial societies (Correia et al., 2010). According to Norris and Philips (2003), scientific literacy encompasses having knowledge of science, being able to use scientific thinking and problem-solving skills, developing curiosity and appreciation for science, thinking critically, and being able to make informed judgements on science-related issues.

In order to overcome the challenges of the 21st century in the fields of science and technology, students must be equipped with a variety of skills. These skills include digital literacy, creative thinking, effective communication and high productivity. Scientific literacy is an important part of digital literacy and is necessary for individual decision-making, social participation, and economic efficiency. These skills are taught to students through science courses, along with basic and integrated scientific process skills, thereby supporting the development of 21st-century skills (Turiman et al., 2012).

Science education is extremely important for ensuring that students succeed in today's complex and rapidly changing world. Today, countries place great importance on science education in order to remain competitive and stay ahead in the fields of science and technology (DeBoer, 2011). In science education, methods such as laboratory experiments, observation and interaction-based learning play an important role. The pandemic process brought about sudden and necessary changes in education systems, bringing online education to the forefront. This process necessitated pedagogical change, a different type of relationship with students, and a redefinition of teacher-student roles (Paliwal & Singh, 2021). This situation has been an important turning point, especially for science education, which has a strong practical component. During this process, while teachers tried to support students' scientific process skills through digital tools and virtual laboratories, various difficulties were observed in students' participation in class, motivation, and level of understanding of scientific concepts.

With the emergence of emergency and distance learning, the need for digital applications has increased, and it has become necessary to digitally reorganize educational processes to meet the learning needs of the digital age. In particular, in science education, it has become important to develop alternative solutions so that students are not deprived of experiments (Durkaya, 2022). At the same time, the online education process has created an opportunity for science teachers to develop their digital competencies and has highlighted the importance of more effective use of technology in education. The experience gained during the pandemic has led to permanent changes in educational practices, and it is expected that this change will continue in order to prepare for similar situations (Howard et al., 2020).

Online teaching requires technological skills as well as pedagogical approaches that differ from face-to-face teaching in order to support online learning (Gurley, 2018). In online teaching, science teachers are expected to adapt their pedagogical approaches to digital platforms, ensure student participation, support scientific inquiry, and communicate effectively in virtual environments (Olofsson et al., 2019). In this process, teachers should be able to effectively use learning management systems and digital tools to plan, teach, assess, and provide feedback (Haleem et al., 2022; Tondeur et al., 2018). Nguyen and Habók (2024) stated that teachers' digital competence is important in teaching-learning processes, professional development, and supporting students through digital skills, and that teachers should be encouraged to use technology to assess student achievement and improve learning processes.

According to Hasyim and colleagues (2024), the better teachers are prepared for online education, the higher the online learning outcomes of students will be. Teachers' digital skills, technological pedagogical content knowledge (TPACK), online teaching self-efficacy, institutional support, and the ability to use online learning and teaching strategies are the most important factors in the process of preparing for online education (Hasyim et al., 2024; Hung, 2016; Koehler et al., 2014). TPACK, which is particularly important for online learning and advocates for the integration of teachers' pedagogical and technological knowledge, focuses on how online courses are designed and online teaching materials (Archambault and Crippen, 2009). Integrating technology and pedagogy is challenging for instructors with insufficient experience (Brinkley-Etzkorn, 2018).

Factors influencing readiness for online education include positive or negative attitudes, motivation levels, and perceptions of technology's contribution to learning (Mekheimer, 2025; Teo, 2011). Positive attitudes and high motivation increase active participation in the online education process. In addition, institutions must provide the hardware requirements for teaching and learning, internet connectivity, and necessary training. A robust technical infrastructure and continuous support mechanisms enable teachers to feel more secure in the online education process (Ally, 2004; Trust and Whalen, 2020).

Teachers with high readiness plan online lessons that are more effective from a pedagogical and technological perspective, use different teaching materials, increase interaction, and can adapt to students' individual needs (Baran, Correia, & Thompson, 2011; Mishra & Koehler, 2006). Additionally, by using online platforms and digital tools more effectively and creatively, they ensure a seamless flow of lessons and increase the speed of problem-solving in the face of technical issues (Hung, 2016; Tondeur et al., 2018). By improving the quality of student-teacher interaction, they can apply methods such as online discussion, instant feedback, and group work more effectively (Ally, 2004; Martin, Budhrani, & Wang, 2019). This increases students' motivation to participate in class and their learning success (Trust & Whalen, 2020). In unexpected situations such as a pandemic, teachers with high readiness transition to online teaching more quickly and effectively (Rapanta et al., 2020). Research shows that teachers' high level of readiness for online education provides a critical advantage not only in terms of technical skills but also in terms of pedagogical flexibility, student interaction, and the ability to adapt to crisis situations.

In the literature, undergraduate students (Deveci Topal, 2016); classroom teachers (Geniş, 2022), teachers from different disciplines (Hasyim et al., 2024; Howard et al., 2020; Hung, 2016; Trust & Whalen, 2020) and faculty members (Barua & Urme, 2025; Gurley, 2018; Martin et al., 2019; Paliwal & Singh, 2021; Rapanta et al., 2020; Tezcan et al., 2025) regarding their readiness for online teaching. Although the literature has examined the readiness of teachers and teaching staff at different levels for online teaching, studies specific to science teachers are limited.

The lack of studies on the readiness of science teachers for online education is critical, particularly due to the unique requirements arising from the practical and experiment-based nature of science courses. Science education provides opportunities for students to develop their experimental, observational, measurement, and scientific process skills; however, it is challenging to conduct these activities as effectively in online teaching environments as in face-to-face settings (DeCoito & Estaiteyeh, 2022; Fernández-Batanero et al., 2021; Klein, 2021; Pavlou & Zacharia, 2024). The limited availability of virtual laboratories and digital experiment tools can make it difficult to concretise science topics, which can also affect students' motivation and comprehension levels. Therefore, determining the level of readiness of science teachers for online teaching is vital in terms of identifying technical and pedagogical needs and developing effective and practical strategies.

Science teachers working in institutions affiliated with the Ministry of National Education play an important role in emergency and distance education processes. This research was conducted to determine teachers' readiness for online teaching and the factors that influence it, to reveal the current situation, and to identify the shortcomings that need to be addressed before the transition to mandatory distance education in the future, in order to enable teachers to deliver effective and efficient instruction. With the rapid introduction of distance education into educational life, the opinions of science teachers on this subject are of great importance for the effective continuation of education and the improvement of its efficiency (Halder, 2012). These findings will form the basis for the development of more effective online teaching strategies for the future.

The purpose of this study is to determine science teachers' readiness for online teaching and their experiences with distance learning. In this study, the concept of readiness was examined in terms of teachers' technological competence, perceptions of online teaching, student interaction, institutional support, lesson design, and their views and competence regarding the use of technology in assessment and evaluation processes. The study sought answers to the following questions.
What are science teachers'

1. perceptions of the online learning and teaching process?
2. perceptions of the learning and teaching process in online teaching?
3. perceptions of social bonds and student participation in online courses?
4. What variables influence their use of technology and their attitude towards technology?

5. What methods and techniques do they use to monitor assessment and evaluation in online courses?

Studies Conducted in Literature

Various studies have been conducted in the literature on teachers' readiness for online teaching. These studies emphasize the importance of teachers' technical, pedagogical and communicative competencies in the transition to online education. For example, Paliwal and Singh (2021) found that teaching staff's course design, communication, and time management competencies were insufficient to manage online education during the pandemic, but that they were able to adopt online teaching more quickly due to their higher technical competencies. This finding shows that technical skills play a decisive role in adapting to online teaching.

Similarly, Hung (2016) examined the readiness of primary and secondary school teachers for online learning and identified differences based on gender and educational level. The study found that male teachers demonstrated higher readiness in learning-transfer self-efficacy than female teachers, and that master's degree graduates had higher communication and learning-transfer self-efficacy than bachelor's degree graduates. Additionally, it was found that teachers with less experience had higher communication self-efficacy, while teachers with more experience had higher self-directed learning levels. These results indicate that both individual characteristics and experience levels influence readiness for online teaching.

Hasyim and colleagues (2024) focused their study on teachers in urban and suburban areas in Indonesia and examined their readiness levels for online teaching and learning using mind mapping techniques. The research showed that teachers in urban areas had a higher level of online readiness than those in suburban areas, and that this had a positive impact on student achievement. This finding highlights that geographical location and access to resources are important factors in adapting to online teaching.

On the other hand, Howard et al. (2020) examined the readiness of secondary school teachers to transition to online teaching at both the individual (TPACK self-efficacy beliefs and online presence) and institutional (support provided by the institution) levels and identified four different ‘readiness profiles’ using latent profile analysis. These profiles show that teachers have different levels of individual and institutional readiness and emphasize the importance of personalized support strategies that take into account the needs of each group.

Research conducted by Trust and Whalen (2020) during the COVID-19 pandemic revealed significant differences in teachers' readiness to use technology to support remote learning. Teachers who frequently used technology adapted to the process more quickly, while most teachers had to learn online teaching methods and tools during the process. This situation shows that adaptation to online teaching is not limited to technical skills, but also requires pedagogical preparation and experience.

Similarly, Martin, Budhrani, and Wang (2019) examined faculty members' readiness to teach online in terms of their perceptions of the importance of course design, communication, and technical competence, as well as their self-confidence. The study found that faculty members perceived the importance of competencies in course design and communication to be higher than their own abilities, while confidence in their abilities was higher than their perception of importance in time management. Additionally, factors such as gender, duration of online teaching experience, and teaching method were found to have significant effects on both competency perception and self-confidence.

In the context of Turkey, Tekcan et al. (2025) examined the readiness of teaching staff at a state university for online teaching using decision tree analysis. The findings show that teaching staff have high technology usage skills, moderate perceptions of online teaching, and positive perceptions of social connection and student participation. Additionally, increased access to web resources and the ability of those who have used learning management systems in face-to-face education to more easily transfer their skills to online exams have positively influenced their perceptions of online teaching. However, it was found that faculty members with no prior online experience tend to have negative perceptions.

Overall, these studies reveal that the readiness levels of teachers and instructors for online teaching vary depending on factors such as gender, educational level, years of experience, technical competence, institutional support, and geographical location. The findings indicate that technical skills are an important facilitator in the transition to online teaching, but that personalized and continuous support programs are needed to develop pedagogical and communicative competencies.

Method

In this study conducted to determine the readiness of science teachers for distance education, survey model was used and quantitative data were collected. This model examines individuals, groups, institutions, methods and materials to identify, compare, contrast, classify, analyze and interpret the entities and events that constitute different dimensions of the research (Cohen, Manion and Morrison, 2017).

Study Group

The population of the study consists of 306 science teachers working in institutions affiliated to the Ministry of National Education in Istanbul in the 2023-2024 academic year. In the quantitative part of the study, convenience sampling method was used. Convenience sampling is a sampling method preferred especially to speed up the research process and to reach the sampling units more easily. Table 1 shows the demographic information of the teachers who participated in the study.

When the ICT tools used by the teachers for educational purposes were analyzed, it was determined that the teachers who participated in the study used computers (98.4%) and smart phones (94.1%) the most, and smart boards (2.0%) the least. When the purposes of teachers' use of the internet were analyzed, it was seen that the participants used the internet mostly to follow social media (87.9%) and to read news-blocks (85.6%), and the least to play games and have fun (50.3%).

Table 1. Demographic Information of the Science Teachers Participating in the Study

Gender	N	%	Educational Background	N	%
Female	181	40.8	Undergraduate	270	88.2
Male	125	59.2	Master's Degree	34	11.1
Total	306	100	PhD	2	7
Age	**N**	**%**	**Professional Experience**	**N**	**%**
19-24	6	2	1-5 year	32	10.5
25-30	38	12.4	6-10 year	57	18.6
31-36	76	24.8	11-15 year	85	27.8
37-42	110	35.9	16-20 year	63	20.6
43-54	57	18.6	21-25 year	47	15.4
55-65	19	6.2	26 year and above	22	7.2
ICT tools used by science teachers for educational purposes			**Purposes of Science Teachers' Use of the Internet**		
Computer	301	98.4	Receiving/ Giving Training	236	77.1
Smartphone	288	94.1	Playing games - having fun	154	50.3
Video Camera	131	42.8	Reading News-Block	262	85.6
Tablet	179	58.5	To follow social media	269	87.9
Smart Board	6	2.0	Doing research/reading	224	73.2

Data Collection Tools

In this study, 'Online Teaching Readiness Questionnaire' adapted into Turkish by Hoşgörür and Adnan (2018) was used as a data collection tool. The questionnaire was developed by Chi (2015) as a measurement tool to meet the strategic planning needs of the University of Denver Morgridge School of Education. Hoşgörür and Adnan (2018) adapted the questionnaire into Turkish. The questionnaire consists of five separate sections: learning-teaching process, social connection and student engagement, technology support to instructors, course design and instructional design, and measurement and evaluation. In addition to structured questions rated on a 5-point Likert scale (1: strongly disagree to 5: strongly agree), the questionnaire includes open-ended questions; thus, qualitative and quantitative data can be collected together. Hoşgörür and Adnan (2018) found that the Cronbach's Alpha internal consistency coefficient of the questionnaire was 0.91. Developed by Chi (2015), this scale is based on internationally recognized quality standards, incorporates both infrastructure and teacher-learner perspectives, and also assesses institutional expectations.

Data Collection Process

The necessary permissions and ethics committee approval were obtained for the study. Data were collected from teachers who volunteered to participate in the study through Google Forms. Before the application, the participants were informed about how the collected data would be processed, by whom it could be accessed and how it would be protected in terms of the reliability of the research and the protection of the rights of the participants.

Analyzing the Data

Qualitative and quantitative analyses were performed on the data in order to understand the readiness and experiences of science teachers towards distance education in depth and to achieve the aims of the study. The methods used for the analysis of quantitative data include descriptive statistical techniques and CHAID algorithm. Among the descriptive statistical techniques, basic statistical measures such as percentage (%) and frequency (f) were used. CHAID algorithm, a decision tree algorithm used for classification analysis, was used to determine the interactions between categorical independent variables and a dependent variable and to discover and classify the interactions and relationships in the data set. Decision trees can be created using the CHAID algorithm to determine which factors affect the result in the data set, to reveal the complex relationships of factors and to determine the importance ranking of these factors (Breiman, et al. 1984). In decision trees, the root of the tree (Root Node) is located at the beginning of the structure and this root expresses the dependent variable (Milanović & Stamenković, 2016). While the branches in the tree express the values of the relevant attributes, the leaf nodes express the final result of the decisions. SPSS 22 package program was used for the analysis of quantitative data. In the interpretation of arithmetic averages; 1.00-1,79 point range was evaluated as 'strongly disagree', 1.80-2,59 point range as 'disagree', 2.60-3,39 point range as 'slightly agree', 3.40-4,19 point range as 'agree' and 4.20-5 point range as 'strongly agree'.

Findings

In this study, the variables affecting science teachers' use of and attitudes towards technology, their perceptions about online learning, and their perceptions about social connection and student engagement were analyzed. For this purpose, the decision tree algorithm that classifies according to the most important variables affecting the situation was used. With decision trees, the effect of the variables of digital tools used in distance education, teaching techniques used in online teaching, taking courses on online education and the ability to use online applications on the scores obtained from these scales were examined. Mean scores were taken into consideration while evaluating the scales.

The averages obtained from the scales were first analyzed according to the frequency of using digital tools in distance education. These tools are EBA (Education Information Network), accessing web resources, software and applications, taking screenshots, virtual classroom, video conferencing, video camera and/or video processing system, smart board, student response system, projection, computer laboratory, needing help while using EBA and support provided by EBA. In the second stage, scale averages were analyzed according to the frequency of using teaching techniques used in distance education such as lecture, question-answer, discussion, demonstration, cooperative learning, drama, problem solving, case study, educational game. In the third stage, the effect of the variables of taking at least one online course as a student, receiving training on online teaching, creating applications in online teaching and having knowledge about best practices, using electronic quizzes, discussions and chats in lessons, and using EBA in face-to-face lessons on the scale scores were examined.

In line with the first aim of the study, science teachers' competencies and attitudes towards using technology in online teaching process, their perceptions towards online teaching, and their perceptions about social bonding and student engagement were analyzed and the arithmetic mean and standard deviation values of the scales are given in Table 2.

Table 2. Teachers' Perceptions about their Competences in Using Technology in Online Teaching, their Perceptions towards Online Teaching, and their Perceptions about Social Bonding and Student Engagement

Scales	N	$\bar{X}$	SD
Competences and attitudes towards using technology in online teaching	306	4.07	.61
Perception towards online teaching	306	3.69	.68
Perceptions of social bonding and student engagement	306	3.57	.69

In general, it can be stated that teachers' competences and attitudes towards using technology in online teaching, their perceptions about online teaching, and their perceptions about social connection and student engagement are at a good (agree) level.

Learning and Teaching Process in Online Teaching

In the first model, the digital tool variables affecting science teachers' perceptions towards online teaching are shown in Figure 1. According to this model, it is seen that the participants' perceptions towards online teaching are at a good (agree) level.

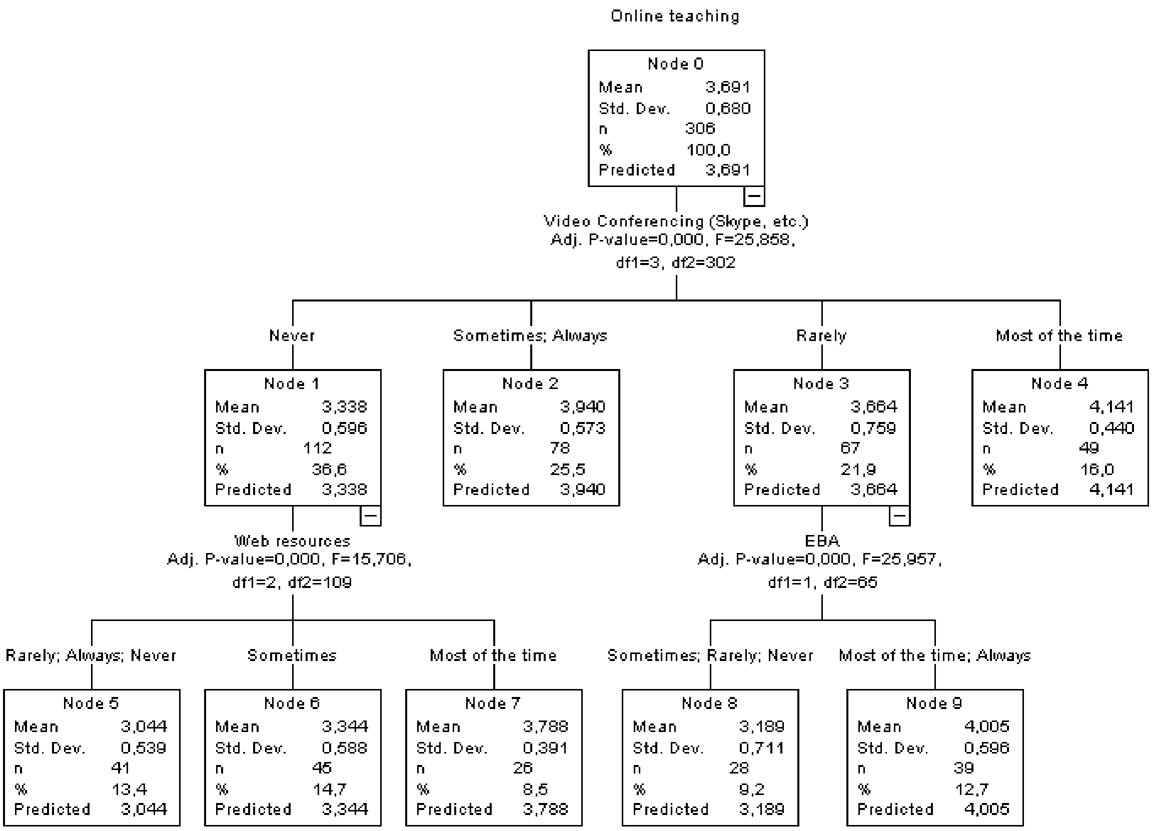

Figure 1. Digital Tool Variables Affecting Science Teachers' Perceptions of Online Teaching (Model 1)

According to Model 1, the most important factor affecting the participants' perceptions towards online learning is the frequency of using video conferencing, and the second factor is the frequency of using web resources and EBA. The most crowded first profile is the group that never uses video conferencing in online teaching processes (Node 1, 36.6%). The perceptions of the teachers in this profile towards online teaching are at a moderate level (slightly agree) and their perceptions towards online teaching become more positive as the frequency of using web resources increases. The second profile under the first main branch (Node 2, 25.5%) is the group that sometimes and always uses video conferences and their perceptions towards online teaching are good. The third profile (Node 3, 21.9%), which rarely uses video conferences, has good perceptions towards online teaching and their perception levels increase as the frequency of using EBA increases. According to this model, as the frequency of using video conferences and EBA increases, the perception towards online teaching becomes more positive. In cases where video conferences are not used, the frequency of using web resources has a positive effect.

In the second model, the effect of the teaching techniques used by the teachers in the distance education process on the perception of online teaching was analyzed (see Figure 2).

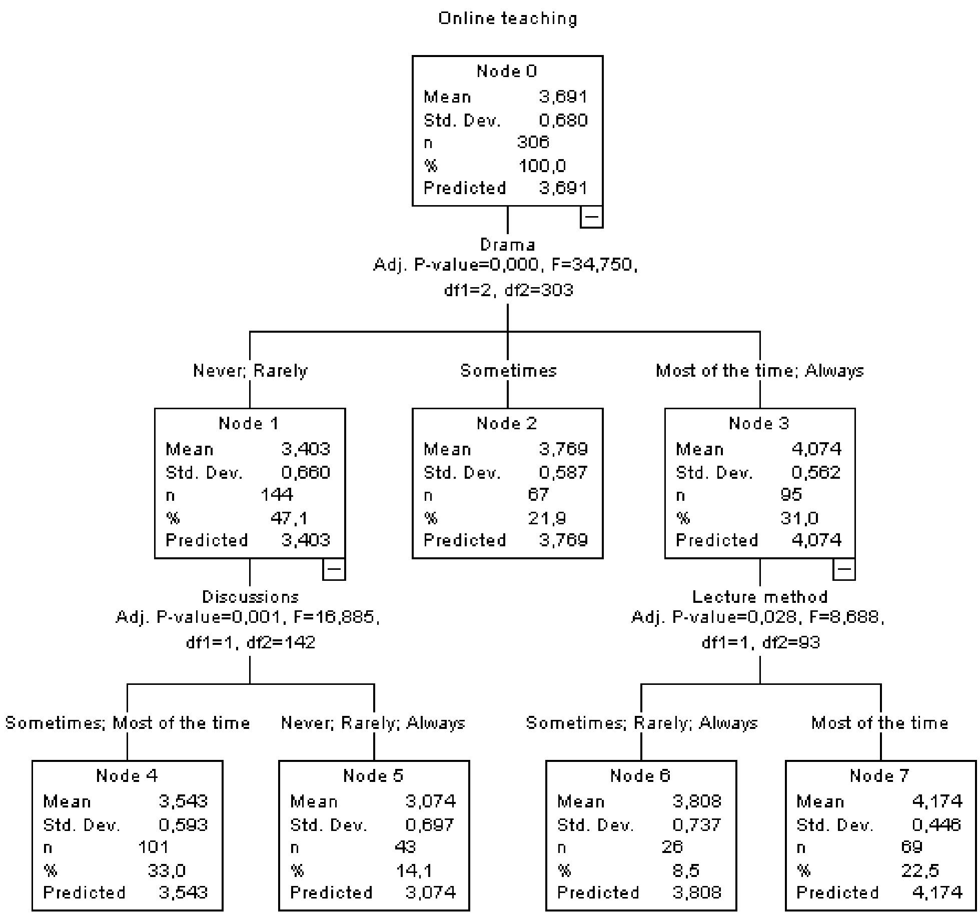

Figure 2. Teaching Techniques Variables Affecting Science Teachers' Perceptions of Online Teaching (Model 2)

According to Model 2, the most important teaching technique affecting teachers' perceptions towards online teaching is drama. It is seen that those who never or rarely use the drama technique are in the majority (Node 1, 47.1%) and their perceptions towards online teaching are at a moderate level. In this profile, those who use the discussion method most of the time and sometimes are in the majority and their perceptions towards online teaching are at a good level, while those who never, rarely or always use it are at a medium level. In the profile where drama technique is usually used (Node 3, 31%), the perception towards online teaching is better and lecture technique is preferred. Those who use the lecture technique most of the time have higher perceptions towards the online teaching process. As the frequency of using drama technique and discussion method increases, the perception towards online teaching becomes more positive.

In Model 3, the variables of taking courses on online education and ability to use online applications that affect teachers' perceptions towards online teaching were analyzed (see Figure 3).

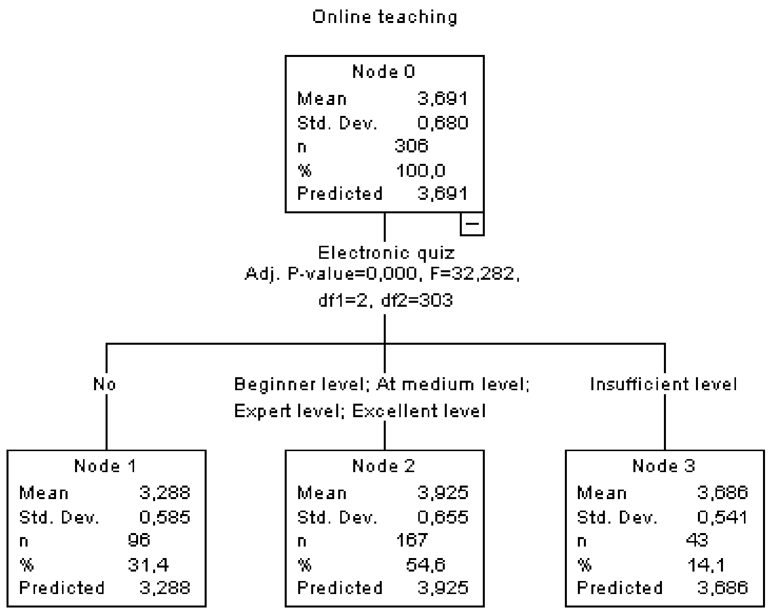

Figure 3. The Variables of Taking Courses on Online Education and Ability to Use Online Applications that Affect Science Teachers' Perceptions towards Online Teaching (Model 3)

According to Model 3, the variable affecting the perception of online teaching is the ability to use electronic quizzes. In this model, as the teachers' ability to use electronic quizzes increases (Node 2, 54.6%), their perceptions of online teaching become more positive.

The frequency and percentage values of science teachers‘ having given online courses before the pandemic, how much of the content can be carried out using online technologies in order for a course to be online in online teaching, and science teachers' willingness to give online courses even if it is not a necessity are given in Table 3. When The table is analyzed, 73.2% of the teachers who participated in the study stated that they did not teach online courses before the pandemic and 70.3% of them stated that for a course to qualify as an online course, it should be conducted using 50% or more online technologies. In addition, 49% of the teachers stated that they would usually consider teaching online, while 5.6% stated that they would never consider teaching online.

Table 3. Frequency Analysis of Teachers' Having Given Online Courses, How Much of the Content of a Course should be Given Online in order for it to Qualify as Online, and their Willingness to Give Online Courses even if it is not a Necessity

Amount of the content			**Willingness to teach online even if it is not an obligation**		
	f	%		*f*	%
Less than 30%	24	7.8	Never	17	5.6
30%-50%	67	21.9	Rarely	52	17
50%-79%	157	51.3	Sometimes	87	28.4
More than 80%	58	19.0	Most of the time	116	37.9
Having taught online courses before the pandemic			Always	34	11.1
Yes	82	26.8			
No	224	73.2	**Total**	306	100

The motivations of science teachers towards online teaching and their views on the EBA platform are given in Table 4. According to this table, it is seen that science teachers' motivation for online teaching in their current work environment is low (slightly agree, $\bar{X}$=3.10). The participants stated that EBA platform is easy to use (agree, $\bar{X}$=3.75) and EBA platform is sufficient in the process of presenting and managing the lessons (agree, $\bar{X}$=3.51).

Table 4. Science Teachers' Motivation towards Online Teaching and their Views on EBA Platform

Online Education and EBA Platform	***N***	**$\bar{X}$**	**SD**
My current work environment motivates me to do online teaching.	306	3.10	1.037
The Educational Information Network (EBA) used in the process of presenting and managing online courses is easy to use.	306	3.75	.871
The Educational Information Network used in the process of presenting and managing online courses is sufficient.	306	3.51	.873

The frequency values of the responses of science teachers regarding the teaching strategies, methods and techniques they used in online courses are given in Figure 4.

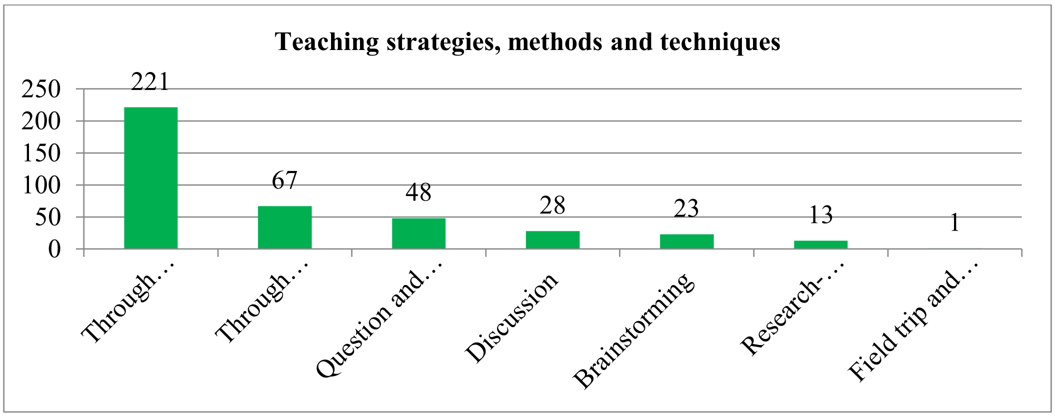

Figure 4. Teaching Strategies, Methods and Techniques used by Science Teachers in Online Courses

Social Bonding and Student Engagement in Online Teaching

The fourth model shows the effect of the digital tools used by teachers on their perceptions of social bonding and student engagement (see Figure 5).

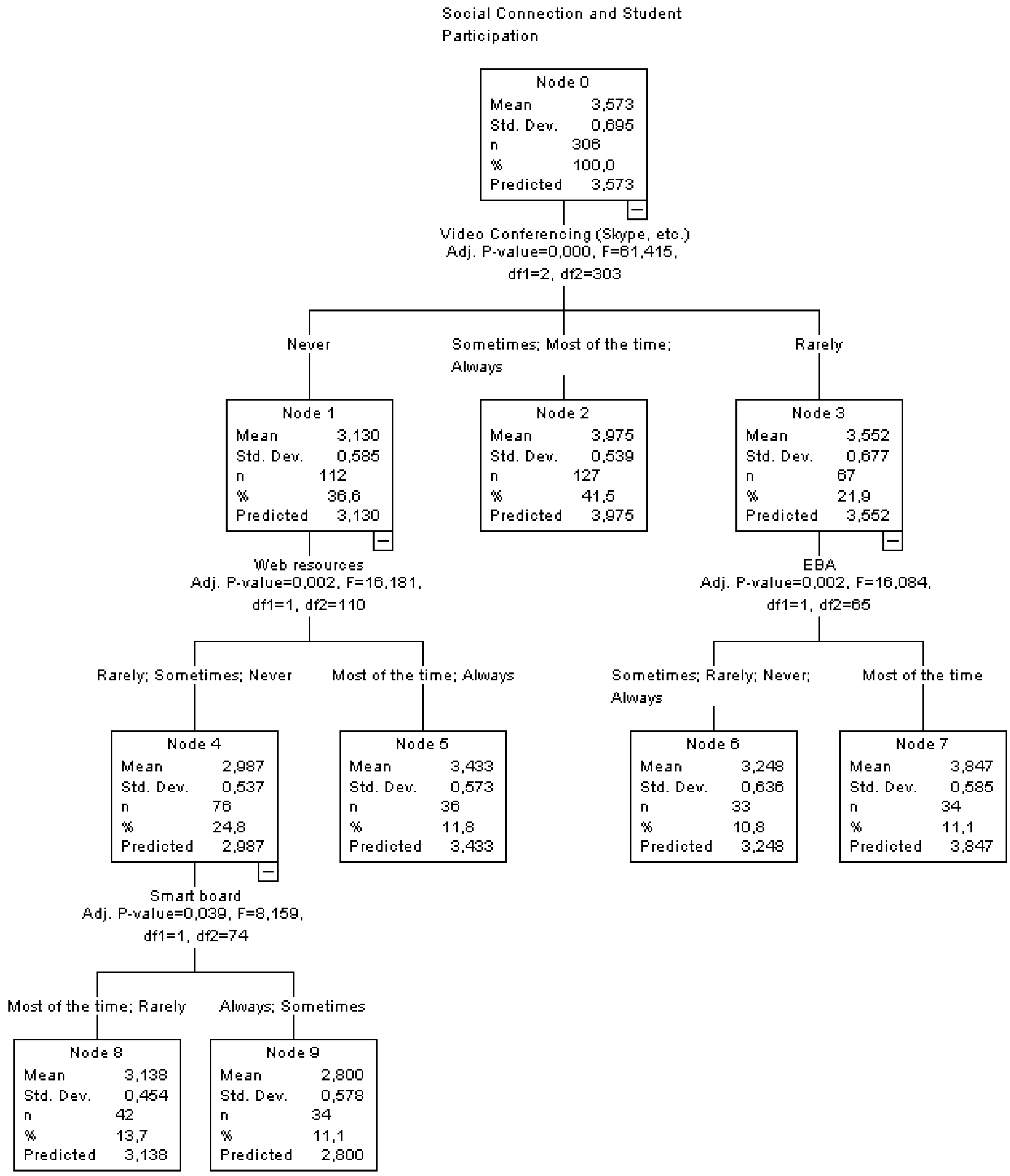

Figure 5. Digital Tool Variables Affecting Science Teachers' Perceptions of Social Connection and Student Engagement (Model 4)

According to this model, the participants' perception of social bonding and student engagement is good (agree, $\bar{X}$=3.57). According to Model 4, the frequency of using video conferences is the most important factor affecting participants' perceptions of social bonding and student engagement. It is seen that the majority of the participants who use video conferences sometimes, most of the time and always (Node 2, 41.5%) and the perception of this profile about social bonding and student engagement is more positive than the perception of the participants in other profiles ($\bar{X}$=3.98). In the profile that never uses video conferences (Node 1, 36.6%), it is seen that they mostly use web resources sometimes, rarely and never (Node 4, 24.8%) and their social bonding-student engagement levels are moderate (slightly agree) and the most important variable affecting this profile is the rate of using smart boards. The frequency of using EBA plays an important role for those who rarely use video conferences (Node 3, 21.9%). The average of those who use EBA most of the time is higher than the other frequency of use. This result shows that as the frequency of using video conferencing, web resources and EBA increases, teachers' perceptions of social bonding and student engagement become more positive.

The fifth model analyzed the effect of the teaching techniques used by teachers in distance education on the perception of social bonding and student engagement (see Figure 6).

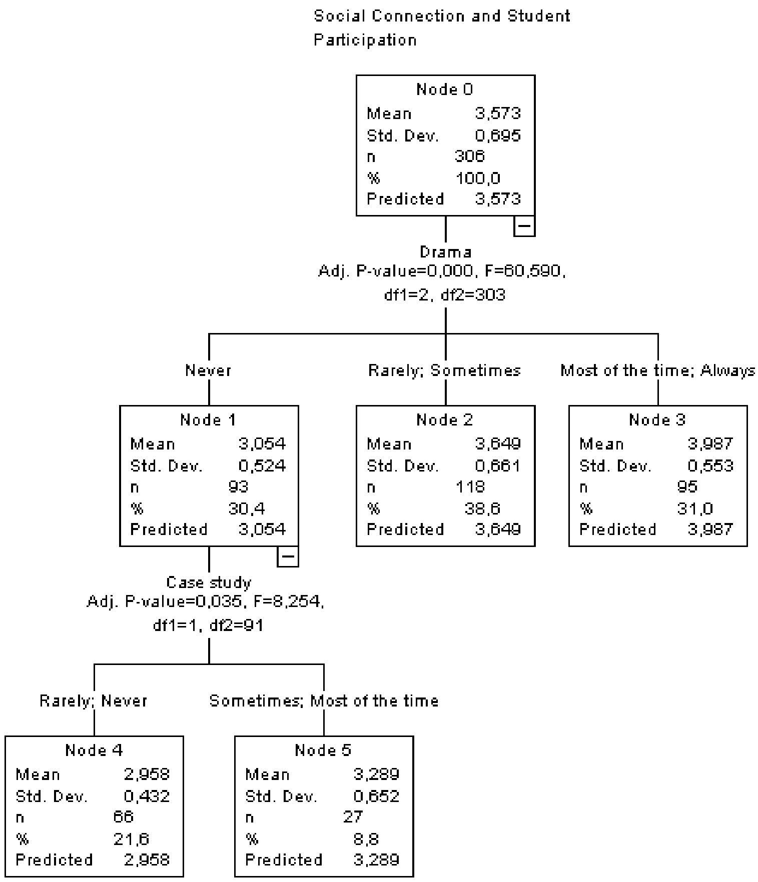

Figure 6. Teaching Techniques Variables Affecting Science Teachers' Perceptions of Social Bonding and Student Engagement (Model 5)

In Model 5, the most important method affecting teachers' perceptions of social bonding and student engagement is drama. In this model, the perception of social bonding and student engagement in the profile of those who never use the drama method (Node 1, 30.4%) is at a moderate level. The perceptions of those in this profile who frequently use the case study method are more positive. The profile of those who use the drama method most of the time and always (Node 3, 31%) has the highest perception of social bonding and student engagement and is interpreted as a good level. Drama method positively affects teachers' perceptions of social bonding and student engagement.

In Model 6, the variables of taking courses on online education and ability to use online applications that affect teachers' perceptions of social bonding and student engagement were analyzed (see Figure 7).

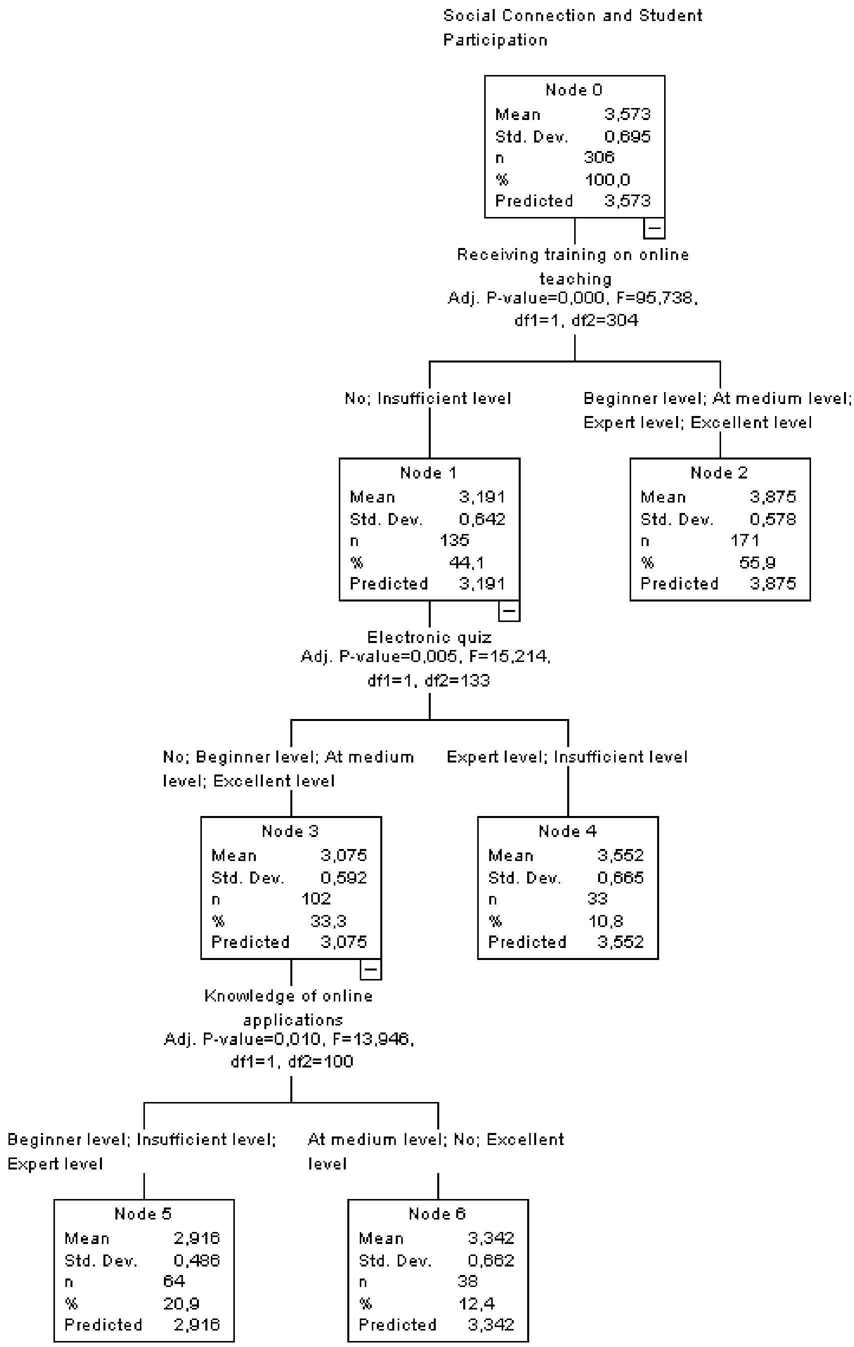

Figure 7. Variables Affecting Science Teachers' Perceptions of Social Bonding and Student Engagement, Taking Courses on Online Education and their Ability to use Online Applications (Model 6)

In Model 6, the most important variable affecting the participants' perceptions of social bonding and student engagement is the level of education about online teaching. In this model, it is seen that teachers who received various levels of training (Node 2, 55.9%) are in the majority and their perceptions of social bonding and student engagement are good. It is seen that the perceptions of those who have received insufficient or no training are at a medium level (Node 1, 44.1%), and the perceptions of those in this profile who have high skills in using electronic quizzes (Node 4, 10.8%) are better and at a higher level than those who do not (Node 3, 33.3%). The profile with low ability to use electronic quizzes is best affected by having knowledge about online applications. Receiving training on online teaching and the ability to use electronic quizzes positively affect the perception of social bonding and student engagement.

Technology Support for Science Teachers in Online Teaching

In the seventh model obtained, the impact of the digital tools used by science teachers, their level of technology usage, and their attitudes towards technology is shown in Figure 8. Accordingly, it can be seen that a large portion of the participants have high levels of technology usage and attitude scores (agree).

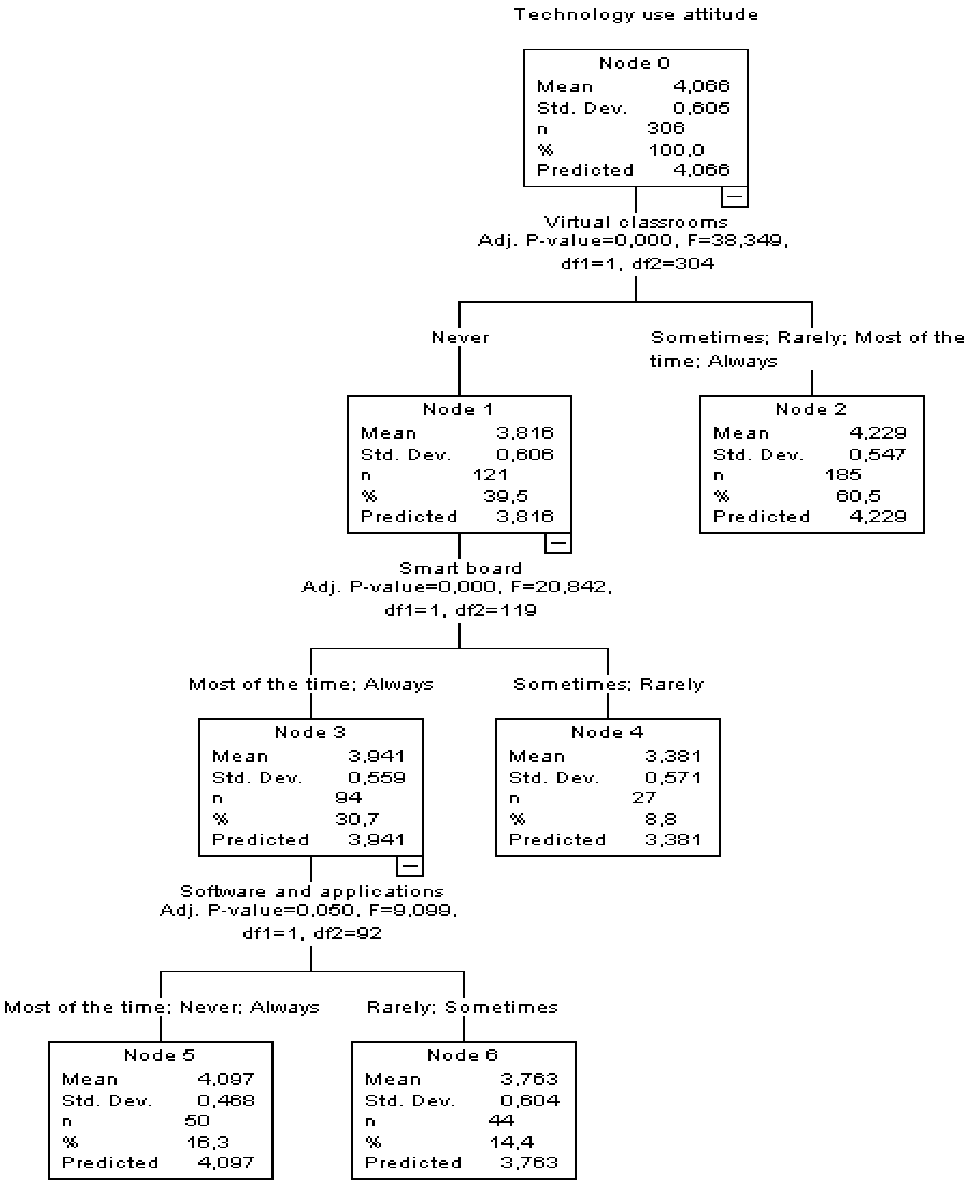

Figure 8. Digital Tool Variables Affecting Science Teachers' Technology Usage and Attitudes Towards Technology (Model 7)

According to Model 7, the frequency of using virtual classrooms is the most significant factor affecting the participants' technology usage and attitudes. The group that never uses virtual classrooms (Node 1, 39.5%) has good technology usage and attitude scores ($\bar{X}$=3.82), while the second and larger group (Node 2, 60.5%) has a very good level of technology usage ($\bar{X}$=4.23). In the group that never uses virtual classrooms, the frequency of using the smartboard is an important variable, whereas in the group that uses virtual classrooms, the frequency of using the EBA platform is significant. Participants in the group that never uses virtual classrooms but frequently uses the smartboard (Node 3, 30.7%) show a close proportion of those who use software and applications rarely or sometimes (Node 8, 14.4%) to those who use them frequently or always (the number of those who never use software and applications is 12, so its impact on this tree is limited and has not been interpreted here). However, as the frequency of using applications increases, the level of positive perception towards technology usage increases. This indicates that as the frequency of using virtual classrooms increases, teachers' technology usage skills and attitudes improve positively. It also shows that those who do not use virtual classrooms prefer using the smartboard more, and as the frequency of using the smartboard with software and applications increases, their technology usage skills improve.

In the eighth model, the impact of the teaching techniques used by teachers in distance education on their perceptions of technology usage skills and attitudes is examined (see Figure 9).

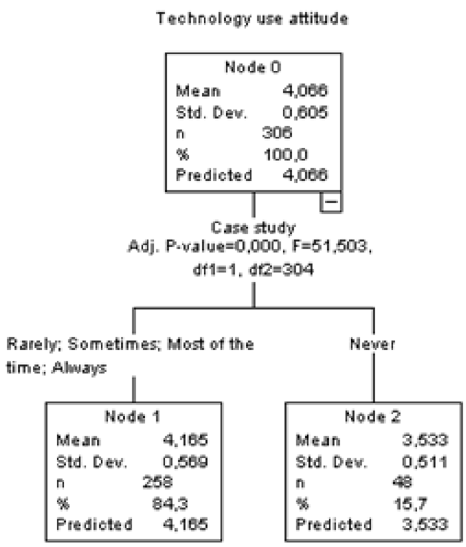

Figure 9. Teaching Technique Variables Affecting Science Teachers' Perceptions of Technology Usage Skills and Attitudes (Model 8)

According to this model, the only teaching method affecting teachers' perceptions of their technology usage skills and attitudes is the case study method. Teachers who use the case study method with varying frequencies have good technology usage skills and attitudes (Node 1, 84.3%), while those who do not use it have an average level of skills and attitudes. Using the case study method positively influences teachers' technological skills and attitudes.

In Model 9, the variables related to taking online courses and the ability to use online applications that affect teachers' technology usage and attitudes are examined (see Figure 10).

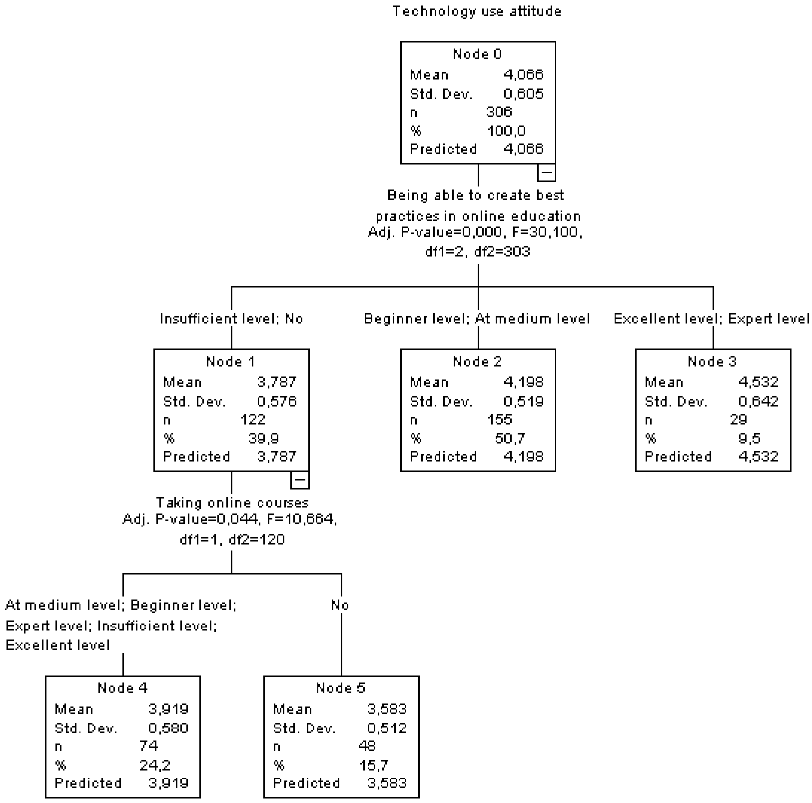

Figure 10. Variables of Taking Online Courses and the Ability to use Online Applications Affecting Science Teachers' Technology Usage and Attitudes towards Technology (Model 9)

According to Model 9, the most significant variable affecting teachers' technology usage and attitudes towards technology is their knowledge of how to create best practices in online education. In this model, those who do not know how to create these practices or have insufficient knowledge (Node 1, 39.9%) have good perceptions of technology usage and attitudes, but these are lower than the other profiles. This profile is also influenced by the status of taking online courses. The proportion of those who have taken online courses at different levels (Node 4, 24.2%) and their perceptions towards technology are higher compared to those who have not taken online courses. The group that is able to create best practices for online teaching at an expert and excellent level (Node 3, 9.5%), despite being the smallest group, has the highest technology usage skills, which are at a very good level. The ability to develop good practices for online teaching and having previously taken an online course enhances the participants' technology usage skills.

Measurement and Evaluation in Online Teaching

The frequency and percentage values of the responses given by science teachers regarding the use of technology in the process of assessing students' learning in online teaching are provided in Table 5. According to this table, 33.3% of science teachers stated that they used technology at a rate of 0-20% in the assessment and evaluation process of their students in online education. A small portion, 2.3%, expressed that they used technology at a rate of 81-100% in this process. Overall, it can be said that technology is used at a low level for measurement and evaluation.

Table 5. Use of Technology in the Process of Measurement and Evaluation in Online Teaching

Ratio	% 0-20	% 21-40	% 41-60	% 61-80	% 81-100	Total
f	102	91	68	38	7	306
%	33.3	29.7	22.2	12.4	2.3	100

The frequency values of the responses given by science teachers regarding the different technologies they use to monitor students' learning status in online teaching are given in Figure 11.

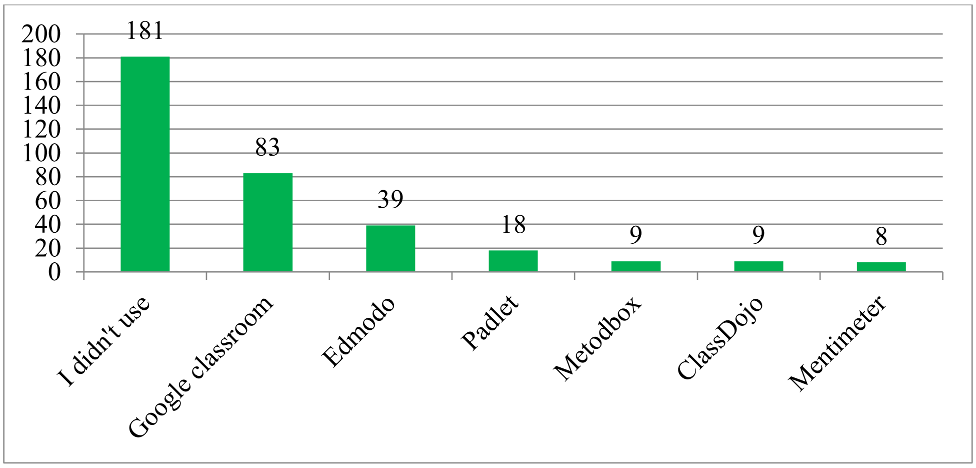

Figure 11. Different Technologies used to Monitor Students' Learning Status in the Online Teaching Process

When the graph in Figure 11 is examined, the majority of science teachers (59.15%) stated that they use technologies determined by the Ministry of National Education (MNE) to monitor students' learning status. 13.39% of teachers stated that they use more than one technological application to monitor students' learning status. The frequency values of the responses given by science teachers regarding the different technologies they use to monitor students' success in online teaching are given in Figure 12.

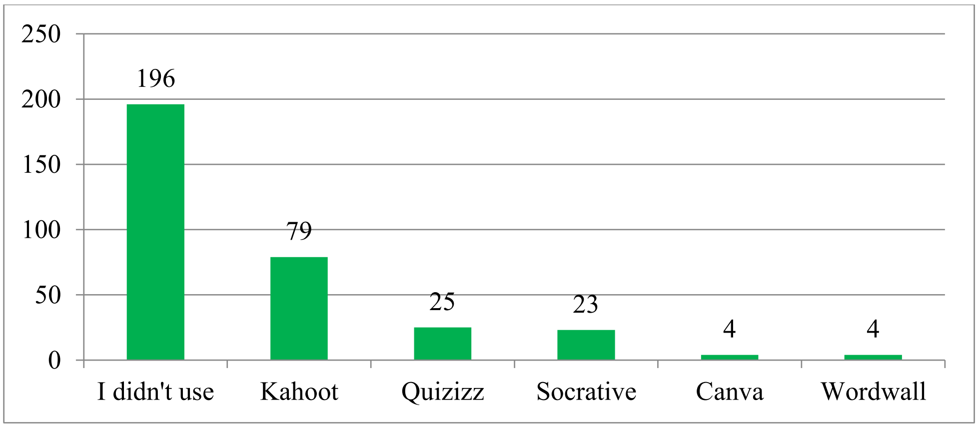

Figure 12. Different Technologies Used to Track Students' Success in Online Teaching Process

When examining the graph in Figure 12, it is observed that the majority of science teachers do not use different programs, and those who do use programs most frequently use tools such as Kahoot, followed by Quizizz and Socrative.

Discussion and Conclusion

The aim of this research was to assess the readiness of science teachers working in institutions affiliated with the Ministry of National Education for online teaching, examine their distance education experiences, and thereby understand the current situation in education. Science teachers' readiness for online teaching was examined under the headings of the teaching-learning process, social bonds and student participation, technology support for teachers, and measurement and evaluation.

Decision tree algorithms were used to understand the readiness of science teachers for distance education, and the variables affecting teachers' technology use, perceptions of online learning, social bonds, and student participation perceptions were investigated. The effects of variables such as technological tools used in distance education, teaching techniques used in online education, skills in taking online classes, and abilities to use online education tools on the scores obtained from the scales were examined.

According to the research results, it is seen that the participants' competencies and attitudes regarding the use of technology in online teaching, along with their perceptions of online teaching, social bonds, and student participation, are favorable (at an agree level). Aldhahi, et al. (2022) also observed a positive relationship between the level of technology use and attitudes toward distance education in their study. Having good competencies and attitudes in using technology in online teaching can enhance the quality of the online teaching process and support student success.

Models 1, 2, and 3 examine the variables affecting teachers' perceptions of online learning, while models 4, 5, and 6 focus on social bonds and student participation, and models 7, 8, and 9 explore digital tools, teaching techniques, and the ability to use online applications that affect technology use and attitudes toward technology. According to Model 1, the frequency of using video conferencing is the most important factor affecting teachers' perceptions of online learning, with the second factor being the frequency of using web resources and EBA (Educational Informatics Network). Teachers who do not use video conferencing at all have moderate perceptions of online teaching, while those who use web resources more frequently have more positive perceptions. As the frequency of using video conferencing and EBA increases, the perception of online teaching improves. Video conferencing systems allow individuals in different geographical locations to communicate simultaneously via audio and video. These systems enable participants to hold interactive meetings with each other (Gillies, 2008). In distance education, they allow students to follow lessons more effectively and make it easier for teachers to interact with students. Therefore, video conferencing systems are considered one of the most effective presentation methods in distance education (Chapman, 1996). In a study by Arkan and Kaya (2018), platforms such as EBA, which provide access to various resources for students and teachers using technology in education, were found to be an essential resource and need. Kuyubaşıoğlu and Kılıç (2019) stated that teachers can easily access information through EBA, facilitating learning, serving as the teacher's new tool, and making lessons more enjoyable.

According to Model 2, the most significant teaching technique affecting teachers' perceptions of online teaching is drama, followed by discussion and direct instruction techniques. As the frequency of using drama and discussion methods increases, the perception of online teaching becomes more positive. Drama and discussion techniques are methods that encourage active student participation and create interactive learning environments (Liyanawatta, et al. 2022). Başaran and colleagues (2020) stated that the use of techniques such as educational games, question-answer, discussion, and case studies, along with direct instruction, positively impacts teachers' perceptions of online teaching.

According to Model 3, as teachers' ability to use electronic quizzes increases, their perceptions of online teaching become more positive. It is crucial for teachers to effectively use technology and adopt online learning processes to succeed in online education environments. Therefore, technology must be viewed as a natural tool in online teaching and learning processes and integrated harmoniously with pedagogical methods (Carrillo and Flores, 2020).

According to Model 4, as the frequency of using video conferencing, web resources, and EBA increases, teachers' perceptions of social bonding and student participation become more positive. Interaction is frequently emphasized in the literature as an extremely important issue in distance education. Researchers like Swan (2002) and Wilson and Stacey (2004) have stated that interaction plays a critical role in the learning process and that ensuring interaction in distance education environments has a positive impact on student success and satisfaction. In their study Fabriz et al. (2021) found that synchronous learning environments increase students' motivation toward lessons, provide opportunities for more effective participation, and allow students to actively engage in the learning process. In our research, when teachers' responses were examined, it was seen that there were also many negative views on this matter. Another study (Ali et al., 2011) found that the lack of face-to-face communication between the instructor and student in distance education leads to some problems, which decreases students' interest in the lessons.

According to Model 5, the most significant teaching technique affecting teachers' perceptions of social bonds and student participation is the drama technique, followed by case study techniques. As the frequency of using drama and case study techniques increases, teachers' perceptions of social bonds and student participation improve. During the distance education process, teachers reported that they could not effectively use student-centered methods and techniques. Approaches such as drama, collaborative learning, and project-based learning were found to be rarely used in distance education (Ayaydın & Küçük, 2022). If teachers can use these methods in online classes, it could allow them to engage more deeply with students, make the learning process more dynamic and engaging, and enable them to observe students' development more closely.

In Model 6, the most significant variable affecting participants' perceptions of social bonds and student participation is whether they have received training related to online teaching. Teachers who have received online teaching training have positive perceptions of social bonds and student participation. Training on online teaching and the ability to use electronic quizzes have positively affected teachers' perceptions of social bonds and student participation. Factors such as teachers' willingness to use technology, their technology skills, and how effectively they can use technology for educational purposes significantly affect students' attitudes toward distance education (Dada, 2006). The use of various materials in online classes and the application of different methods and techniques in the teaching process are essential factors that highlighted the pedagogical value of multimodal instructional strategies in fostering learner engagement in online settings (Trifonova & Kiryakova, 2025).

According to Model 7, it has been observed that as the frequency of using virtual classrooms and the frequency of using software and applications increases, technology use skills develop and positive attitudes emerge. It has been determined that those who do not use virtual classrooms prefer to use smart boards more. Virtual classroom applications offer teachers the ability to manage course content, assign homework, track student progress, and provide feedback more efficiently, allowing for better planning and management of lessons (Daviset al., 2019; Manegre & Sabiri, 2020). Teachers' ability to use digital technology effectively depends on their knowledge, skills, and attitudes toward digital technology. The frequency and manner in which teachers use digital technologies for teaching and learning are also important. For teachers to use digital technology effectively and create learning opportunities for students, they need to view technology not only as a tool for transmitting information but also as interactive learning environments (Sailer et al., 2021).

According to Model 8, using the case study method positively affects teachers' technological skills and attitudes. In distance education, direct instruction can be an effective method for conveying complex topics, but it is essential to use various supportive strategies to capture students' attention and ensure participation. Monroe-Baillargeon's (2002) study revealed that the case study method is an effective tool for teachers' integration with technology. It was concluded that teacher candidates developed their technology knowledge and application skills, making teaching processes more efficient and effective. In another study with teacher candidates, it was determined that the case study method, supported by multimedia, had a positive impact on participants' knowledge of teaching technologies (Kinzer, 2008).

According to Model 9, the most important variable affecting teachers' use of technology and attitudes toward technology is knowing how to create best practices for online education. The ability to develop applications for online teaching and having previously taken an online class has enhanced participants' technological skills. Teachers' use of educational technologies depends on the training, experience, and personal preferences they have in this field. Some teachers can effectively use educational technologies, while others may have limited knowledge or experience. To encourage and support teachers in using educational technologies effectively, it is essential to provide them with the necessary training and resources (Sugar, 2002). Teachers' educational programs should be designed to suit today's technology-focused education environments and include courses to enhance technological literacy. By providing training, teachers can gain the skills to use digital tools effectively.

Before the pandemic, science teachers had limited experience with online education, and the pandemic created a necessity in this field. When teachers were asked if they would teach online if it weren't mandatory, a significant portion of them (most of the time) stated that they would be able to teach online. Despite their hesitation toward online education, only a very small group said they would never want to teach online. In their study, Bojović et al. (2020) stated that distance education will be a part of the lives of teachers and students from now on, and Antoninis et al. (2023) stated that distance education should not replace face-to-face education.

It was observed that teachers' motivation for online teaching in their current work environments is low. Teachers' motivation for online education can be increased by support from the institutions they work for, educational support, and applications and software related to their field. An example of such software and applications in the literature is the Target program developed by Weeldenburg et al. (2024). This program involved teachers as active and reflective participants in their professional development, with the digital application they prepared to support teachers' professional development and increase their motivation, and how this led to changes in all areas of professional development. Bayındır (2021) stated that student-teacher interaction in online environments, the appropriateness of lesson durations, class size, and students' sufficient knowledge and skills in using technology have a significant impact on teachers' motivation.

A large majority of teachers indicated that they did not participate in professional development and certification programs provided by MNE for distance education (online education). In October 2020, MNE launched a project called "Turkey Safe Schooling and Distance Education Project," which emphasized the importance of distance education after the negative experiences during the pandemic. This project highlighted the significance of strong e-learning support, digital content, and pedagogical support.

When examining teachers' responses regarding the measurement and evaluation process in distance education, it was found that the majority did not use a different technological tool for tracking the measurement and evaluation process. Most teachers stated that they made assessments related to the process, such as homework and projects. To make measurement and evaluation methods in distance education more effective and diverse, it is important to increase teachers' technological knowledge and skills. Introducing teachers to Web 2.0 technologies and using them effectively can improve the quality of distance education processes. To enhance the quality of online education, the number of in-service training programs provided by MNE should be increased, where teachers can be informed about which web resources they can use and how to access these resources (Arslan, 2021).

According to the research findings, science teachers' perceptions of distance education are positive, but their knowledge about educational technologies is limited. They reported difficulty applying the teaching methods and techniques they use in face-to-face education in online teaching. This situation creates a negative perception of student participation and motivation toward the lessons. This study can provide guidance on what factors are effective in preparing teachers for distance education and what steps should be taken based on influencing variables.

Recommendations

Based on the results obtained from the research, the following suggestions have been made:

- Teachers can be given distance teaching experience to increase their attitudes toward distance education.

Practical training on technologies, web resources, software, applications, and environments that enhance student-teacher interaction can be organized.

- Training programs can be offered on how to use digital tools and how to create and implement online education activities and evaluations, particularly for science teachers.
- Courses can be provided to teach teachers how to use learning management systems (LMS), online assessment tools, and educational software.
- Teachers can be encouraged to utilize educational applications and tools such as Kahoot, Quizizz, and Socrative for more interactive and engaging online learning environments.
- Teacher motivation for online teaching can be increased by offering online training and professional development programs.
- Research can be conducted to identify existing shortcomings, flaws, and negative opinions in order to increase the diversity and reliability of measurement and evaluation systems in distance education, and the necessary adjustments and improvements can be made to solve the identified problems.
- In order to ensure that the results are generalizable and to obtain more comprehensive results, the research can be repeated in different universes and sample groups, in different provinces or regions.

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A Unified Model for Innovation and Technology in Education: A Framework for Teachers' Adoption of AI Tools in Teaching

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Abstract

In today's technologically advanced classrooms, artificial intelligence (AI) offers promises of enhanced teaching and personalized learning. Yet integrating AI tools into teaching hinges on teachers' willingness and ability to adopt these innovations. This study develops and validates the Unified Theory of Innovation and Technology in Education (UNITED) model an integrated framework grounded in the Unified Theory of Acceptance and Use of Technology (UTAUT) and related theories to explain secondary school teachers' behavioral intent and actual use of AI tools. A descriptive-causal design with structural equation modeling (SEM) was employed, involving 428 secondary teachers in Northern Mindanao, Philippines. Results confirmed an excellent-fitting model explaining teachers' AI adoption. Perceived usefulness of AI and social influence emerged as significant positive predictors of teachers' intention to adopt AI tools, while perceived ease of use showed no direct effect on intention. Facilitating conditions (infrastructure and support) proved critical for translating intention into actual AI use in the classroom. The final UNITED model unifies multiple technology acceptance constructs, offering both theoretical and practical insights. We recommend targeted professional development to boost teachers' AI competencies and improved institutional support to foster effective AI integration in education.

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Introduction

Artificial Intelligence (AI) is rapidly transforming educational practices, reshaping how teachers deliver instruction and how students learn. AI-driven tools can automate routine tasks, personalize learning experiences, and augment teachers' capabilities in the classroom. AI-powered tutoring systems and content generators can instantly support learning and cognitive tasks, enabling more individualized and efficient instruction. To harness these benefits, teachers must become adaptive facilitators who skillfully integrate AI into their pedagogy. However, despite increasing availability of AI tools, many educators remain hesitant to adopt them due to unfamiliarity and uncertainty about their value (Abdullah & Fraidan, 2024; Banerjee, 2024). This gap between promise and practice raises a critical question: What factors influence teachers' adoption of AI tools in teaching?

Globally, educational systems recognize that integrating AI can facilitate personalized learning and improve outcomes (Eden et al., 2024). In the Philippines, initiatives to leverage AI in classrooms are gaining momentum despite infrastructural challenges like intermittent connectivity. Teacher readiness and willingness to adopt AI are pivotal to these efforts (Venkatesh, 2022). Prior studies suggest that teachers' adoption decisions depend on their perceptions of AI's usefulness and the availability of institutional support (Solak, 2024). In other words, if teachers see clear benefits to instruction and have adequate technical support, they are more likely to embrace AI tools.

Over past decades, researchers have developed multiple theoretical models to explain technology adoption in educational settings, including the Technology Acceptance Model (TAM), the Unified Theory of Acceptance and Use of Technology (UTAUT), and the Theory of Planned Behavior (TPB). Each provides valuable insight into the determinants of users' behavioral intentions to adopt technology. TAM posits that an individual's intention to use a technology is driven by its perceived usefulness (the extent to which it enhances job performance) and perceived ease of use (the effort required to use it) (Davis, 1989). UTAUT extends this by adding factors like social influence (pressure from others) and facilitating conditions (available support/resources), which have been shown to affect technology use in organizational contexts (Venkatesh et al., 2003). TPB further emphasizes the roles of attitudes, subjective norms, and perceived behavioral control in shaping behavioral intentions (Ajzen, 1991). These models have been applied to educational technology adoption, but often in isolation. There remains a knowledge gap in how these key theories can be comprehensively integrated into a unified framework to explain teachers' adoption of AI tools.

To address this gap, the present study developed the Unified Theory of Innovation and Technology in Education (UNITED) model, a synthesized framework that integrates core constructs from TAM, UTAUT, TPB, and related models in order to holistically explain secondary school teachers' adoption of AI tools. The UNITED model incorporates Perceived Usefulness (PU) and Perceived Ease of Use (PEOU) from TAM (Davis, 1989; (Venkatesh & Davis, 2000; Solak, 2024), Social Influence (SI) and Facilitating Conditions (FC) from UTAUT (Venkatesh et al., 2003; (Yessenova et al., 2023), with Behavioral Intention (BI) mediating their effects on Actual Use (AU). Grounded in TPB (Ajzen, 1991) and the Theory of Reasoned Action (Fishbein & Ajzen, 1975), the model assumes that a strong intention to use AI will translate into actual classroom implementation of AI tools. It also acknowledges contextual factors: teachers' personal and professional profiles (e.g. experience, training) may condition their perceptions and adoption behaviors (Mishra & Koehler, 2006; Magat & Sangalang, 2024).

By empirically testing this unified model, the goal is to identify the critical factors and pathways that drive or impede AI adoption among teachers. Such insights are both theoretically and practically significant. A unified model can advance theory by reconciling overlapping constructs, the like of TAM's usefulness and UTAUT's performance expectancy and revealing how external conditions and personal beliefs jointly influence adoption. Practically, understanding these factors can help educational leaders design more effective interventions such as professional development programs to improve teachers' perceived ease of using AI, or policies to strengthen infrastructure and technical support (facilitating conditions) that enable actual AI usage.

In this paper, we present the results of a study that surveyed 428 secondary school teachers about their perceptions and usage of AI tools. We use structural equation modeling to validate the hypothesized UNITED model. The key research questions addressed include: (1) What are the demographic and professional profiles of teachers currently engaging with AI tools? (2) How well does the initial hypothesized model fit the data, and what modifications are needed to improve it? (3) Which factors significantly predict teachers' behavioral intention to adopt AI and their actual use of AI in teaching, according to the final validated model? We also discuss how the findings align with or diverge from prior research, and propose recommendations to support successful AI integration in education. By unifying multiple frameworks, this study aims to provide a comprehensive yet practical model to guide and explain teachers' adoption of AI tools in teaching, thereby contributing to the scholarship and practice of educational technology integration

Method

Research Design and Participants

We employed a descriptive-correlational research design with a causal modeling approach to examine the determinants of teachers' AI adoption. Specifically, we used covariance-based Structural Equation Modeling (SEM) to test the relationships in the UNITED conceptual model. The target population was secondary school teachers in one of the Divisions in the Department of Education in Northern Mindanao, Philippines. Using stratified random sampling, we selected a sample of n = 428 teachers from various public secondary schools in this division. Stratification ensured representation across different schools and districts.

The profile of respondents reflects typical demographics of public high school teachers in the region. About 69.6% of the respondents were female and 30.4% male, consistent with the predominance of women in the teaching profession. The teachers' ages ranged from early 20s to mid-60s, with the largest age groups being 26–35 years (33.2%) and 36–45 years (29.7%). A small fraction (1.4%) were under 25, while about 12% were over 55, indicating that most participants were young to mid-career educators. In terms of teaching experience, over half (58.2%) had 1–10 years of service, 22.0% had 11–20 years, and roughly 19.9% had more than 20 years in service. The majority held the rank of Teacher I (43.5%), with others being Teacher II (18.5%), Teacher III (29.7%), and a small percentage (≈8%) in Master Teacher I/II positions. These characteristics suggest our sample includes a diverse mix of early-career and veteran teachers, though relatively few in administrative or senior teaching roles.

Importantly, participants varied in their familiarity with AI tools. Exactly half (50.0%) described themselves as “familiar” with AI applications in education, and an additional 22.7% considered themselves “very familiar”. Meanwhile, about 26.4% were only “somewhat familiar” and a negligible proportion (<1%) reported being not familiar with AI tools. This range of familiarity levels provides a meaningful context to examine how perceptions of ease and usefulness of AI might form among teachers with different exposures.

All participants voluntarily responded to an online survey administered in early 2025. Prior to data collection, necessary permissions were obtained from school authorities, and informed consent was secured from teachers. Respondents were assured of anonymity and that their responses would be used for research purposes only.

Instrumentation and Measures

Data were gathered using a structured questionnaire composed of two main parts: (1) items on teacher profile and AI usage, and (2) scales measuring the latent constructs in the UNITED model. The first part asked for demographic information (gender, age, years of service, job designation) and assessed the respondents’ technology background including their self-reported familiarity with AI tools and which types of AI applications they have used in the classroom (e.g. chatbots, intelligent tutoring systems, AI-based grading tools, etc.).

The second part comprised Likert-scale items representing each construct in the model: Perceived Usefulness (PU), Perceived Ease of Use (PEOU), Social Influence (SI), Facilitating Conditions (FC), Behavioral Intention (BI), and Actual Use (AU) of AI tools. Wherever possible, we adapted established survey instruments from prior research to ensure content validity. Specifically, many items were drawn and modified from the following sources: the UTAUT instrument by Venkatesh et al. (2003) for social influence and facilitating conditions, the original TAM scales by Davis (1989) for perceived usefulness and ease of use, and Ajzen’s (1991) TPB-related measures for intention (also informed by technology adoption studies). Additional items were devised for actual AI use, capturing frequency and ways AI tools are integrated in teaching. All items were phrased to fit the context of K–12 teaching with AI. For example, a sample item for Perceived Usefulness is “*Using AI tools in my teaching enhances my instructional effectiveness*,” and for Social Influence: “*My colleagues and school leaders encourage me to use AI tools in teaching.*” Respondents rated each statement on a 5-point Likert scale (1 = *Strongly Disagree* to 5 = *Strongly Agree*).

Content validity of the instrument was established via expert review. Three experts in educational technology examined the items to ensure they were relevant and clear for measuring the intended constructs in an AI education context. Minor wording revisions were made based on their feedback. A pilot test with 30 teachers was also conducted to check the survey’s clarity and reliability before full deployment; pilot responses indicated good internal consistency across the scales (Cronbach’s α values > 0.80 for all constructs).

Procedure and Data Analysis

The online survey was distributed through official school email lists and messaging platforms, and data collection spanned approximately four weeks. Participation was voluntary, and teachers could complete the survey at their convenience. In more than 500 surveys distributed, 428 were completed and valid for analysis (yielding a satisfactory response rate for SEM requirements). We examined the dataset for missing values and outliers; only minimal random missing responses were found, which were handled by mean imputation. Screening for multivariate normality indicated significant skew/kurtosis (Mardia's tests, $p < .001$), so we opted for robust estimation in the SEM analysis to account for non-normality (Hair et al., 2019; Kline, 2016). Specifically, we employed the Diagonally Weighted Least Squares (DWLS) estimator, which is appropriate for ordinal Likert data and handles non-normal distributions effectively.

Data analysis proceeded in two major phases using JAMOVI 2.3.28 and JASP SEM modules. In the measurement model phase, we conducted confirmatory factor analysis (CFA) to evaluate the reliability and validity of the constructs. We calculated Cronbach's α and McDonald's ω for internal consistency, and Composite Reliability (CR) as another measure of construct reliability. Convergent validity was assessed through the Average Variance Extracted (AVE) for each construct, and discriminant validity was examined using the Heterotrait-Monotrait (HTMT) ratio between constructs. Table 1 summarizes the reliability and convergent validity results. All constructs exceeded the recommended thresholds of $\alpha \geq .70$ and $CR \geq .70$, demonstrating excellent internal consistency (Hair et al., 2019). The AVE values ranged from .638 (for Social Influence) to .781 (for Perceived Ease of Use), all well above the .50 criterion (Fornell & Larcker, 1981), indicating strong convergent validity. As shown, Perceived Usefulness had $\alpha = .939$ and $AVE = .740$, and Behavioral Intention had $\alpha = .983$ and $AVE = .722$. These statistics suggest that each set of survey items reliably measures a single underlying construct and captures a substantial portion of that construct's variance (Fornell & Larcker, 1981; Hair et al., 2019).

Table 1. Reliability and Convergent Validity of Constructs

Construct	Cronbach's α	McDonald's ω	CR	AVE
Perceived Usefulness (PU)	.939	.947	.948	.781
Perceived Ease of Use (PEOU)	.983	.940	.916	.722
Social Influence (SI)	.954	.954	.925	.774
Facilitating Conditions (FC)	.898	.897	.868	.638
Behavioral Intention (BI)	.939	.934	.906	.740
Actual Use (AU)	.926	.926	.906	.759

Moreover, HTMT ratios (see Table 2) between constructs were all below the conservative .85 cut-off (Henseler et al., 2015), except the PU–PEOU pair which was .892, slightly above .85 but still below .90 (Kline, 2016; Hair et al., 2019). This minor high correlation is theoretically acceptable given the known linkage between ease of use and perceived usefulness in TAM. Overall, we concluded the measurement model was sound, justifying use of these latent constructs in the structural model analysis.

In the structural model phase, we specified the hypothesized paths among the latent constructs as per the UNITED model: PU, PEOU, SI, and FC all served as exogenous predictors of Behavioral Intention (BI), and BI in turn was posited to predict Actual Use (AU). We also included direct paths from PU and FC to AU, anticipating that perceived usefulness and adequate support might independently facilitate some AI usage, consistent with TAM and UTAUT literature (Venkatesh et al., 2003; Hazzan-Bishara et al., 2025). The structural model was first tested in its initial form. We evaluated model fit using multiple indices such as Chi-square (χ^2), Comparative Fit Index (CFI), Tucker-Lewis Index (TLI), Incremental Fit Index (IFI), Root Mean Square Error of Approximation (RMSEA), and Standardized Root Mean Square Residual (SRMR). Because χ^2 is sensitive to large sample sizes, greater emphasis was placed on the other fit indices and their recommended cut-offs (CFI, TLI, IFI ≥ 0.90 for acceptable fit; RMSEA ≤ 0.08; SRMR ≤ 0.08) (Hair et al., 2019; Kline, 2016).

Table 2. Heterotrait-Monotrait (HTMT) Ratio Correlations of Latent Variables

Latent Variables	PEU	BI	AU	SI	PU
Perceived Ease of Use (PEU)					
Behavioral Intention (BI)	.724				
Actual Usage (AU)	.712	.754			
Social Influence (SI)	.740	.590	.745		
Perceived Usefulness (PU)	.892	.783	.673	.628	
Facilitating Conditions (FC)	.499	.366	.560	.661	.415

The initial model (see Figure 1) demonstrated mixed fit.

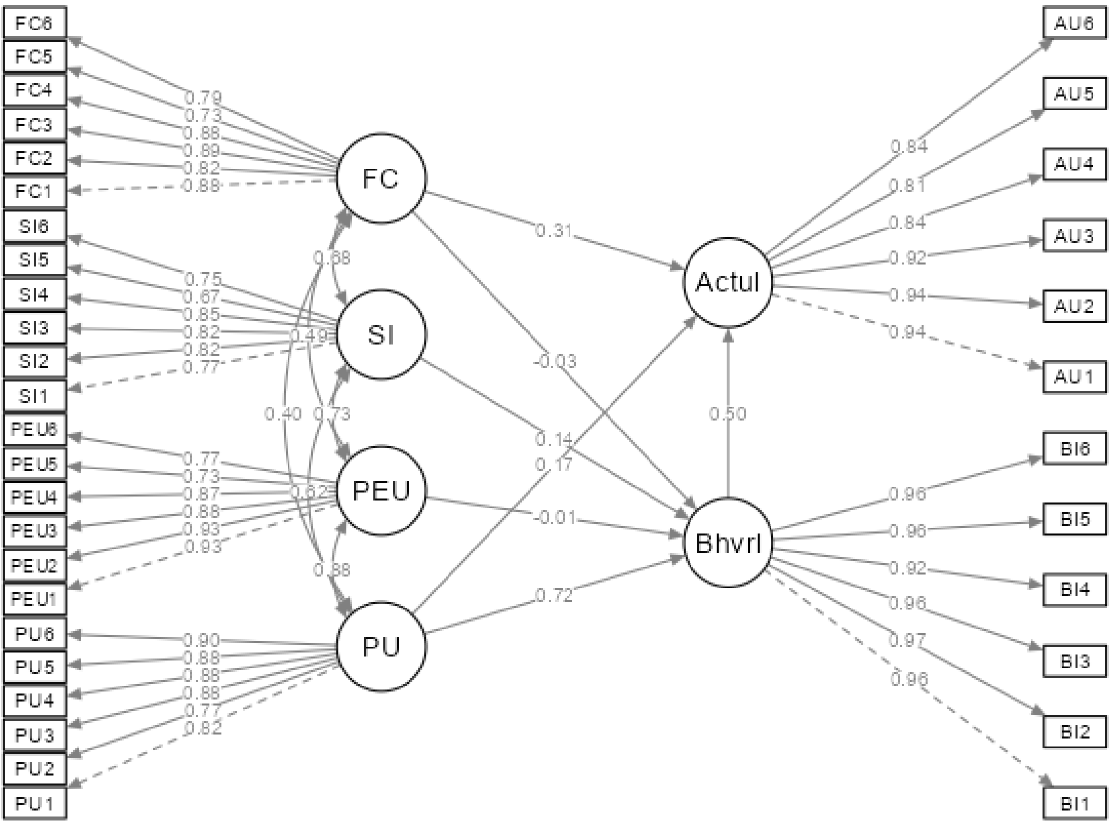

Figure 1. The Hypothesized (Initial) Structural Equation Model

On one hand, incremental fit indices were good: CFI = .998 and SRMR = .062 met the criteria, indicating the model explained a large portion of the variance and residuals were low. However, some absolute fit indices fell short: RMSEA was .115, above the .08 threshold, and TLI = .824 and IFI = .838 were below .90. The Goodness-of-Fit Index (GFI = .851) and Adjusted GFI (.820) also suggested only mediocre fit. These results implied that while the overall model structure captured the data well in relative terms, there were areas of misspecification that needed improvement. We examined modification indices and the significance of paths to guide model respecification. As detailed in the Results section, a few modifications were made specifically, removing a non-significant path and adding theoretically justified links to arrive at a refined final model with substantially improved fit. All statistical analyses were conducted using two-tailed tests with a significance level of $p < .05$ for path coefficients. The next section presents the findings in detail, including descriptive results for teachers' AI usage, the SEM path analysis outcomes, and the final validated model structure.

Results

Teachers' Use of AI Tools and Profile Summary

Before examining the SEM results, we present a summary of teachers' current AI tool usage and familiarity, as this context informs interpretation of the model. Overall, the survey revealed moderate to high engagement with certain AI applications among the teachers. A large majority reported that they had used AI chatbots (77% of respondents) or image generators (73%) in their teaching or preparation (Chiu et al., 2022). These were the most commonly utilized AI tools, likely reflecting the popularity of generative AI like ChatGPT and image creation tools for educational content. Over half (56%) had used a virtual learning platform with AI features, and about one in five had tried adaptive learning systems (23%) or automated grading tools (21%) (Chounta et al., 2022). Uses of AI for lesson planning and virtual assistance were also reported (around 35–37%). However, more advanced or specialized AI applications were less widespread, for instance, only 11% had used AI-based assessment generators, and about 15% had experience with intelligent tutoring systems for students. The least utilized were automated feedback tools for teaching (just 4% had used them). These figures suggest that teachers primarily use AI for content generation, information retrieval, and routine tasks, whereas adoption of AI for assessment and feedback is still nascent.

Reflecting on these findings, teachers predominantly leverage AI to assist with lesson content creation, presentations, and student engagement, while AI for grading or personalized tutoring is not yet common (Policar, 2025). This may be due to limited awareness or confidence in those advanced functions, as well as concerns about reliability. Notably, half of the respondents considered themselves at least "familiar" with AI tools, indicating a decent baseline of exposure. The variety in familiarity (from not familiar to very familiar) underscores the need for differentiated support – some teachers may require fundamental training on AI tools, whereas others are ready to integrate them more fully.

In terms of gender differences in adoption, the sample had more women using AI simply because more women are employed as teachers, a pattern in many countries' education workforce (Alissa & Hamadneh, 2023). However, it is interesting that our data contradicts some earlier findings which suggested male teachers tend to adopt new technologies at higher rates than females (Ofosu-Ampong, 2023; Møgelvang et al., 2024). In the context of this study, female teachers not only outnumbered males but also showed comparable if not greater willingness to use AI tools, aligning with at least one recent study in the Middle East that found female teachers reported a higher level of AI usage than their male counterparts (Alissa & Hamadneh, 2023; Otis et al., 2025). This could be attributed to the supportive school environment or targeted training that empowered many female teachers in our sample to experiment with AI in teaching. It also suggests that gender is not a barrier in this community; when given opportunity and support, teachers of all demographics engage with AI.

Overall, the profile analysis establishes that our participants are fairly representative of in-service secondary teachers, with a skew toward younger, early-career individuals who are building familiarity with AI. There is a strong interest and positive disposition toward AI (as evidenced by many indicating "*Agree*" on intention to continue using AI, with an average BI rating around 4.0 or "*high intention*"). At the same time, there are varied levels of actual integration such as AI tools are used "*whenever helpful*" by many teachers, but not yet embedded in all daily practices. These findings set the stage for understanding which factors most influence the teachers' decision to adopt AI and to what extent that intention leads to sustained usage.

Measurement Model Results

The confirmatory factor analysis affirmed that the survey indicators loaded well on their intended constructs. All item loadings were statistically significant ($p < .001$) and most were quite high with standardized loadings within .761 to .957 range for each factor (UCLA, 2021; Kline, 2016). For instance, the six observed items for Perceived Usefulness had loadings from .792 to .901, indicating each item (e.g. AI tools improve student learning outcomes, AI makes teaching easier) strongly reflected the underlying usefulness construct (see Table 3).

Table 1 presented earlier shows that each latent construct achieved excellent reliability. As reflected, almost all Cronbach's α values were all greater than .90 except for Social Influence (α = .898), with Behavioral Intention reaching α = .983 which suggests some redundancy, though ω also supported its reliability. Composite Reliability (CR) values ranged .868 to .948 all above the 0.70 threshold (Hair et al., 2019). The Average Variance Extracted (AVE) for each construct exceeded .63, confirming that on average more than 63% of the variance in item responses is explained by the construct, satisfying convergent validity (Fornell & Larcker, 1981). We also checked discriminant validity using the HTMT ratio, none of the inter-construct HTMT values surpassed the 0.90 upper bound (Henseler et al., 2015; Hair et al., 2019).

The highest HTMT was between Perceived Ease of Use and Perceived Usefulness (HTMT = .892), which is expected since TAM theory posits these are related constructs which suggests that easier-to-use technology tends to be perceived as more useful (Luo et al., 2024; Lee et al., 2025). This value is marginally above a strict .85 criterion but below .90, so we judged it acceptable given strong theoretical justification for their correlation. All other construct pairs had HTMT well below .85 (e.g. Ease of Use vs. Social Influence = .74; Intention vs. Actual Use = .75; Facilitating Conditions vs. others < .66), indicating good discriminant separation (Henseler et al., 2015; Roemer et al., 2021).

Table 3 Descriptive Statistics and Factor Loadings of Observed Variables

Latent	Observed	Mean	SD	Factor Loading	
				Initial	*Final*
Perceived Usefulness	PU1	3.95	.88	.816	.827
	PU2	3.79	.97	.769	.851
	PU3	4.13	1.00	.880	.901
	PU4	3.90	.95	.882	.862
	PU5	3.96	1.05	.877	.855
	PU6	4.00	.97	.901	.792
Perceived Ease of Use	PEU1	3.80	1.01	.926	.957
	PEU2	3.80	1.00	.930	.930
	PEU3	3.85	1.00	.877	.872
	PEU4	3.74	1.05	.869	.879
	PEU5	3.55	1.17	.730	-
	PEU6	3.66	1.11	.768	.792
Social Influence	SI1	3.53	.98	.767	.810
	SI2	3.37	.98	.819	.761
	SI3	3.44	1.00	.819	.882
	SI4	3.62	.97	.854	.846
	SI5	3.23	1.14	.667	-
	SI6	3.42	.94	.749	.666
Facilitating Conditions	FC1	2.99	1.07	.876	.875
	FC2	3.20	1.12	.820	.848
	FC3	3.27	1.03	.891	.879
	FC4	3.07	1.09	.879	.884
	FC5	2.70	1.19	.732	-
	FC6	2.85	1.20	.790	-
Behavioral Intention	BI1	4.05	.96	.962	.832
	BI2	4.08	.97	.965	.846
	BI3	4.04	.93	.963	.863
	BI4	3.88	1.06	.916	.844
	BI5	3.99	.98	.959	.864
	BI6	3.99	.97	.956	.851
Actual Usage	AU1	3.52	.96	.936	.923
	AU2	3.55	.98	.944	.915
	AU3	3.40	1.04	.922	.880
	AU4	3.85	.91	.836	.906
	AU5	3.28	1.14	.813	.815
	AU6	3.59	.99	.842	.864

In summary, the measurement model demonstrated that each construct in the UNITED model is measured reliably and is empirically distinct, albeit with expected interrelations (PU–PEOU in particular). These results gave us confidence to interpret the structural paths without concern that measurement issues (like multicollinearity or unreliability) would bias those relationships.

Initial Structural Model Findings

We first tested the initial hypothesized model with all theorized direct paths: PU → BI, PEOU → BI, SI → BI, FC → BI, PU → AU, FC → AU, and BI → AU. The model also implicitly included the mediated pathway PU/PEOU/SI/FC → BI → AU. As mentioned, the initial SEM did not achieve a fully satisfactory fit (χ^2=28,766, df = 5456, RMSEA= .115), suggesting some model modification was necessary (Kline, 2016). We examined the path coefficients and their significance (Table 4 below summarizes key estimates). Two hypothesized paths were non-significant: the effect of Perceived Ease of Use on Behavioral Intention was near zero (β = –0.007, p = .935), and the effect of Facilitating Conditions on Behavioral Intention was also negligible (β = –0.031, p = .507). These paths' t-values were very low, indicating they did not contribute meaningfully to explaining teachers' intention to adopt AI (Hair et al., 2019). All other paths were significant at $p < .05$ or better.

Notably, Perceived Usefulness (PU) had a very strong positive effect on teachers' Behavioral Intention (BI) to use AI (β = 0.718, $p < .001$). This confirms that teachers who believe AI tools are useful for teaching are far more likely to intend to adopt them (Hazzan-Bishara et al., 2025; Zuo et al., 2025). Social Influence (SI) also showed a positive influence on BI (β = .144, p = .024), though much smaller in magnitude. This suggests that encouragement or pressure from colleagues, administrators, or the broader educational community does play a role in teachers' decisions to use AI, but it is a secondary factor compared to perceived usefulness (Abdalla, 2024; Feng et al., 2025). Interestingly, as noted, Perceived Ease of Use (PEOU) did not have a significant direct effect on BI in this model. This implies that simply finding AI tools easy or user-friendly was not enough to drive teachers' intention – a result that diverges from the classic TAM expectation (where ease of use often influences intention, especially indirectly via usefulness). Our finding aligns with some prior studies in education technology that reported non-significant PEOU→BI effects when teachers are already fairly adept with basic tech (Chao, 2019). It appears that for these teachers, if an AI tool is not initially easy to use, they may still consider adopting it if they perceive it as highly useful. Conversely an easy but not useful tool won't be adopted. Ease of use might instead act indirectly by enhancing perceived usefulness (Mailizar et al., 2021). We explore this in the final model.

Turning to Actual Use (AU) of AI, the initial model included both direct and mediated predictors. As expected, Behavioral Intention (BI) emerged as the strongest predictor of Actual Use (β = 0.495, $p < .001$). This is consistent with UTAUT, TPB, and TRA theories which all posit intention as the proximal antecedent to usage behavior. Teachers who had firm plans and willingness to use AI were indeed much more likely to actually use AI tools in their teaching practice. Additionally, we found two direct factors significantly affecting Actual Use: Perceived Usefulness had a small but significant direct effect on AU (β = 0.170, p = .002), and Facilitating Conditions had a moderate effect on AU (β = 0.312, $p < .001$). The positive FC → AU link suggests that having access to resources, training, and infrastructure (e.g. reliable internet, available devices, tech support) enabled teachers to translate their intentions into action. In other words, even if facilitating conditions didn't shape intention in our data, they were crucial for implementation, that is, teachers who actually incorporated AI in class tended to be those who had better support systems and environment for doing so. This finding reflects real-world constraints which suggests that no matter how willing a teacher is, without the necessary tools and stable connectivity, actual use of AI will be limited (Feng et al., 2025; Yuan et al., 2023). It echoes recent observations that infrastructural support is a foundational requirement for effective classroom technology integration (Zhang & Wareewanich, 2024). Meanwhile, the direct PU → AU effect could indicate that some teachers went ahead and used AI tools because they personally found them useful, even if they hadn't strongly formed an intention beforehand or independent of other factors. However, this direct effect was relatively weak (standardized β ~0.17), implying most of PU's influence on use is mediated through intention.

In summary, the initial model results confirmed some hypotheses while contradicting others: Usefulness and social influence significantly drive intention, whereas ease of use and facilitating conditions did not directly drive intention. Intention is the dominant predictor of actual use, though supportive conditions and usefulness also help push usage. These results provided a basis for refining the model. Given the non-significance of PEOU → BI, we decided to remove that direct path in the revised model, consistent with parsimony and to improve fit. We also noted from modification indices that an omitted link between PEOU and PU could improve fit – theoretically, TAM suggests PEOU influences PU (if something is easier to use, one might perceive it as more useful). We thus added a PEOU → PU path in the model respecification. Additionally, the data hinted at a possible mediated relationship involving facilitating conditions and social influence: qualitative feedback and theory (e.g. the role of leadership support in shaping norms) led us to consider that Facilitating Conditions might indirectly affect BI through Social Influence. For instance, a school with strong infrastructure and training (high FC) could foster a culture where teachers encourage each other to use AI (higher SI), thereby increasing intention. We tested this by introducing a FC → SI path in the final model. Finally, because FC already had a strong direct effect on AU, and BI covers the mediation to AU, we removed any unnecessary direct paths to AU that might no longer be needed after adding the new mediation chains. The resulting adjustments – dropping PEOU→BI, adding PEOU→PU and FC→SI, and allowing PEOU to influence FC (since ease of tech might enable use of available supports) – were theoretically grounded in TAM/UTAUT extensions and significantly improved model coherence.

Final Model Fit and Structural Relationships

After modifications, the final UNITED model achieved an excellent fit to the data. As shown in Table 2, all fit indices now exceeded the recommended standards: CFI = .998, TLI = .998, IFI = .998, RMSEA = .017, and SRMR = .061(Hair et al., 2019). The chi-square also dropped dramatically relative to degrees of freedom ($\chi^2/df \approx$ 1.20), indicating the revised model closely reproduces the observed covariance structure. The improvement from the initial model was substantial – for example, RMSEA fell from 0.115 to 0.017, reflecting a near-perfect fit (Hooper et al., 2018). Incremental indices like IFI and TLI increased from the mid-0.8s to essentially 1.0, showing that the model now explains virtually all covariation among the constructs that could be explained (Stone, 2021). Such high fit metrics suggest that the refined model specification was appropriate and that no major relationships affecting model fit were missing or misspecified.

Figure 2 illustrates the final structural model with significant paths (standardized coefficients) based on the final SEM. In the final model, we confirmed the following key relationships: Perceived Ease of Use (PEOU) now indirectly influences Behavioral Intention via other constructs. We found that PEOU has a strong positive effect on Perceived Usefulness (PU) ($\beta \approx 0.65$, $p < .001$ in the final model). This means that teachers who find AI tools easy to learn and use are much more likely to appreciate their usefulness for teaching (Vardar et al., 2024). This aligns with TAM theory and our expectations that usability boosts perceived utility (Davis, 1989; Luo et al., 2024). Through this route, PEOU contributes to intention because an easier-to-use tool becomes regarded as beneficial, which then drives intention. Our participants echoed in comments that once they got the hang of an AI tool's interface and saw how seamlessly it fit into their workflow, they started to recognize its potential advantages for teaching. Thus, PEOU's effect on BI is fully mediated by PU in the final model; the direct PEOU→BI path remained out and was not needed.

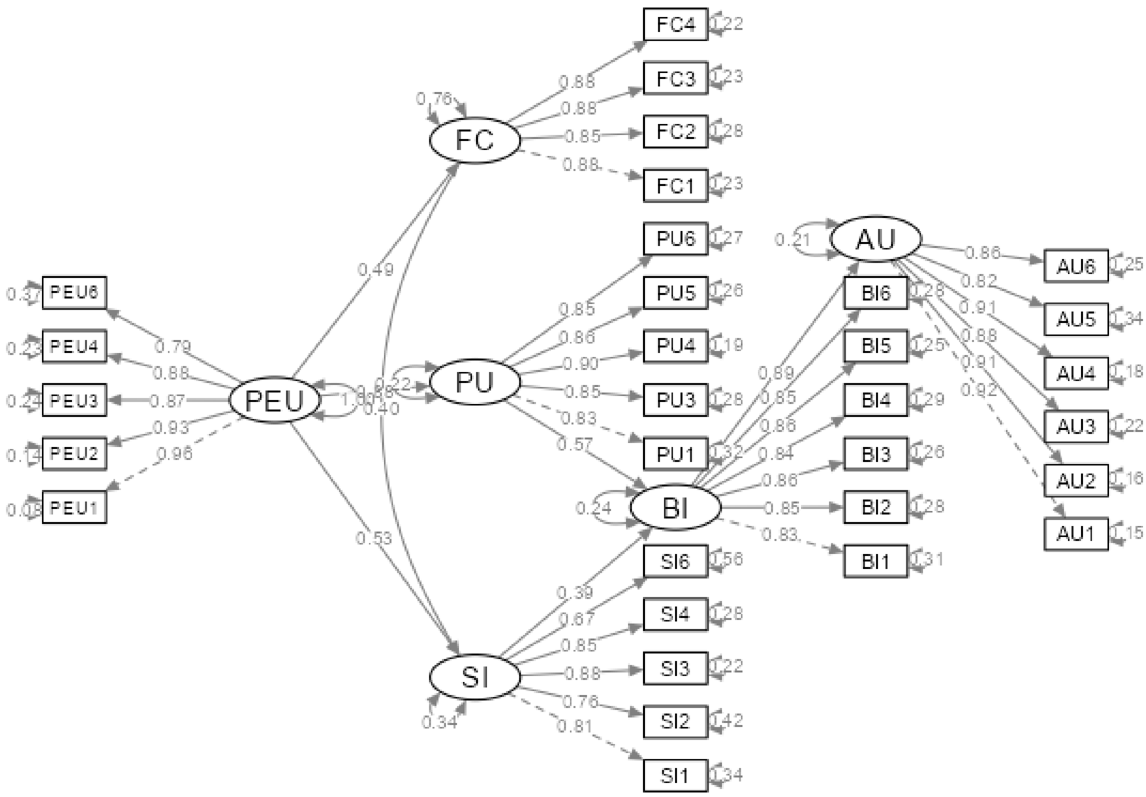

Figure 2. The Validated Structural Model of Unified Theory of Innovation and Technology in Education (UNITED)

Perceived Usefulness (PU) remains a dominant predictor of Behavioral Intention (BI). In the final model, after accounting for the PEOU → PU linkage, the influence of PU on BI was still very large (standardized $\beta \approx 0.72$, $p < .001$). This reaffirms that teachers' intention to adopt AI is primarily driven by their belief that these tools will be useful in enhancing their teaching effectiveness or efficiency (Yao & Wang, 2024). Among all factors, PU had the greatest impact on BI. This finding is consistent with numerous studies on technology acceptance that identify performance expectancy (usefulness) as the strongest determinant of intention (Alissa & Hamadneh, 2023). In practical terms, teachers who saw clear benefits such as time saved in grading, improved student engagement, or better differentiation – were the ones most inclined to plan on continued AI use.

Social Influence (SI) in the final model is influenced by facilitating conditions and in turn affects BI. We introduced and found support for a path from Facilitating Conditions (FC) to Social Influence (SI) ($\beta \approx 0.55$, $p < .001$). This suggests an interesting dynamic: when schools provide strong infrastructure, training, and support for AI (high FC), it can lead to a culture where AI use is more visible and encouraged among peers, thereby elevating social influence. Essentially, adequate institutional support empowers teacher leaders and colleagues to become champions of AI integration, creating positive peer pressure (Magat & Sangalang, 2024). For example, in schools where administration organized AI workshops and ensured stable internet, we observed teachers more frequently sharing AI success stories and recommending tools to each other. This manifests as higher SI in those environments. In turn, Social Influence has a modest but significant direct effect on Behavioral Intention ($\beta \approx 0.15$, $p < .01$), similar in magnitude to the initial model. Thus, SI serves as a mediator for FC's impact on BI: facilitating conditions boost social influence, which then nudges teachers' intentions upward. Notably, in the final model Facilitating Conditions no longer had a direct path to BI, consistent with our initial finding that FC did not significantly predict intention on its own. Instead, its influence is channeled through SI. This reflects the idea that simply having resources doesn't make a teacher decide to use AI but those resources enable a supportive community that can influence the teacher's decision.

Behavioral Intention (BI) remains the sole direct predictor of Actual Use (AU) in the final model. We removed the direct FC → AU and PU → AU paths to simplify the model because BI captures those effects in a mediated way. In our final analysis, BI had a very strong effect on AU ($\beta \approx 0.80$, $p < .001$), highlighting that once a teacher is determined to use AI, they are highly likely to follow through when conditions allow. The absence of a direct FC → AU path in the final model might seem contrary to the initial results where FC was significant to AU. What happened is that FC's effect on AU is now indirectly accounted via SI and BI. This suggests that good facilitating conditions foster higher SI (colleagues advocating AI), which increases BI, which in turn drives AU. With BI so dominant, any extra direct contribution of FC to AU became statistically unnecessary in the presence of the new mediated paths. This underscores that the intention to use AI is a critical gateway to actual implementation that infrastructure alone won't lead to usage unless teachers form the intent to integrate AI into their teaching (Wibowo & Sobari, 2023; (Akinnuwesi et al., 2022). Our final model aligns with prominent theories (UTAUT, TRA/TPB) in reaffirming that intention is the proximate cause of usage behavior.

To summarize the final model, Perceived Ease of Use → Perceived Usefulness → Behavioral Intention → Actual Use forms one primary causal chain, indicating that making AI tools easy for teachers can enhance their perceived value and thus encourage adoption. Parallel to that, Perceived Ease of Use → Facilitating Conditions → Social Influence → Behavioral Intention forms a secondary chain, suggesting that ease of use also helps teachers make better use of institutional supports and encourages a pro-technology social environment, indirectly boosting their intention to use AI. All roads in the model lead to Behavioral Intention, which then leads to Actual Use (with no other direct routes to AU in the final model). This integrated structure provides a nuanced understanding of AI adoption: a teacher is more likely to use AI if they intend to, and they intend to if they find it useful (influenced by ease of use) and feel social encouragement (influenced by good support conditions).

The validated UNITED model thus unifies core elements of TAM, UTAUT, and related theories in our educational context. It retains TAM's insight that usefulness is key and that ease of use bolsters usefulness. It incorporates UTAUT's notion that social influence and facilitating conditions matter, but clarifies that facilitating conditions matter largely through social and indirect means rather than directly shaping intent. It also echoes TPB in that internal beliefs (attitude/perceived usefulness) combined with social norms drive intention, and perceived control/resources (facilitating conditions) are required to realize behavior, albeit indirectly in our model.

Table 4. Standardized Path Coefficients – Initial vs. Final Model

Structural Path	Initial Model β	Final Model β
Perceived Usefulness → BI	.718**	0.720**
Perceived Ease of Use → BI	.007 (n.s.)	(path removed)
Social Influence → BI	.144*	0.153
Facilitating Conditions → BI	.031 (n.s.)	(path removed)
Perceived Ease of Use → PU	–(not in initial)	0.647**
Facilitating Conditions → SI	(not in initial)	0.553**
Behavioral Intention → AU	.495**	0.804**
Perceived Usefulness → AU	.170*	(path removed)
Facilitating Conditions → AU	.312***	(path removed)

Note: $^{**}p < .01$, * $p < .05$, n.s. = not significant. BI = Behavioral Intention, PU = Perceived Usefulness, PEOU = Perceived Ease of Use, SI = Social Influence, FC = Facilitating Conditions, AU = Actual Use. The final model's R^2 for Behavioral Intention was 0.68, and for Actual Use 0.70 (with BI as sole direct predictor). Model fit (final): $\chi^2(\approx 5460)=6544.8$, CFI=0.998, TLI=0.998, RMSEA=0.017.

Table 4 presents a concise comparison of the initial and final model path coefficients for reference. All hypothesized relationships supported in the final model are significant at p < .01, except the SI → BI path which is p < .05. The table also highlights which paths were dropped or added in the refinement process. With the final UNITED model validated, we now turn to discussing these findings in the broader context of teacher adoption of educational technology, drawing comparisons with existing literature and distilling implications for practice.

Discussion

This study set out to unify elements of prevailing technology acceptance theories into a single model explaining teachers' adoption of AI tools. The UNITED model we developed and tested provides a comprehensive understanding of how various factors, from individual perceptions to social and organizational factors – interplay to influence Filipino secondary teachers' AI adoption. The results yield several important insights, many of which resonate with prior research while also offering unique contributions to the discourse on AI in education.

Perceived Usefulness as the Primary Driver

Consistent with the Technology Acceptance Model (TAM) and much subsequent research, we found that a teacher's belief in the usefulness of AI tools is the most potent motivator for their intention to adopt those tools.

This underscores a timeless lesson: educators, like other users, are pragmatic. This means that if they can clearly see how a tool will benefit their teaching or student learning, they are inclined to use it. Our qualitative observations revealed specific perceived benefits that fueled this sense of usefulness: teachers mentioned AI helping to speed up lesson planning, generate new ideas or materials, differentiate instruction for varied student needs, and automate mundane tasks (like checking grammar or grading quizzes). These align with documented advantages of AI in education such as reducing teacher workload and enabling personalized learning (Kelly et al., 2023). The findings reinforce that school leaders and EdTech developers should emphasize and demonstrate tangible instructional benefits of AI tools. For instance, professional development sessions should highlight success stories and evidence of AI improving student outcomes as these will strengthen teachers' performance expectancy (Venkatesh et al., 2003) and drive adoption.

Ease of Use

In contrast to some earlier studies like Šumak et al. (2011) that found perceived ease of use to be a weak or non-significant factor, our model clarifies that ease of use matters, but primarily by enhancing perceived usefulness. We discovered no direct impact of ease on intention, a result similar to Chao's (2019) finding in a different educational context suggesting that once a minimum usability threshold is met, teachers focus on utility. However, ease of use had a significant indirect role which suggests that teachers who found AI tools user-friendly were more likely to appreciate their utility and also more likely to take advantage of available supports (which made them more confident and socially supported). This aligns with Unified Theory of Acceptance and Use of Technology (UTAUT) notions that effort expectancy contributes to performance expectancy and facilitates usage under conducive conditions (Venkatesh, 2022). Practically, this implies that to foster AI adoption, designers should prioritize intuitive interfaces and smooth user experiences, and training programs should reduce complexity and build teachers' confidence in using AI tools. As educators become comfortable with basic operations of AI, they can better envision pedagogical applications (thus boosting perceived usefulness). Our data showed many teachers initially tried simpler AI functions (like asking a chatbot questions) and once they felt at ease, they started realizing how it could aid instruction, corroborating the PEOU→PU pathway.

Social Influence and Cultural Context

The moderate yet significant influence of Social Influence (SI) on intention highlights that teachers are affected by the attitudes of colleagues and administrators a finding well-aligned with UTAUT and with social learning theories. In cultures with collaborative work environments or strong communal values (such as in many Filipino schools), peer endorsement and administrative encouragement can validate a teacher's decision to adopt new technology. Interestingly, our integration of SI with facilitating conditions suggests that social influence doesn't operate in a vacuum: it is amplified when the institution actively supports the innovation. This dovetails with findings by Lu et al. (2020) and Zhang and Wareewanich (2024) that organizational context can magnify normative pressures in technology adoption. In our case, when schools invested in AI infrastructure and training (facilitating conditions), it not only provided means but also signaled an expectation – creating a "culture of AI" that teachers did not want to be left out of. The policy implication is that school leaders aiming to increase AI integration should not only provide resources but also foster a supportive culture: celebrate AI usage successes, encourage experienced teachers to mentor others, and possibly form communities of practice around AI in teaching. These can heighten the positive social influence and alleviate fears, making AI adoption a collective effort rather than an isolated personal choice.

Facilitating Conditions

Our results around facilitating conditions (FC) are revealing. Initially, facilitating conditions did not drive intention that teachers didn't decide to use AI simply because resources were available. However, FC strongly determined actual usage (initial model) until we accounted for its indirect effects. Essentially, good infrastructure and support are necessary enablers for adoption but not motivators by themselves (Xue et al., 2024). This aligns with the idea in TAM/UTAUT literature that facilitating conditions often become significant only after users have experience (Venkatesh et al., 2003). In our sample, many teachers likely formed intentions based on perceived value (or social factors), and when it came time to act, those with adequate support managed to implement AI (hence the FC→AU effect). By restructuring the model, we see FC influences the social environment and indirectly intention. This indicates that schools must ensure the basic conditions (like internet connectivity, access to devices, technical help) are in place for AI adoption to actually happen. Without these, even enthusiastic teachers will be stymied, a point echoed by Alenezi (2024) on the necessity of reliable connectivity. Our work reinforces a practical point: educational authorities should invest with strong ICT infrastructure and ongoing technical support if they expect teachers to embrace AI. Teachers in our study noted barriers such as patchy internet and lack of technical assistance as reasons they couldn't consistently use AI, which mirrors common challenges in integrating ICT in schools (Zulkarnain & Yunus, 2023). By improving facilitating conditions, schools remove external barriers and also send a message that technology use is supported which, as we found, can galvanize social influence and adoption efforts.

Intention-Behavior Gap and Fulfillment

One encouraging finding is that once teachers formed a clear behavioral intention (BI) to use AI, the likelihood of them actually using it was very high (BI had a strong effect on AU, explaining a large share of variance). This suggests relatively little intention-behavior gap in this context; committed teachers did follow through, assuming conditions allowed. It underscores the importance of nudging that intention formation to begin with. It also aligns with TPB and TRA assumptions about the primacy of intention (Fishbein & Ajzen, 1975), our data empirically validate that in educational AI adoption, intention is the crucial pivot point. Teachers' intentions were generally positive (mean intention was ~4 out of 5, indicating "Agree" to intending to use AI), which translated into moderate actual usage (mean ~3.5 for actual use frequency, on a scale where 3 = sometimes and 4 = often). Some gap remains not all who intend end up using AI daily, likely due to obstacles or lack of time. The discussion of facilitating conditions covers much of that: intentions may not convert to action if, say, the AI requires computing power or internet that isn't available in a given classroom. Another reason might be lack of time or curriculum fit; a teacher may intend to use AI but find it hard to align with a packed syllabus. These factors were not explicitly measured in our model but could be captured under facilitating conditions (e.g. time could be seen as a resource issue). Nonetheless, the high BI→AU coefficient is promising: it means if we can effectively increase teachers' intentions through the identified levers (usefulness, social encouragement, ease and support), we are likely to see actual adoption follow.

Comparisons with Other Studies

Our results both concur with and diverge from findings in the emerging literature on AI adoption among educators. For instance, a recent study by Alissa and Hamadneh (2023) in Jordan found that teachers' overall employment of AI in teaching was at a moderate level and that female teachers showed higher engagement than males. Our study of Filipino teachers similarly observed moderate overall AI use and a strong representation of female teachers using AI, supporting a cross-cultural notion that when opportunities are equal, women educators are eager participants in ed-tech innovation, refuting any stereotype of tech adoption being a predominantly male domain in education. Another study by Khan et al. (2021) reported that in general technology adoption models, perceived usefulness, ease of use, and social influence all had significant effects on behavioral intention and actual use. We partly echo that: usefulness and social influence are confirmed, but we qualify ease of use's role (indirect rather than direct). This might be due to the specificity of AI tools which often have a learning curve, meaning early perceptions of ease might not form until one gains some experience. Xue et al. (2024) emphasized social influence's significant role in users' behavioral intention for new technologies, which we did observe albeit as a smaller factor than usefulness. Our finding that perceived ease of use did not significantly impact intention is consistent with Chao (2019) and others who noted that once baseline technology familiarity is present, additional ease may not spur much higher intent. It's possible that as digital literacy among teachers grows (most of our respondents are digital natives or immigrants comfortable with tech), ease of use becomes an expectation rather than a differentiator. Instead, training should focus on demonstrating pedagogical value, as ease barriers are gradually lowering with improved user-centered design of tools.

Contributions of the UNITED Model

The unified model approach allowed us to see a bigger picture of AI adoption. It confirmed that no single theory fully captures the phenomenon rather, elements from each contribute: TAM's usefulness reigns, UTAUT's social and facilitating factors play supporting roles, TPB's emphasis on intent leading to behavior holds true, and even TPACK's implication that training (knowledge) is needed emerges (since ease of use and facilitating conditions essentially relate to knowledge and support). By integrating these, the UNITED model provides a more holistic framework for understanding and predicting teacher adoption of not just AI, but potentially other emerging technologies. It demonstrates that technology adoption in education is multi-faceted: personal conviction of value, peer culture, and practical logistics all matter. We thereby answer the call by researchers like Xue et al. (2024) and Greener (2022) who suggested combining perspectives for a richer analysis of ed-tech adoption.

Limitations and Future Research

While our study benefitted from a large sample and a theory-driven model, it is not without limitations. First, the data are self-reported and cross-sectional, which might introduce common method bias and limits causal interpretations. We mitigated this risk by using SEM to test the plausibility of causal paths and found the model consistent with theory, but future studies could incorporate longitudinal designs to track how intentions convert to usage over time, or even experimental interventions to see causality more directly. Second, our sample was drawn from one city's public school system; thus, caution is warranted in generalizing to other contexts (e.g., private schools, other countries). Different regions may have varying levels of AI readiness and cultural factors influencing adoption. We encourage researchers to test the UNITED model in other populations – for instance, rural schools or different cultural contexts to validate its generality. Third, there are other potentially relevant factors we did not include, such as teacher attitudes (affect) toward AI, perceived student outcomes, or personal innovativeness. We focused on core TAM/UTAUT constructs for parsimony. Future research could extend the model by examining, for example, how AI-related anxiety or ethical concerns temper adoption, or whether teacher ICT competency moderates the relationships (e.g., perhaps ease of use matters more for less tech-savvy teachers). Additionally, qualitative follow-ups with teachers could enrich understanding of why certain factors mattered – for instance, what specific support or social influences were most persuasive.

Lastly, as AI in education is a fast-evolving field, the nature of "AI tools" will expand. Today's prevalent tools include chatbots and content generators; tomorrow's might be more advanced adaptive systems or AI teaching assistants. Our model should be revisited as technology evolves to ensure these relationships hold or to update it with new constructs (e.g., trust in AI might become crucial if AI takes on more autonomous teaching roles). We also note that actual use in our study was measured by frequency and breadth of use future studies could delve into impact of use (are high-intention teachers using AI in ways that significantly improve outcomes?).

Despite these limitations, our study provides a timely contribution by empirically validating an integrated model of AI tool adoption in an education setting. It offers a foundation upon which further scholarly inquiry and practical innovation can build, ensuring that the introduction of AI into classrooms is guided by an understanding of human factors as much as technological capabilities.

Conclusion

In an era where Artificial Intelligence has the potential to revolutionize education, understanding the human factors behind teacher adoption of AI is critical. This study introduced and validated the UNITED model, which cohesively explains teachers' adoption of AI tools by synthesizing major technology acceptance theories. Our findings highlight that teachers will embrace AI in their teaching when they perceive clear value in it and feel supported by their peers and institutions. Conversely, even promising AI innovations will languish if teachers find them cumbersome or if schools fail to provide the necessary environment for their use.

The model's confirmation that "perceived usefulness" is king in driving adoption means that policymakers and developers should focus on aligning AI tools with genuine pedagogical needs making AI not just a novelty, but a solution to real classroom challenges. At the same time, the roles of ease of use, social influence, and facilitating conditions remind us that teachers operate within systems; thus, training, community, and infrastructure must all be addressed. For instance, a school aiming to implement AI should ensure teachers are trained in an approachable manner (tackling ease of use), celebrate AI champions (leveraging social influence), and upgrade IT support and connectivity (strengthening facilitating conditions).

Importantly, our study shows that when these factors are in place, teachers are not only willing to intend using AI, but many follow through to implement it in their practice. The path from intention to actual integration can be traversed successfully if the roadblocks are removed and motivators amplified. In practical terms, education stakeholders – from ministry officials to school principals – can use the insights from the UNITED model as a checklist for crafting AI integration initiatives: Is the AI tool clearly beneficial? Is it teacher-friendly? Do we have the infrastructure? Are we fostering a culture that encourages adoption? Addressing these questions can significantly increase the likelihood of successful AI adoption.

Finally, this study contributes to the academic literature by demonstrating the value of a unified approach. The robust fit of the UNITED model and its consistency with observed behavior suggest that a unified theory of teachers' technology adoption is indeed achievable and can guide both research and practice. We encourage further research to refine this model, examine its applicability to other technologies (like AR/VR or future digital tools), and explore its implications for student outcomes. As AI continues to evolve, so must our understanding of how teachers adapt to and adopt these tools. With a solid framework now in hand, educators and researchers can work hand-in-hand to ensure that the infusion of AI into education is done thoughtfully, effectively, and for the ultimate benefit of teaching and learning..

Recommendations

For practitioners and policymakers, our findings yield actionable insights: to promote AI tool adoption among teachers, efforts should concentrate on (a) increasing the perceived instructional value of AI (through showcasing best practices and evidences of effectiveness), (b) simplifying AI tool use and providing training (so that teachers don't find complexity a deterrent), (c) building a supportive community and leadership advocacy for AI (creating positive social influence), and (d) ensuring robust infrastructure and technical support (so that willing teachers can implement AI without hindrance). Interventions that simultaneously address these areas – for example, a program that provides easy-to-use AI platforms, trains teachers on pedagogical use-cases, equips schools with needed technology, and establishes teacher mentor groups are likely to be most successful. Indeed, our research suggests that technology adoption is not just an individual choice but an institutional endeavor. Schools that treated AI integration strategically (with policies, resources, and culture-building) saw more of their teachers both intending to and actually using AI in teaching.

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Motivation and Persistence in STEM Education: Addressing Attrition in the STEM Pipeline

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Abstract

Despite job growth in science, technology, engineering, and mathematics (STEM) careers and an educational emphasis on developing STEM programs, there is still a shortage of graduates prepared to fill these jobs. This literature review examines the motivational factors that influence persistence in STEM and programs or curricular changes that encourage STEM participation and skill development. The lack of STEM participation threatens the health of national economies and equity, as gender and racial disparities disproportionately affect underrepresented groups. Key motivational factors that impact participation are self-efficacy, growth mindset, and belonging. Active learning that emphasizes personal growth and questioning, along with supportive learning environments, increases engagement. STEM learning should connect to real-life applications, and student benefit from participation in STEM opportunities in their community. Mentorship and role models help students envision themselves in STEM careers, particularly for underrepresented groups, helping them work past perceived barriers. Schools should implement STEM programs at the elementary level and continue to reinforce participation through various programs until graduation.

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Introduction

Science, technology, engineering, and mathematics (STEM) have become an area of focus in education to meet the growing need for a workforce that is increasingly interdisciplinary (Asunda, 2018). While the number of jobs in STEM careers is growing, there is a global shortage of qualified professionals to fill them. STEM education is seen as a strategic response to these challenges. However, schools have met difficulties because many students fall away from STEM studies during their educational path. This loss of potential students is most pronounced among women and underrepresented minorities. A lack of a unified STEM definition has led to inconsistent practice and research, with a lack of clarity about the level of integration that is needed. This literature review examines the following questions:

- What motivational factors influence student persistence in STEM education?
- What programs and curricular changes increase student participation in the STEM pipeline?

STEM

STEM combines science branches with an interdisciplinary approach that combines science, engineering, technology, and mathematics to expose students to how these subjects are applied in real life (Armtcu & Bal, 2023). The STEM emphasis in education was created to develop more positive student attitudes in STEM classes to foster greater interest in STEM fields (Farrell, 2023). This emphasis is based on the need to fill jobs that require mathematics and science skills (Waters & Orange, 2022), a job market that is growing without enough qualified graduates to fill positions (Flores, 2023). Despite efforts to increase participation in STEM fields, there is a global deficit of graduates, and the need is especially high in math-intensive careers (Ozturk, 2024).

The changing job market reflects the changing landscape of global problems and technological advances, requiring new skills for the workplace. Many students are not prepared to meet the needs of the future economy, where problem-solving skills and critical thinking are essential (Waters & Orange, 2022). The term *21st-century skills* refers to the skills needed to meet these needs and includes higher-thinking skills such as critical thinking, estimation, problem-solving, and reasoning, as well as social skills of cooperation, entrepreneurship, communication, creativity, and innovation (Armutcu & Bal, 2023). Students must understand the complex nature of problem solving in real life, where there may be more than one valid approach and more than one acceptable solution. Students experience various dilemmas and explore different strategies (Makonye & Moodley, 2023). The emphasis is not on what a student knows, but how they can apply that knowledge (Asunda, 2018). Traditionally, learning mathematics has focused on skills and routines, but computers are increasingly capable of performing these tasks. Therefore, education needs to emphasize modelling and applications (Kristensen et al., 2024). For STEM education, this often comes through an emphasis on problem-based learning (PBL), which has been shown to lead to increased retention, life-long learning skills, exposure to real-life experiences, and increased motivation towards STEM fields (Asunda, 2018).

STEM education has the potential to help students navigate through real-world problems by applying knowledge and skills from the individual disciplines to complex and interdisciplinary contexts (Kristensen et al., 2024). The interdisciplinary approach helps students make real-life connections, contributing to students' competence in complex contexts while promoting individual disciplinary knowledge and practices. STEM learning occurs through an engineering design process where they learn by doing, developing understanding by learning from mistakes and refining ideas (Margot & Kettler, 2019). Learners gain knowledge and skills in the disciplines of science, technology, engineering, and mathematics while focusing on creativity, critical thinking, and problem solving (Bayanova et al., 2023). Creating interest and engagement are important goals of STEM education to prepare a STEM workforce and make connections between the STEM disciplines (Margot & Keller, 2019).

Barriers and Challenges

Unfortunately, Asunda (2018) observed that there is a lack of clarity in defining STEM that reduces STEM education to more of a slogan. The lack of a clear definition has been a criticism of STEM, complicating research because of inconsistent implementation (Farrell, 2023). STEM lessons often lack clarity about what connections should be made or how learning will be assessed (Wang et al., 2022; Wiesselmann et al., 2021). There is no consensus on whether STEM is just an interdisciplinary approach or if it could place more emphasis on each individual discipline (Kristensen et al., 2024). Watson et al. (2022) found 9 different levels of STEM represented in literature: a reference to any one of the single disciplines, referencing science and math, separate science disciplines incorporating other science disciplines (such as chemistry and biology), individual disciplines (sometimes called *silos*), science and math connected by technology or engineering, coordination across any two or more disciplines, combination of two or more disciplines, integration across disciplines, or as a transdisciplinary course or program. Waters & Orange (2022) called for more case studies of STEM schools to develop common frameworks and language.

There is insufficient research to inform theory, policy, and practice when STEM may have multiple interpretations, including multidisciplinary, interdisciplinary, or transdisciplinary approaches (Goos et al., 2023). It is not always possible or desirable to teach every STEM concept through cross-disciplinary lessons because some concepts require individual attention. Wielselmann et al. (2022) found that inclusive schools that emphasize PBL lack an individual focus, leading math and science content to suffer. Makonye and Moodley (2023) found that students often do not recognize the mathematics in an integrated course. Furthermore, the math that is integrated into STEM activities is often at a low computational level, leading math teachers to believe their expertise is not needed for integration. In articles about integrated STEM lessons, Goos et al. (2023) found that math was rarely given attention and was mostly just a tool to support the learning of the other subjects. Through these lessons, students were not learning new math skills or deepening their mathematical thinking. Collaboration was often unbalanced, with science learning goals dominating the content for integrated lessons. This is unfortunate, because mathematical modelling is a powerful tool for understanding and predicting the world, and all branches of science require mathematical modeling (Armutcu & Bal, 2023). Most real-world problems are interdisciplinary, and mathematical modeling is a tool to express and solve unique problems.

Another barrier to integration is the demands of high-stakes testing. Schools are often reluctant to add STEM integration because they prioritize state mandates (Waters & Orange, 2022). Teachers are reluctant when standardized test scores are used for evaluation, questioning whether the STEM implementation will meet the required subject area curriculum (Watson et al., 2022). Furthermore, at least at the secondary level, departments and teacher training are still divided by discipline, and accountability is tied to discipline-specific standardized tests (Jiang, 2019).

The STEM Pipeline

With the number of jobs in STEM fields increasing, there is a need to produce more STEM university graduates (Chambers et al., 2022). A strong STEM workforce is needed for future economic prosperity and resilience, yet, despite efforts to boost STEM participation, there is a global deficit of graduates (Ozturk et al., 2024), especially in jobs requiring science and math training (Waters & Orange, 2022). STEM jobs are available, but there are not enough graduates to fill them (Flores, 2023). The term *STEM pipeline* refers to the track followed by young students through elementary to university graduation (Farrell, 2023). The term, explained Farrell, rose from the need to develop professionals from a young age for preparation in STEM fields. There is a need to encourage more students to gravitate towards STEM fields and prepare them to work in these fields (Bayanova et al., 2023).

However, the STEM pipeline is leaky. Initial interest in STEM is not enough because students either lose interest in STEM or abandon it (Farrell, 2023). These leaks happen at many levels of education for varying reasons. Flores (2023) found that the leakage begins as early as 5th grade for many girls, where they lose confidence in their STEM abilities. Moving on through 12th grade, interest in STEM careers continues to drop among minority groups and females as they become aware of social inequalities that act as barriers, while feeling helpless to effect systemic changes (Flores, 2023; Mulvey et al., 2023). Despite the growing job market and the emphasis on spending to encourage more students to pursue STEM careers, minority groups and females are underrepresented and earn significantly less than their White male counterparts. Flores argued that males have been encouraged towards STEM fields while teachers, social influence, and peers encourage women to perform in other fields. Students may have an interest in STEM, but the awareness of the barriers leads to the belief that it is unattainable or they do not belong (Mulvey et al, 2023).

Watson et al. (2022) recommended that STEM should be introduced at the elementary level, encouraging positive attitudes and engagement with STEM. As students continue through school, they begin to face barriers to persistence. Often, a parent's lack of STEM confidence or anxiety about STEM subjects is passed on to their children unintentionally. Math anxiety leads students to struggle in developmental math courses, deterring them from persisting in STEM (Samuel et al., 2023). Math anxiety leads to the avoidance of advanced study, especially by women and ethnic minority students by weakening resilience and persistence. This leads to decreased academic performance, which in turn increases educational disparities. The pipeline continues to leak at the university level, where many students abandon STEM majors after facing challenges. Chambers et al. (2022) found in a study at one institution that many students did not pass the first course in their STEM major, and most had left the STEM major before the end of their sophomore year, leading to a low 25% retention rate for STEM majors. To change these high attrition rates, students need to be prepared with the skills and mindsets to persist in the gate-keeper courses. Students often leave because of the perceived difficulty, poor learning environments and pedagogy, and a lack of support systems. Chambers et al. found the need to foster identity, commitment, and confidence in addition to developing skills.

These leaks disproportionately affect females and minority students (Farrell, 2023). Selective STEM schools are often highly competitive and have low minority representation (Wieselmann et al., 2021). STEM schools that emphasize equity provide a place to serve underrepresented youths. These schools encourage the enrollment of students regardless of past experience and lack of success in science and math, with the hope of developing interest and abilities in STEM. Studies have shown that these inclusive schools benefit students and contribute to increased equity. Ozturk et al. (2024) believed that promoting more interest in math-intensive fields is an important factor in closing the gender gap and pay disparities for women and racial minorities. Makonye and Moodley (2023) found that learners from historically oppressed groups benefited from learning from role models and mentors, especially in learning through practice situated in real-world activities. Dasgupta et al. (2022) found that girls were more interested in STEM careers and felt greater belonging in science and math when they observed female scientists working towards communal goals. Mulvey et al. (2023) encouraged out-of-school STEM experiences to increase interest among adolescents. Community engagement helps students feel connected and see the relevance of STEM in their community. It helps students see themselves in STEM to address problems that their community faces, helping them believe they could have a place in STEM.

Motivation

Motivation is an important factor for active engagement, interest, and achievement, and has a significant influence on a student's learning outcomes and career choices (Bayanova et al., 2023). Psychological factors involving belonging and perceptions of discrimination affect both classroom engagement and out-of-school engagement in STEM (Mulvey et al., 2023). Modern motivational theory emphasizes the importance of task value, goals, and beliefs in influencing motivation (Farrell, 2023). Success and engagement in the classroom are closely tied to indicators of motivation, including self-efficacy, task value, self-regulation, and learning goal orientation. Yeager and Dweck (2020) attributed the level of engagement and persistence to beliefs about their ability to achieve a goal, leading to either avoidance or engagement with difficult tasks. A helpless pattern will lead to avoidance when faced with obstacles, but a mastery-oriented pattern will seek out challenging tasks and maintain effort in the face of failures (Hargreaves et al., 2021). Researchers have found that active participation in discussions and questioning through STEM activities leads to higher STEM interest, increased academic success, and positive effects on daily awareness and life skills (Armtcu & Bal, 2023). One goal of STEM education is to improve the learners' satisfaction and motivation while decreasing stress (Dasgupta et al., 2022).

Self-efficacy

Math anxiety leads to negative cognitive responses, including feelings of helplessness and mental disorganization (Samuel et al., 2023). These feelings hinder learning, causing poor test performance and reinforcing self-doubt about math competence. This self-doubt leads students to withdraw from math-related activities. S*elf-efficacy* refers to the beliefs individuals have about their ability to achieve specific levels of performance to exercise influence over their life (Bandura, 1977). Bandura found that people avoid difficult situations when they believe they lack the skills to effectively engage. On the other hand, a person is likely to engage in an activity if they believe they are able to handle any difficulties that might arise. The individual's perception of their own efficacy is a predictor of whether they will persist, and persistence leads to outcomes that reinforce self-efficacy. Self-efficacy influences academic and career choices as well as performance outcomes (Flores, 2023). Students are less motivated to pursue goals that they do not believe they can accomplish (Farrell, 2023). Self-efficacy is closely tied to the student's *goal orientation* (choices about what goals to pursue), *task value* (how worthwhile a goal is worth pursuing when compared with the necessary effort), and *self-regulation* (the perseverance and discipline to achieve a goal).

Often, the move from elementary to middle school is a time when students display a decline in self-efficacy, likely from factors outside the classroom (Farrell, 2023). Self-efficacy is understood to be correlated with more positive participation in STEM activities, especially for minority and female students (Kramer et al., 2023). Kramer et al. also found that high-performing female students tended to have lower self-efficacy than lower-performing male peers. The lower-performing male students were more likely to pursue STEM due to their beliefs about their abilities. Kramer et al. encouraged STEM educators to build self-efficacy by using mastery performance strategies, vicarious experiences, and social persuasions. Vicarious experiences and social persuasion could involve, among other things, exposing students to speakers or role models representing diverse backgrounds. Mulvey et al. (2022) found that emphasizing the personal relevance of STEM led to students placing higher value on the work, and they reported higher self-efficacy, motivation, and achievement. Addressing knowledge gaps is an important factor in building self-efficacy (Dasgupta et al., 2022), so educators should encourage positive participation in STEM.

Self-efficacy is often built through past mastery performance, but it is also developed through vicarious experiences and social persuasions (Kramer et al., 2023). These experiences and persuasions include speakers, mentors, role models, and peers encouraging the pursuit of STEM careers. Self-efficacy is a strong predictor of a student's choices, effort, and perseverance in achieving goals (Farrell, 2023). Therefore, self-efficacy is a high predictor for the choice to pursue STEM (Kramer et al., 2023). Unfortunately, researchers have found that self-efficacy often drops about the time children transition from elementary to middle school, with many of the factors leading to this drop happening outside the classroom (Farrell, 2023). This drop in can affect student engagement, so it is important to implement strategies that strengthen self-efficacy.

Higher self-efficacy in STEM classrooms has led to students completing more tasks in project-based learning units (Farrell, 2023). If students do not believe they can accomplish a goal, they will be less motivated to try, so it is important to understand strategies to improve self-efficacy. Mulvey et al. (2023) found that connecting mathematics to socially relevant topics increased participation in their math classes. According to Dasgupta et al. (2022), the emphasis on personal relevance of STEM to real life leads students to place a higher value on the work, resulting in higher self-efficacy, motivation, and achievement. The value that students place on tasks is an aspect of expectancy-value theory, which addresses the desire to complete a task based on the value an individual places on that task (Farrell, 2023). Expectancy-value theory balances expectancy beliefs with subjective task values (Ozturk et al., 2024). Expectancy beliefs can be seen as the task-specific expectations of success based on self-efficacy. Subjective task values weigh perceptions about the value of achieving a goal against the perceived cost. These expectancy beliefs are closely tied to the career interests of adolescents towards math-intensive fields.

Growth Mindset

Learning through mistakes is often cited as an important aspect of the STEM learning framework (Margot & Kettler, 2019), mirroring the concept of productive failure that is a key part of the engineering process (Waters & Orange, 2022). This need to embrace failure appears to be at odds with traditional attitudes towards education that reward proficiency. This orientation is addressed through *incremental theory*, which holds that intelligence is something that can be developed and increased through effort and performance, and its counter *entity theory*, which finds intelligence to be a fixed attribute that cannot change even with effort (Bernardo et al., 2021). A person's beliefs towards either orientation are either a *fixed mindset*, that intelligence is a fixed talent, or a *growth mindset*, that intelligence can be developed over time through practice and performance (Samuel et al., 2023). Under a fixed mindset, low self-efficacy leads at-risk students to become self-sabotaging by exerting less effort. Feelings of anxiety lead to disengagement when the student feels doomed to failure despite their effort. The belief that abilities cannot change may lead students to feel like they do not belong in STEM, which will increase anxiety and lower their STEM interest (Canning et al., 2019).

Even proficient students suffer from a fixed mindset because they are less likely to attempt tasks that do not make them look good (Dweck & Yeager, 2019). The emphasis on performance goals leads students to learn through external motivations, by seeking favorable judgments about their competence from others (Hargreaves et al., 2021). This leads lower-attaining children to have a helpless attitude and higher-attaining students to avoid challenges. In either case, the student is sacrificing the opportunity for new learning out of a fear of making an error or appearing incapable. A fixed mindset can negatively affect students because they are less likely to seek feedback, less likely to check for errors, and are less likely to accept critical feedback (Samuel et al., 2023). Students with a fixed mindset are more likely to focus on competition, comparing themselves to other learners as a measure of their ability (Yeager & Dweck, 2020). As students reach higher levels of education, a fixed mindset might lead them to believe they cannot change how they perform (Chambers et al., 2022). They are less likely to try again after their first failure, preventing them from reaching their full potential. This view is often evident in mathematics, where students come to believe that mathematics is an innate ability, as they heard from parents or others (Ozturk et al., 2024). This leads some students to avoid math-intensive careers.

People with a growth mindset, on the other hand, believe their abilities are malleable and are developed through persistence, the use of learning strategies, and mentoring (Canning et al., 2019). Kramer et al. (2023) connected a growth mindset with a tendency to persist when faced with challenges and being motivated by the desire to improve ability. An individual with a growth mindset is more likely to persevere, seeing obstacles as difficult but achievable (Kroeper et al., 2022). Under a growth mindset, students will seek improvement for their own satisfaction and to gain competence (Hargreaves et al., 2021). Dweck and Yeager (2019) found that displaying a growth mindset increased educational outcomes because it led to challenge seeking and resilience. Growth mindset has been tied to positive learning behaviors, building self-efficacy, creativity, and a higher motivation for learning (Vongkulluksn et al., 2021). The belief that abilities can be developed means students are more likely to set mastery goals and persist despite challenges. Interventions that promote a growth mindset have been shown to relate to positive participation in STEM, especially for minority students (Kramer et al., 2023). Meta-analyses have found positive links between growth mindset and math engagement while improving academic outcomes, especially among at-risk subgroups (Mulvey et al., 2023).

Growth Mindset and Self-efficacy

Students' attitudes, beliefs about their ability, motivation, and cultural influences can affect how they view the potential growth of their intelligence, which may impact their interest in STEM careers (Flores, 2023). Teachers who understand that self-efficacy affects motivation should encourage students to overcome obstacles to build self-efficacy. Stohlmann (2022) found that students with a growth mindset are more likely to have higher self-efficacy. Building a growth mindset is not just about expending more effort, but also learning and trying new approaches and seeking assistance when it is needed. Students build self-efficacy when they experience success through learned behaviors. Yeagar and Dweck (2020) found that students with a growth mindset demonstrated more challenge seeking behavior, such as choosing to take and stay in more advanced mathematics courses in high school. Interventions encouraging a growth mindset have been found to have the most meaningful effect when participants are currently experiencing challenges or setbacks.

Challenges in Studying Beliefs

One criticism to growth mindset theories is that it is difficult to measure beliefs, and it is possible that factors other than growth mindset are responsible for academic achievement in these studies (Macnamara & Burgoyne, 2023). Macnamara and Burgoyne pointed out that growth mindset interventions also include teaching strategies for overcoming setbacks, normalizing mistakes, goal setting, and individualized study plans. Proponents counter that many studies have shown academic improvement in students, especially among vulnerable groups (Yeager and Dweck, 2020). Burnette et al. (2020) reported positive psychological outcomes of students expressing a growth mindset, including reduced anxiety and fewer symptoms of depression.

Studying STEM engagement through abstract mental processes creates challenges for researchers. Beliefs are complex and dynamic, not always internally consistent or coherent, often happen outside of conscious awareness, and evolve over time (Kramer et al., 2023). In one study into growth mindset and STEM, Kramer et al. found students expressing conflicting beliefs. They would talk about growth mindset ideas, where effort can increase intelligence, but then expose a fixed mindset by referring to innate abilities acting as a barrier. There was also a misalignment between the qualitative and quantitative findings, exposing incoherent beliefs about intelligence. Sisk et al. (2018) also noted that measuring mindsets is often on a subjective scale, and students may respond to questionnaires the way they think they should instead of their actual beliefs.

Many teachers also confuse growth mindset, which is a belief orientation, with the associated behaviors such as intellectual risk-taking (Clark & Soutter, 2022). Displaying specific behaviors is not always associated with beliefs and can be influenced by other factors. Some of the controversy around growth mindset is that academic success might be associated more with the learned skills taught alongside growth mindset rather than affective motivations. Measures of mindset that are tied to academic achievement measures, such as grade point average (GPA), could also be skewed, because students who have a growth mindset should be more willing to engage in more difficult coursework, risking a lower GPA for the sake of personal growth (Sisk et al., 2018). Dasgupta et al. (2022) questioned the high volume of research into abstract attitudes about STEM, where the actual behaviors and lived experiences of engagement in classrooms may be more significant.

Increasing Engagement

Educators should be asking how they can keep more students interested in STEM when the leaking STEM pipeline is leading to STEM jobs that are unfilled. Of course, achievement is important, but educators need to focus on keeping students engaged (Farrell, 2023). Clark and Soutter (2022) pointed to a body of literature stressing the importance of creating educational environments that are mastery-oriented, focus on learning over performance, emphasize thought processes over solutions, normalize confusion, genuinely value mistakes, foster positive learning behaviors through explicit instruction, and thoughtfully create safe classrooms and trust with students. Furthermore, knowledge is a product of the situations where learning takes place, so instruction must be placed within a context where students can meaningfully relate learning content to their lives (Koehler et al., 2013).

Developmental Stages

The emphasis on STEM learning should begin at the elementary level (Flores, 2023; Stohlmann, 2022; Waters & Orange, 2022; Watson et al., 2022). Early exposure increases the likelihood that students will build an interest in STEM careers (Flores, 2023) that will persist in later grades (Stohlmann, 2022). Students should be given experience in how STEM skills are connected to real-life applications and possible careers while building fundamental skills. Moving into early adolescence in the middle school grades, students are highly influenced by communal values and interests formed at this age are likely to persist through high school and predict university majors (Dasgupta et al., 2022). Algebra performance and interest in grade 8 are highly critical, as they are closely connected to later STEM motivation and interest.

Adolescence is when students begin to form a sense of their own identity, balancing the desire for peer acceptance with an awareness of approaching adulthood, particularly in recognizing their intellectual growth and the need to build skills for future economic independence (Parkay et al., 2014). The sense of belonging is especially important at this age, where students are motivated to engage when they are able to see themselves in STEM (Mulvey et al., 2023). Exposure to representative role models and mentors in STEM careers is an important motivator for career aspirations, especially for groups that are underrepresented or have historically faced barriers to STEM careers (Flores, 2023). Students who are fully emersed in STEM during high school are more likely to pursue STEM in university (Farrell, 2023).

Focus on Meaningful Content

The teaching of STEM subjects can often be a sanitized version of the real thing, carefully compartmentalized into individual skills. Teachers cannot just tell students STEM is relevant; the connections from in-class content to real-world applications need to be made explicit (Kramer et al., 2023). STEM activities should emphasize connections between classroom learning and out-of-school contexts (Scherer et al., 2019). Often, the emphasis on STEM is framed in terms of addressing economic concerns, both for national and individual benefit, but STEM also acts as a motivating force when students see the power it has to address ecological and cultural issues (Nicol et al., 2023). There are limitations to classroom teaching, and students should be exposed to the benefits of studying things in the natural world and in their communities.

Out of School Engagement and Activism

Experiencing STEM outside of the classroom provides several benefits for students. Ozturk et al. (2024) found that out-of-school opportunities such as programs at museums, zoos, and aquariums promote career interest and a sense of belonging, especially for traditionally marginalized students. Participation in STEM camps has a positive impact on students' career aspirations (Flores, 2023). STEM internship programs develop self-efficacy, goal orientation, and persistence (Farrell, 2023). Student engagement in a community-based STEM course was correlated with higher math and science proficiency (Mulvey et al., 2023). Mulvey et al. suggested that these programs encourage students to pursue STEM careers because they can see how STEM is relevant personally and to the future of their community. Some researchers have also pointed out that students from some demographic groups, particularly Black, Latinx, and Native American, are more likely to be influenced by community benefits than self-oriented reasons when choosing an educational path (Dasgupta et al., 2022). These experiences also offer opportunities for students to make connections with professionals in these fields who can serve as mentors and role models (Watson et al., 2022). Personal connections increase the likelihood that a student will consider a STEM field.

Often, subjects like math and science are not seen as community activities, but their applications in the real world affect communities (Dasgupta et al., 2020). There are many ethical dilemmas in the world that can be addressed through scientific research and technological development (Maass et al., 2019). Many students are motivated by opportunities for responsible citizenship and ethical stewardship of the planet. STEM can draw attention to issues of social justice and technology innovation for building a more just and beautiful world (Nicol et al., 2023). Community activism can encourage participation in STEM careers.

Subject Area Emphasis

Ensuring the integrity of the STEM pipeline requires that students have interest and the necessary skills. STEM lessons are often weakened by vagueness or uncertainty about what and how to assess the lessons, or even by what subjects and skills are being emphasized (Scherer et al., 2019; Wang et al., 2022). When integration takes place, it needs to be made explicit so learners understand the intentional connectedness of each discipline (Margot

& Kettler, 2019). Unfortunately, reviewing literature on STEM lessons reveals that most integrated lessons do not focus on mathematics, and integrated lessons are rarely used to support higher mathematical thinking (Kristensen et al., 2024). Students need to be able to apply math concepts to real-world situations, but building strong modeling capabilities requires abstract algebraic principles (Reinke, 2019). Similarly, technology is frequently used as a tool in STEM, but is rarely taught explicitly (Wieselmann et al., 2021).

Sometimes it is necessary to build on domain-specific skills. Problem-based learning (PBL) increases student engagement and motivation (Mujumdar et al., 2024). As students increase their interest in STEM, they will be more willing to engage with increasingly abstract concepts. Sun (2018) advocated PBL as a multidimensional approach for math that emphasizes both the sense-making aspect of problem solving and procedural fluency. Unfortunately, low-achieving students are often grouped into remedial tracks where they focus only on basic skills, missing the conceptually rich activities that would benefit them. Sun encouraged teachers to have high expectations for all students and value student ideas, representations, and strategies over correctness. Mistakes can become an opportunity for the class to engage in making meaning from mathematical processes.

Having high expectations still means that students need time to think deeply about learning. Galanti and Miller (2021) warned against rushing students through accelerated programs because students may focus on speed, memorization, and correctness without finding time to really do the math and internalize concepts. The core of mathematics is not the discrete skills students learn. Mathematics is about sense-making, which involves the ability to connect and reason.

School Culture

School culture reflects the school's norms, goals, and values (Waters & Orange, 2022). It is reflected through teaching and learning practices and organizational structures. A positive school culture will be reflected in behaviors that increase student engagement so that students can thrive and find academic success. Teachers need to lead the way by making students feel safe in taking risks and accepting failure. Developing 21st-century competencies requires an emphasis on collaboration and creativity, and the school culture should foster those values.

Encourage Growth Mindset

Creative thinking and a growth mindset toward learning can be threatened by a systemic promotion of conformist behaviors and competition, including comparisons between students (Hargreaves et al., 2021). Instructors and school culture play a critical role in building a growth mindset in students through their expectations and class norms (Chambers et al., 2022; Jarrard et al., 2025; Samuel et al., 2023, Wang et al., 2021). To succeed, students need to develop an attitude of pursuing growth rather than natural ability (Chambers et al., 2022). Teachers who believe students have fixed abilities were more likely to lower expectations for their students, sacrificing educationally rich activities for remedial work (Samuel et al., 2023). Canning et al. (2019) found that students from underrepresented groups had lower performance when they had fixed mindset STEM teachers, regardless of the race or ethnicity of the teacher. Perceptions about the instructor are often more important than the instructor's actual beliefs. Students whose instructor communicated growth mindset principles of effort and growth predicted higher grades, higher self-efficacy, and better expectations of fair treatment from the instructor (Jarrard et al., 2025).

Learning should be process-oriented, which involves frequent questioning, feedback, and providing opportunities for revision (Yan et al., 2021). Students should be active throughout the learning process (Armtcu & Bal, 2023). They should be asked to express problems in their own words, consider any research they may need to do to solve the problem, and reflect on their solution to express real-world meanings. One effective strategy is the use of ill-structured problems (Manalaysay, 2024). Ill-structured problems more closely represent real-world problems because there is no clear solution. Open-ended questions and ambiguity could be central to any meaningful STEM investigation (Goos et al., 2023). Often, students may need to interpret the question itself, meaning there is no one correct solution. Problems with no clear solution are often a key component of makerspace classrooms where students rely on 21st-century skills of collaboration, problem solving, creative thinking, and computational thinking (Vonkulluksn et al., 2021). Another key component of makerspace environments is the importance of failure in the engineering process. Collaborative learning environments lead to more positive educational outcomes than competitive environments (Dasgupta et al., 2022). This emphasis on community building encourages STEM participation, especially among minority and female students.

Parents

Communicating growth mindset principles and STEM opportunities to parents is also important (Watson et al., 2022). Parents who lack confidence in STEM knowledge often pass that on to their children, while parents who hold positive attitudes will pass on positive attitudes. Dweck and Yeager (2019) found that the kinds of feedback that parents gave their children played the highest role in a child's mindset. Watson et al. (2022) also found that students are most likely to follow the occupations of their parents, so schools should promote STEM opportunities to parents. Schools should actively raise awareness among parents, promoting the benefits of STEM learning and opportunities for their children to participate in STEM programs.

School Leaders

School leaders may see the need for change, but need to communicate a clear vision, support teacher growth, and promote teacher buy-in (Waters & Orange, 2022). When new curricula are implemented, teachers are usually the first group impacted (Watson et al., 2022). To build a school that emphasizes collaboration, creativity, and risk-taking, school leaders need to include teachers in the decision-making process and provide autonomy, while encouraging teacher collaboration (Goos et al., 2023). Rather than relying on a single leader, leadership roles should be distributed to emphasize a collaborative approach, building teacher motivation and sense of professional community (Wieselmann et al., 2021). Administrators need to focus on being instructional leaders rather than managers while providing opportunities for professional development and providing access to STEM experts. Effective STEM integration requires training and professional development opportunities should reflect what effective integration looks like (Havice et al., 2018).

Professional Development

Goos et al. (2023) credited teacher expertise as the most important factor for successful integration. However, many teacher education programs are still discipline-specific, and few teachers are trained in multiple STEM fields. Asunda (2018) found that teachers lacked the pedagogical knowledge to understand the complex interrelatedness of each STEM discipline. One approach is for interdisciplinary planning between subject area specialists, but these teachers still need to understand the philosophy behind the integration and share a common vision. Teachers need specific training on how to effectively integrate STEM subject matter (Flores, 2023). Havice et al. (2018) promoted the development of a clear conceptual framework that includes the role and purpose of STEM education and how individual content standards can be taught through an interdisciplinary approach.

Conclusion

STEM education needs to start early to face the challenge of an unprepared workforce. There is a need to both motivate students and to develop skills, beginning at the elementary level. Watson et al. (2022) argued that there should be more schools with a specific STEM focus, while introducing STEM programs into all schools. High schools should offer advanced STEM courses using pedagogical practices of inquiry, evaluating claims, and using evidence and reasoning. Schools should have more collaboration with STEM professionals and companies, while providing more STEM extracurriculars and summer programs. More opportunities for student engagement increase interest and develop ability.

A lack of a clear definition or framework for STEM has led to varied implementation and research. Some areas for future research are creating frameworks and definitions for clarity in lesson planning and research, the connections between affective dispositions towards STEM and intellectual skill development, and effective community STEM programs. When discussing specific STEM lessons or programs, studies should also be more explicit about the targeted disciplines, content, and level of integration. Bayanova et al. (2023) found that most studies were quantitative, but recommended more qualitative studies to explore the problems in STEM education, including the relationship between motivation and other variables. Bayanova et al. also encouraged more research at the elementary level to improve STEM attitudes at this formative age.

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Implementing a Technology-Integrated Problem-Based Learning (TIPBL) Strategy in a Higher Education Mathematics Classroom

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Abstract

This study examined the influence of Technology-Integrated Problem-Based Learning (TIPBL) on engagement, academic grit, mathematical mindset, and perceptions of technology among first-year Bachelor of Secondary Education major in Mathematics (BSEd-Mathematics) students at a state university in the Philippines. Using a collaborative action research design utilizing modified explanatory sequential mixed-methods approach, quantitative data were collected via validated scales (Academic Grit Scale, Mathematical Mindset Scale, and Perception of Technology in Teaching and Learning Scale), while qualitative insights were derived from post-intervention interviews. Results indicated high levels of academic grit and growth-oriented mathematical mindset, with technology perceived positively for teaching and learning. Qualitative themes highlighted collaborative learning, technology efficacy, and resilience, though concerns about over-reliance on technology and access disparities emerged. Further, the qualitative data revealed that students perceived TIPBL as engaging, collaborative, and motivating. They described increased participation, stronger perseverance, a more open mindset toward solving problems, and positive attitudes toward the integration of technology. The findings suggest TIPBL develops perseverance, mindset development, and critical thinking, but equitable implementation and balanced technology integration are essential. Recommendations include scaffolding self-regulation, addressing digital inequities, and promoting collaborative problem-solving. It is also recommended that educators incorporate TIPBL strategies in their instruction This study contributes to literature on technology-enhanced pedagogies and their psychological impacts in teacher education.

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Introduction

The integration of technology into mathematics education is a growing priority in 21st-century learning environments. Existing literature has highlighted that digital tools, when used alongside innovative pedagogies, can support both cognitive and non-cognitive learning outcomes in mathematics (Hwang et al., 2020; Bicer et al., 2021). While Problem-Based Learning (PBL) has been shown to enhance students' conceptual understanding and problem-solving abilities (Savery, 2015), the specific approach of Technology-Integrated Problem-Based Learning (TIPBL) remains underexplored, especially within teacher education programs in developing countries (Alakrash & Razak, 2021). This study aims to investigate the influence of TIPBL on pre-service mathematics teachers' engagement, academic grit, mathematical mindset, and perception toward technology in learning. Using a mixed-methods action research design, the study integrates technology-enhanced PBL activities into a mathematics education course and examines their effects through both quantitative and qualitative lenses.

Mathematics education faces persistent challenges, including high levels of student anxiety (Dowker et al., 2016) and declining engagement during transitional academic periods (Attard, 2018). These challenges are particularly acute in the Philippines, where recent international assessments revealed that 81% of Filipino students failed to reach minimum proficiency levels in mathematics (OECD, 2019). This crisis has prompted urgent calls for pedagogical reforms that address both the cognitive and affective domains of mathematics learning (Bernardo et al., 2022).

Recent scholarship has identified two critical psychological constructs that influence mathematics achievement: academic grit (Clark & Malecki, 2019) and mathematical mindset (Megawanti et al., 2024). Grit, defined as "perseverance and passion for long-term goals" (Duckworth et al., 2007, p. 1087), has been shown to predict academic success beyond measures of intelligence (Credé et al., 2017). Similarly, growth mathematical mindset—the belief that mathematical ability can be developed through effort (Dweck, 2006)—has been linked to greater resilience in facing mathematical challenges (Yeager et al., 2019).

The intersection of technology integration and these psychological factors remains underexplored in pre-service teacher education (Tourón et al., 2018). This study addresses this gap by examining how TIPBL influences academic grit, mathematical mindset, and perceptions of technology among future mathematics educators—a population critical to educational reform (Ball et al., 2008).

Theoretical Framework

This study draws upon three interconnected theoretical perspectives that collectively inform the design and implementation of the Technology-Integrated Problem-Based Learning (TIPBL) intervention. First, Vygotsky's (1978) Constructivist Learning Theory provides the foundational understanding that knowledge is actively constructed through social interaction and authentic problem-solving experiences. The TIPBL approach operationalizes these constructivist principles by engaging students in collaborative, technology-mediated activities that mirror real-world mathematical challenges (Jonassen, 2011). This theoretical lens emphasizes the importance of scaffolding within students' zones of proximal development, particularly when working with complex financial mathematics concepts like annuities.

Building upon this foundation, Dweck's (2006) Mindset Theory informs the intervention's approach to fostering students' beliefs about mathematical ability. The study incorporates research-documented practices for cultivating growth mindsets, including process-focused feedback and the normalization of productive struggle in mathematics learning (Boaler, 2016). Empirical evidence suggests that such mindset interventions can enhance mathematics achievement by approximately 0.15 standard deviations, with particularly strong effects for students facing academic challenges (Sisk et al., 2018). The current study extends this work by examining how technology-enhanced problem-solving environments might uniquely contribute to mindset development among pre-service mathematics teachers.

Finally, Mishra and Koehler's (2006) Technological Pedagogical Content Knowledge (TPACK) framework guides the strategic integration of digital tools within the problem-based learning environment. This theoretical model helps avoid the "technocentrism" trap identified by Papert (1987), ensuring that technology serves clear pedagogical purposes rather than being used as an end in itself. Recent applications of TPACK in mathematics education demonstrate how carefully designed technology integration can enhance conceptual understanding while developing students' digital competencies (Geiger et al., 2020). The TIPBL intervention applies these insights by selecting technologies that specifically support the mathematical content (annuities) and pedagogical goals (collaborative problem-solving) of the curriculum.

Together, these theoretical frameworks create a robust foundation for examining how technology-integrated problem-solving experiences might simultaneously enhance pre-service teachers' mathematical understanding, pedagogical skills, and psychological dispositions toward teaching and learning mathematics. The conceptual model emerging from this theoretical integration suggests that when implemented with attention to constructivist principles, mindset development, and technological pedagogical knowledge, TIPBL has the potential to transform both cognitive and affective outcomes in mathematics teacher education.

Statement of the Problem

While Problem-Based Learning with the integration of technology has gained recognition as an innovative pedagogical approach (Chen et al., 2020), critical gaps persist in understanding its comprehensive impact on pre-service mathematics teachers. First, there remains limited empirical evidence regarding how TIPBL influences academic grit, the perseverance and passion for long-term goals (Duckworth et al., 2007), particularly when students engage with challenging mathematical tasks (Eskreis-Winkler et al., 2016). Given that pre-service teachers often encounter complex mathematical concepts during their training, understanding how TIPBL fosters or hinders their perseverance is essential for designing effective teacher education programs.

Second, although growth mathematical mindset, the belief that mathematical ability can be developed through effort (Dweck, 2006), has been widely studied, its cultivation within technology-enhanced learning environments remains underexplored (Claro et al., 2016). Prior research suggests that mindset interventions can improve achievement (Yeager et al., 2019), but it is unclear how digital tools and collaborative problem-solving influence these beliefs in pre-service teachers.

Third, the reciprocal relationship between students' perceptions of technology and their perseverance (grit) in mathematics remains poorly understood (Scherer et al., 2019). While some students may view technology as a motivational tool that enhances learning, others may perceive it as a barrier, particularly when technical difficulties arise. Understanding this dynamic is crucial for optimizing TIPBL implementations in real-world educational settings.

To address these gaps, this study sought to answer the following research questions:

1. What are the baseline levels of academic grit, mathematical mindset, and technology perceptions among first-year Bachelor of Secondary Education major in Mathematics (BSEd-Mathematics) students prior to TIPBL implementation?
2. How do participants describe their experiences with TIPBL in terms of engagement, mathematical mindset, academic grit, and perception of technology in teaching and learning?

By investigating these questions, this study aimed to provide a deeper understanding of the influence of TIPBL in both cognitive and non-cognitive aspects of learning, ultimately contributing to more effective teacher preparation in mathematics education.

Significance of the Study

This research makes substantial contributions across theoretical, practical, and methodological domains, offering valuable insights for diverse stakeholders in mathematics education. The study advances contemporary educational theory by bridging several critical frameworks. First, it extends the Technological Pedagogical Content Knowledge (TPACK) model by investigating its intersection with psychological constructs such as grit and mindset (Chai et al., 2019). This integration addresses a significant gap in understanding how technology-enhanced pedagogies influence non-cognitive learning outcomes. Second, the research expands growth mindset theory (Dweck, 2006) into technology-mediated mathematics contexts, providing empirical evidence on how digital problem-solving environments can shape students' beliefs about mathematical ability (Yeager & Dweck, 2020). Finally, the study refines grit theory (Duckworth et al., 2007) through its domain-specific application in mathematics teacher education, offering nuanced insights into how perseverance develops in technology-rich learning settings (Credé, 2018).

At the classroom level, this research provides educators with empirically validated TIPBL instructional modules for teaching annuities, complete with technology integration strategies and assessment tools (Hmelo-Silver, 2004). These resources are particularly valuable for teacher educators seeking to implement innovative pedagogies in their mathematics methods courses (Desimone, 2009). Beyond immediate classroom applications, the findings inform broader educational policy, particularly in the Philippine context where the Department of Education (DepEd) has prioritized technology integration in STEM curricula (SEAMEO INNOTECH, 2021). The study's evidence-based recommendations can guide decision-makers in allocating resources for teacher professional development and technology infrastructure.

The research demonstrates an innovative mixed-methods action research design that combines quantitative assessments of psychological constructs with rich qualitative exploration of student experiences (Mertler, 2019). This approach serves as a model for studying short-term educational interventions while maintaining scientific rigor. The study also exemplifies best practices in instrument validation, employing both expert review and pilot testing to ensure the reliability and validity of measurement tools (Haynes et al., 1995). Furthermore, the detailed documentation of the 3-week TIPBL intervention provides a replicable template for future studies examining technology integration in teacher education programs (Plano Clark & Ivankova, 2016).

Collectively, these contributions position the study as both theoretically grounded and pragmatically useful, offering actionable insights for researchers, practitioners, and policymakers alike. The findings have particular relevance for institutions navigating the transition to technology-enhanced mathematics instruction, providing evidence-based guidance on effective implementation strategies and potential psychological impacts on learners.

Methods

Research Design

This study employed a collaborative action research design utilizing a mixed-methods approach. Specifically, it adopted a modified explanatory sequential mixed method to explore students' engagement, mathematical mindset, academic grit, and perception of technology in teaching and learning in the context of the implemented intervention. The approach was modified by replacing the traditional follow-up quantitative phase with qualitative interviews, due to the theoretical assumption that mindset and grit remain relatively stable in short-term interventions

In the first phase, quantitative data were collected using instruments that measured students' mathematical mindset, academic grit, and perception towards technology. This survey was conducted prior to the implementation of the TIPBL strategy to establish a baseline understanding of the respondents' dispositions. The intervention used in this study was the Technology-Integrated Problem-Based Learning (TIPBL) strategy, which aims to enhance student engagement and develop deeper learning through the integration of technology within a problem-based learning framework.

Following the intervention, the next phase involved the collection of qualitative data through interviews. These interviews focused on the same constructs, including student engagement, in order to gather rich, reflective insights on students' experiences with the TIPBL strategy. A post-intervention survey using the same instruments was not conducted, as constructs such as mindset and grit are generally not expected to exhibit significant change over a short period. Instead, the qualitative data served to capture any perceived changes, reflections, or enhanced awareness resulting from the intervention. By integrating both quantitative and qualitative data sources, this mixed methods approach provided a more comprehensive and contextualized understanding of the influence of the

TIPBL strategy, aligned with the cyclical and reflective nature of action research.

Research Respondents

The respondents of the study were first-year Bachelor of Secondary Education major in Mathematics (BSEd-Mathematics) students from a state university in Naval, Biliran, Philippines, for the School Year 2024–2025. These students were considered the most appropriate respondents as they are in the foundational stage of their teacher education program, where attitudes toward academic perseverance, mathematical mindset, and the integration of technology in learning are being formed and developed. Their experiences and perspectives are crucial in understanding how early exposure to specific interventions can influence long-term engagement and learning behaviors. The study employed total enumeration sampling, involving the entire population of first-year BSEd-Mathematics students. This method ensures comprehensive coverage, minimizes sampling bias, and enhances the validity of the findings by reflecting the full range of experiences and responses within the target group.

During the post-implementation phase, qualitative data were collected through interviews with all student participants. These interviews focused on the same constructs assessed in the quantitative phase, to provide deeper, more reflective insights into students' experiences with the TIPBL strategy. By involving all respondents, the study aimed to capture a holistic and inclusive account of the intervention's influence, enriching the findings with a comprehensive range of perspectives.

In addition to the student respondents, four experts also participated in the study. These experts were involved in the validation of the researcher-made instrument measuring students' Perception of Technology in Teaching and Learning (PTTL), a 15-item scale designed to assess students' views on the role of technology in education. Furthermore, the same experts validated the instructional module titled Understanding Annuities – Annuity Due and Deferred Annuity (Technology-Integrated Problem-Based Learning Approach), which was developed by the researcher in collaboration with the course instructor. This module was implemented during the intervention phase and was subjected to a rigorous validation process using the institution's standard tool for evaluating learning materials, ensuring its quality, relevance, and instructional value.

Research Instrument

The study utilized the Academic Grit Scale (AGS) by Clark & Malecki (2019), which consists of 10 items measuring academic grit level. The scale demonstrates excellent psychometric properties, including a reliable single-factor structure and high internal consistency (Cronbach's alpha = 0.92). It shows strong construct validity through correlations with general grit and incremental validity by uniquely predicting academic achievement, life satisfaction, and school satisfaction. Its domain-specific focus on determination, resilience, and focus within academics makes it a valuable tool for assessing and supporting student perseverance and success in educational settings. Respondents answered using a 5-point Likert scale.

Additionally, the Mathematical Mindset Scale (MMS) by Megawanti, et al. (2024) was used to assess students' mathematical mindset. The psychometric properties of the scale were established through rigorous development and validation processes. The scale underwent content validation with experts, achieving high content validity based on Aiken's index. Confirmatory Factor Analysis (CFA) was used to assess its structure, resulting in a model with 11 items across five dimensions: challenge, resilience, effort, learning from critics, and learning from mistakes, all with factor loadings above 0.5. The scale demonstrated excellent reliability, with a Construct Reliability (CR) of 0.984 and an Average Variance Extracted (AVE) of 0.925. Fit indices from CFA, such as RMSEA (0.065), CFI (0.95), and TLI (0.928), confirmed the model's goodness of fit, making it a robust instrument for assessing mathematical mindsets in education students. This 11-item scale requires students to rate items on a five-point Likert scale regarding level of agreement (1 = Strongly Disagree, 5 = Strongly Agree).

A researcher-made instrument was developed to measure students' Perception of Technology in Teaching and Learning (PTTL). This 15-item scale was designed to capture students' perception of technology in the educational process. To ensure its validity, the instrument underwent expert validation by four specialists in the field. It demonstrated excellent content validity, with relevance ratings yielding S-CVI/Ave = 0.97 and S-CVI/UA = 0.87, and clarity ratings of S-CVI/Ave = 0.98 and S-CVI/UA = 0.93. A pilot test was conducted to evaluate the internal consistency of the instrument, resulting in a high Cronbach's alpha coefficient of 0.95. The items were rated using a 5-point Likert scale, ranging from 1 (Strongly Disagree) to 5 (Strongly Agree), and were designed to be clear, concise, and directly aligned with the constructs being measured.

In addition to the quantitative instruments, an interview consisting of nine (9) open-ended questions was conducted after the implementation of the intervention. These questions were designed to elicit deeper insights into students' experiences and reflections regarding their engagement, mathematical mindset, academic grit, and perception of technology in the context of teaching and learning. Specifically, the interview included three questions related to student engagement, two questions each focusing on mathematical mindset, academic grit, and perception of technology in teaching and learning. The qualitative data from these interviews provided a richer understanding of how the intervention influenced the participants beyond what could be captured through survey instruments alone.

Data Collection Procedure

The data gathering procedure for this study was conducted in a systematic and ethical manner to ensure the credibility, reliability, and integrity of the collected data. The process began with securing a Letter of Approval signed by the Dean of the School of Teacher Education, which granted formal permission to conduct the study within the institution. This approval not only facilitated access to the intended participants but also ensured compliance with institutional protocols and reinforced the study's adherence to ethical research standards.
The data collection process was carried out in three key phases:

1. Pre-Implementation Phase: Before the intervention, quantitative data were collected using standardized and researcher-made instruments. These instruments measured students' mathematical mindset, academic grit, and

perception of technology in teaching and learning. The instruments were distributed through a Google Form, selected for its accessibility, ease of use, and ability to reach all participants efficiently. At the beginning of the form, a data consent section was included, clearly outlining the purpose of the study, the voluntary nature of participation, confidentiality measures, and the participants' right to withdraw at any time. Ensuring informed and voluntary consent was a critical aspect of maintaining ethical standards in the research process.

2. Implementation Phase: During this phase, the Technology-Integrated Problem-Based Learning (TIPBL) Strategy was implemented over a period of three weeks. A key component of this phase was a module titled Understanding Annuities – Annuity Due and Deferred Annuity (Technology-Integrated Problem-Based Learning Approach), which was developed by the researcher in collaboration with the instructor teaching the course. The module was designed to integrate real-world problem-solving tasks with technological tools, in alignment with the TIPBL approach. To ensure its quality and instructional value, the module underwent a rigorous validation process by four experts, utilizing the institution's standard validation tool for learning materials.

The validated module served a dual purpose: it acted as a comprehensive guide for the instructor in implementing the TIPBL strategy and also as a learning resource for the students, providing structure, context, and support as they explored the topic of annuities through technology-integrated problem-solving activities.

3. Post-Implementation Phase: After the intervention, qualitative data were collected through interviews with all student participants. These interviews focused on the same constructs assessed in the quantitative phase, including student engagement, mathematical mindset, academic grit, and perception of technology in teaching and learning, to provide deeper, more reflective insights into students' experiences with the TIPBL strategy. The interviews allowed participants to share personal observations, perceptions, and the influence of the intervention on their learning journey.

All data collected through the Google Form and interviews were securely stored in a protected digital format, with access limited to the researcher alone. Any identifying information was anonymized or excluded to uphold participant confidentiality and privacy. These steps ensured that the entire data collection process was aligned with ethical research practices and upheld the rights and dignity of all participants.

Data Analysis

The quantitative data analysis was conducted using Jamovi (version 2.4.14) to examine students' mathematical mindset, academic grit, and perception of technology in teaching and learning. Descriptive statistics were applied to summarize students' profiles: frequency counts and percentages were used for categorical data such as sex, while the mean and standard deviation described continuous variables like age. The constructs of mathematical mindset, academic grit, and perception of technology were also analyzed using mean and standard deviation to highlight central tendencies and variability in students' responses.

For the qualitative data, thematic analysis was employed to interpret students' responses to nine questions about their reflections and experiences with the Technology-Integrated Problem-Based Learning (TIPBL) strategy. This method enabled the identification of recurring themes and patterns across interview transcripts, providing in-depth insights into students' engagement, and perceived shifts in mathematical mindset, academic grit, and perception of technology in teaching and learning. Rather than serving solely to explain prior quantitative findings, the qualitative phase played a central role in exploring students' experiences and reflections on the intervention.

This approach aligns with the study's action research design, which emphasizes reflection, participation, and contextual understanding. The study employed a modified explanatory sequential mixed method approach, in which the qualitative phase followed the initial quantitative data collection. However, unlike traditional designs, a post-survey was not conducted, recognizing that constructs such as mindset and grit are unlikely to show measurable change over a short period. Instead, qualitative interviews were used to explore students' perceived changes and experiences in depth. This modification allowed the study to remain responsive and reflective, key principles of action research, while still benefiting from the structured insights of a mixed methods approach.

Results and Discussion

This section presents the results and discussion of the study, highlighting both quantitative and qualitative findings. The data are organized around key constructs, mathematical mindset, academic grit, perception of technology in teaching and learning, and student engagement, reflecting the influence of the TIPBL strategy within the study's action research design utilizing modified explanatory sequential mixed methods approach.

Table 1 presents the demographic profile of the first-year BSEd-Mathematics students who participated in the study. Out of the 17 respondents, 10 were male (58.82%) and 7 were female (41.18%), indicating a higher representation of male students. The participants' ages ranged around a mean of 19.00 years (SD = 1.12), suggesting that most of the respondents were in their late adolescence, a typical age range for first-year college students.

Table 1. Profile of the BSEd-Mathematics 1st Year Students

Variable	Frequency	Percent
Sex		
Male	10	58.82%
Female	7	41.18%
Total	17	100%
Age		
Mean = 19.00, Standard Deviation = 1.12		

The results indicate that BSEd-Math 1 students exhibit high levels of academic grit overall (M = 4.12, SD = 0.60), with individual item scores ranging from high to very high. This suggests that these students generally possess strong perseverance and passion for long-term academic goals, consistent with Duckworth et al.'s (2007) conceptualization of grit (see Table 2).

Table 2. Academic Grit of BSEd-Math 1 Students

	M	SD	Interpretation
1. I push myself to do my personal best in school.	3.94	0.75	High
2. I work toward my academic goals no matter how long they take to reach.	4.00	0.87	High
3. Even when I could do something more fun, I give schoolwork my best effort.	4.00	0.79	High
4. I complete my schoolwork no matter how difficult it is.	4.35	0.79	Very High
5. I am determined to give my best effort in schoolwork.	4.24	0.75	Very High
6. Once I set a goal in school, I try to overcome any challenges that arise.	3.88	0.70	High
7. I am able to balance working hard in school with my other hobbies and interests.	3.82	0.81	High
8. Even if I am struggling in school, I keep trying my best.	4.47	0.80	Very High
9. When it comes to completing work in school, I always try my hardest.	4.24	0.83	Very High
10. In school, I work hard to achieve challenging goals.	4.29	0.69	Very High
Overall	4.12	0.60	High

Several items stood out as demonstrating particularly strong grit characteristics. The highest-rated statement, "Even if I am struggling in school, I keep trying my best" (M = 4.47, SD = 0.80), along with other items regarding completing difficult schoolwork (M = 4.35) and working toward challenging goals (M = 4.29), all received very high ratings. These findings suggest that students maintain their effort and commitment even when facing academic challenges, a key component of academic success (Credé et al., 2017).

While all items were rated in the high to very high range, the relatively lower (though still high) scores on items like balancing schoolwork with hobbies (M = 3.82) and setting goals while overcoming challenges (M = 3.88) may indicate areas where students could benefit from additional support. These slightly lower scores might reflect the difficulties students face in managing multiple responsibilities or maintaining motivation over extended periods.

The findings align with previous research demonstrating the importance of grit in academic achievement, particularly in demanding programs like mathematics education (Duckworth & Quinn, 2009). Also, the results align with Tang et al. (2019), who identified the perseverance component of grit as a significant predictor of academic engagement, underscoring its importance in sustaining effort through obstacles. Similarly, Çınar-Tanrıverdi and Karabacak-Çelik (2022) highlighted grit’s role in reducing academic stress, suggesting its protective effects in demanding academic environments. The high levels of self-reported grit among these students may contribute to their ability to persist through the challenges of their program. However, the presence of variability across items suggests that grit may manifest differently across various academic situations.

These results have important implications for educational practice. While students demonstrate strong persistence overall, the areas with relatively lower scores might represent opportunities for intervention. Programs designed to enhance time management skills or provide support for maintaining motivation during prolonged challenges could be particularly beneficial. Additionally, the findings support the value of developing grit as part of students' academic development, as it appears to be an important factor in their educational experiences.

The results demonstrate that BSEd-Math 1 students possess a strong growth mindset toward mathematics (Overall M = 4.17, SD = 0.61), with individual items ranging from high to very high levels of agreement. These findings suggest that future mathematics teachers in this sample maintain resilient, effort-based beliefs about mathematical ability, consistent with Dweck's (2006) mindset theory (see Table 3).

Table 3. Mathematical Mindset of BSEd-Math 1 Students

	M	SD	Interpretation
1. No matter how much math intelligence I have, I will be able to improve it.	4.18	0.64	High
2. If other people can master mathematics, then I can too.	4.24	0.75	Very High
3. I am aware that I do not have talent in mathematics, but I will do everything I can to become an expert in mathematics.	4.12	0.70	High
4. Even though the lecturer thinks my effort will be useless, I still want to prove that mathematics is a science that anyone can master.	4.24	0.83	Very High
5. I will keep asking anyone until I can really understand mathematics.	4.35	0.70	Very High
6. Even though my friends say that studying without having mathematical talent will be useless, I think otherwise.	3.59	1.06	High
7. Mastering mathematics is not an easy job, but there are opportunities to learn and understand it little by little.	4.53	0.72	Very High
8. Even though I've been told I'm not intelligent many times, I will keep asking questions until I finally understand mathematics.	4.24	0.75	Very High
9. The mathematics lecturer's criticism of me challenged me to prove that I could be better.	3.94	1.03	High
10. A bad grade in mathematics challenges me to continue to master it.	4.18	0.88	High
11. Even though my teacher said that I had no hope in mathematics, I wanted to keep trying.	4.24	0.66	Very High
Overall	4.17	0.61	High

Several particularly noteworthy findings emerged. The highest-rated item, "Mastering mathematics is not an easy job, but there are opportunities to learn and understand it little by little" (M = 4.53, SD = 0.72), along with other very high scoring items about persistence in asking questions (M = 4.35) and belief in one's ability to improve (M = 4.24), reveal a pattern of determined, incremental learning attitudes. This aligns with research showing that growth mindset predicts persistence in STEM fields (Yeager et al., 2019).

While all items scored in the high range, some interesting variations appear. The statement about peer influence ("Even though my friends say that studying without having mathematical talent will be useless...") received the lowest score (M = 3.59, SD = 1.06), suggesting social perceptions may present unique challenges to mindset maintenance. Similarly, responses to lecturer criticism (M = 3.94) showed slightly more variability, indicating these situations may test students' mindset beliefs more than other academic challenges.

These findings have important implications for mathematics education. The generally high growth mindset scores are encouraging for teacher preparation programs, as teachers' mathematical mindsets influence their future pedagogical approaches (Boaler, 2016). The high growth mindset is consistent with research by Polirstok (2017), which emphasized that growth mindset enhances persistence and helps students overcome challenges, particularly in mathematics. Moreover, Wu et al. (2022) identified that students with high grit and growth mindset profiles consistently performed better in mathematics, supporting the interconnectedness of these traits in fostering success.

Table 4 presents the perceptions of BSEd-Mathematics 1 students regarding the use of technology in teaching and learning. The overall mean score of 4.05 (SD = 0.52) indicates a high level of agreement, suggesting that students generally have a positive perception of technology integration in education.

Table 4. Perception of Technology in Teaching and Learning of BSEd-Math 1 Students

	M	SD	Interpretation
1. Technology enhances my learning experience.	4.24	0.66	Very Positive
2. I find it easy to use technology in classroom activities.	4.12	0.86	Positive
3. Technology makes lessons more engaging and interactive.	4.06	0.66	Positive
4. I feel confident using technology for learning purposes.	3.94	0.66	Positive
5. Technology helps me understand complex concepts better.	4.06	0.83	Positive
6. The use of technology in teaching motivates me to learn more.	3.94	0.66	Positive
7. Technology allows me to learn at my own pace.	4.06	0.83	Positive
8. I find technology useful in collaborating with classmates on tasks.	4.18	0.53	Positive
9. Technology provides access to additional learning resources that improve my understanding.	4.47	0.72	Very Positive
10. I feel that using technology makes lessons more enjoyable.	3.82	0.81	Positive
11. Technology improves my ability to retain knowledge.	3.71	0.69	Positive
12. I feel more connected with my teacher when technology is used in teaching.	3.88	0.78	Positive
13. Technology helps me organize and manage my learning tasks effectively.	3.71	0.69	Positive
14. I believe that technology plays a critical role in modern education.	4.24	0.83	Very Positive
15. The use of technology in teaching prepares me for future career opportunities.	4.35	0.70	Very Positive
Overall	4.05	0.52	Positive

Among the individual items, the highest-rated statement was “Technology provides access to additional learning resources that improve my understanding” with a mean of 4.47 (SD = 0.72), interpreted as very positive. This emphasizes the perceived value of technology in enriching learning through resource accessibility, consistent with studies highlighting the internet's role in expanding learners’ access to materials (Johnson et al., 2016).

Three other items also received very positive ratings: “Technology enhances my learning experience” (M = 4.24, SD = 0.66), “I believe that technology plays a critical role in modern education” (M = 4.24, SD = 0.83), and “The use of technology in teaching prepares me for future career opportunities” (M = 4.35, SD = 0.70). These responses reflect a strong recognition of technology’s relevance not only for current learning but also for future professional readiness, aligning with 21st-century skills frameworks (Trilling & Fadel, 2009).

The item with the lowest mean was “Technology improves my ability to retain knowledge” (M = 3.71, SD = 0.69), though still interpreted as positive. This may suggest that while students appreciate the utility of technology, its impact on long-term retention may be perceived as less direct, possibly due to varied learning strategies and cognitive preferences (Fleming, 2001).

The findings imply that BSEd-Math 1 students are receptive to the integration of technology in education and acknowledge its role in enhancing learning, engagement, collaboration, and future preparedness. These results underscore the importance of sustaining and improving technology-supported instructional practices in teacher education programs.

This study examined how students experienced engagement in mathematics through content, peer interaction, and teacher facilitation within a technology-integrated, problem-based learning environment. Thematic analysis of student responses surfaced three key themes: Technology-Enhanced Pedagogy, Collaborative Learning Dynamics, and Teacher-Led Engagement Strategies (see Table 5).

Table 5. Thematic Analysis of Student Engagement in Technology-integrated Problem-based Learning (TIPBL) Strategy

Theme (Frequency)	**Theme Description**	**Sub-Theme (Frequency)**	**Sub-Theme Description**	**Code (Frequency)**	**Example Quotations (Student-Question)**
Technology-Enhanced Pedagogy (23)	Examines how digital tools and technology-mediated instruction enhance engagement in mathematics learning.	Digital Tool Efficacy (13)	Focuses on technological applications that improve engagement through interactivity and efficiency.	Interactive Software (8)	"The app offered hints and instant feedback." (S3-Q1)
				Gamified Learning (5)	"Games made math fun." (S2-Q1)

Theme (Frequency)	Theme Description	Sub-Theme (Frequency)	Sub-Theme Description	Code (Frequency)	Example Quotations (Student-Question)
		Skill Transfer (7)	Highlights how technology facilitates real-world application of mathematical concepts.	Real-World Application (7)	"Modeling investments showed practical value." (S9-Q1)
		Accessibility Challenges (3)	Identifies barriers to implementing technology-enhanced learning.	Resource Barriers (3)	"Most lacked laptops, limiting participation." (S11-Q1)
Collaborative Learning Dynamics (22)	Encompasses peer interactions that enhance mathematical understanding and motivation through social learning processes.	Cognitive Synergy (14)	Focuses on intellectual benefits of peer collaboration.	Diverse Problem-Solving (6)	"Classmates explained concepts in new ways." (S2-Q2)
				Collective Knowledge Construction (8)	"Brainstorming led to optimal solutions." (S10-Q2)
		Affective Support (8)	Emotional and motivational aspects of peer interaction.	Motivational Peer Interactions (8)	"Group's encouragement boosted confidence." (S16-Q2)
		Role Specialization (3)	How students divide tasks during collaborative work.	Task Delegation (3)	"Some solved, others wrote the report." (S2-Q2)
Teacher-Led Engagement Strategies (16)	Covers instructional approaches that foster engagement through designed learning experiences.	Active Learning Design (16)	Hands-on, problem-centered instructional methods.	Problem-Based Instruction (9)	"Real-world tasks made math relevant." (S2-Q3)
				Hands-On	"Hands-on tasks

Theme (Frequency)	Theme Description	Sub-Theme (Frequency)	Sub-Theme Description	Code (Frequency)	Example Quotations (Student-Question)
				Activities (7)	aided understanding." (S2-Q3)
		Differentiated Instruction (5)	Adapting teaching to diverse learner needs.	Adaptive Scaffolding (5)	"Teacher adjusted pacing so no one fell behind." (S10-Q3)

Technology-Enhanced Pedagogy (n = 23) was the most frequently cited theme, emphasizing how digital tools supported student engagement. Within this theme, Digital Tool Efficacy (n = 13) illustrated how applications and gamified tools facilitated motivation and sustained attention. For example, one student shared, *"The app offered hints and instant feedback"* (S3-Q1), while another noted, *"Games made math fun"* (S2-Q1). These responses align with research demonstrating that interactive digital tools enhance motivation and reduce cognitive load (Mayer, 2014; Plass et al., 2015). The sub-theme Skill Transfer (n = 7) further emphasized real-world connections, with a student remarking, *"Modeling investments showed practical value"* (S9-Q1), supporting findings that authentic problem-solving strengthens conceptual understanding (Jonassen, 2011). However, a smaller but crucial sub-theme, Accessibility Challenges (n = 3), revealed issues of digital inequality: *"Most lacked laptops, limiting participation"* (S11-Q1), underscoring the importance of addressing resource gaps to ensure equitable engagement (Warschauer, 2004).

Collaborative Learning Dynamics (n = 22) revealed the value of peer interaction in enhancing both understanding and motivation. The sub-theme Cognitive Synergy (n = 14) encompassed how working with others led to improved problem-solving. One participant stated, *"Classmates explained concepts in new ways"* (S2-Q2), while another highlighted, *"Brainstorming led to optimal solutions"* (S10-Q2), consistent with social constructivist principles (Vygotsky, 1978) and cooperative learning frameworks (Johnson & Johnson, 2009). Emotional benefits also emerged under Affective Support (n = 8), with one student expressing, *"Group's encouragement boosted confidence"* (S16-Q2), reflecting research on the social-emotional benefits of collaborative learning (Slavin, 2014). Additionally, Role Specialization (n = 3) reflected structured collaboration where task delegation supported active participation: *"Some solved, others wrote the report"* (S2-Q2), aligning with studies on productive group roles (Cohen, 1994).

Teacher-Led Engagement Strategies (n = 16) focused on instructional methods that promoted active participation. The dominant sub-theme Active Learning Design (n = 16) included responses referencing both problem-based instruction and hands-on tasks. For instance, *"Real-world tasks made math relevant"* (S2-Q3) and *"Hands-on tasks aided understanding"* (S2-Q3) show how experiential and contextualized learning activities deepened comprehension and interest, reinforcing evidence on inquiry-based learning (Hmelo-Silver, 2004). The sub-theme Differentiated Instruction (*n* = 5) captured how adaptive teaching practices fostered inclusivity: *"Teacher adjusted pacing so no one fell behind"* (S10-Q3), supporting research on responsive pedagogy (Tomlinson, 2014).

These findings reinforce the importance of a multi-dimensional engagement strategy in mathematics education. When technology is meaningfully integrated (Higgins et al., 2019), collaboration is encouraged (Webb et al., 2019), and instruction is thoughtfully designed (Hattie, 2009), students experience deeper engagement cognitively, socially, and emotionally. These insights align with constructivist theories of learning (Vygotsky, 1978) and research on technology-mediated and student-centered instruction (Boaler, 2016). Future research may explore how sustained exposure to such strategies influences long-term achievement, especially among diverse learner groups.

This study examined students' academic grit in the context of mathematics learning, particularly how they persist through difficulties, stay motivated, and commit to long-term improvement. Thematic analysis of the qualitative responses revealed three major themes: Resilience in Learning (*n* = 38), Motivational Foundations (*n* = 21), and Cognitive & Emotional Strategies (*n* = 16). These themes highlight the multidimensional nature of grit, encompassing behavioral, motivational, and psychological factors that support students' perseverance in mathematics, consistent with contemporary frameworks of academic resilience (Martin, 2013) and self-regulated learning (Panadero, 2017) (see Table 6).

Table 6. Emergent Themes, Sub-themes, Codes, and Exemplary Quotations on Academic Grit in Mathematics Learning

Theme (Frequency)	Theme Description	Sub-Theme (Frequency)	Sub-Theme Description	Codes (Frequency)	Exemplary Quotations (Student-Question)
Resilience in Learning (38)	Students' capacity to endure challenges through persistence and adaptive strategies.	Persistence Through Challenges (22)	Sustained effort despite difficulties, demonstrating determination.	Perseverance (14)	"I kept trying different methods, like breaking the problem into smaller parts." (S2-Q1)
				Goal-Oriented Behavior (8)	"I set small goals, like mastering one concept at a time." (S3-Q2)
		Adaptive Problem-Solving (16)	Cognitive strategies to manage and overcome challenges.	Coping Strategies (16)	"Taking short breaks helped refresh my mind." (S3-Q1)
Motivational	Driving forces	Intrinsic Drivers	Motivation from	Motivational	"My love for

Theme (Frequency)	Theme Description	Sub-Theme (Frequency)	Sub-Theme Description	Codes (Frequency)	Exemplary Quotations (Student-Question)
Foundations (21)	behind persistence, including internal/external motivators and social support.	(7)	personal values, interests, or identity.	Drivers (Internal) (7)	mathematics helps me stay committed." (S4-Q2)
		Extrinsic Drivers (5)	External rewards or obligations that motivate effort.	Motivational Drivers (External) (5)	"I want to pay off my parents' sacrifices." (S1-Q2)
		Social Reinforcement (9)	Interpersonal support systems encouraging persistence.	Social Support (9)	"The support of my classmates motivated me." (S9-Q1)
Cognitive & Emotional Strategies (16)	Mental frameworks and self-regulation techniques to interpret challenges.	Growth Mindset (10)	Belief that abilities can develop through effort.	Mindset Shifts (10)	"Struggling is part of learning." (S2-Q1)
		Self-Regulation (6)	Emotional management and reward systems.	Coping Strategies (Emotional) (6)	"I give myself rewards for small accomplishments." (S15-Q1)

The most prominent theme, Resilience in Learning (n = 38), reflects students' capacity to sustain effort and adapt when encountering difficult mathematical tasks. Within this theme, the sub-theme Persistence Through Challenges (n = 22) captured students' unwavering determination to complete tasks despite obstacles. A student expressed, *"I kept trying different methods, like breaking the problem into smaller parts"* (S2-Q1), showcasing perseverance—a core component of grit as conceptualized by Duckworth et al. (2007). This aligns with research demonstrating that task decomposition improves problem-solving efficacy (Jonassen, 2011). Additionally, students exhibited Goal-Oriented Behavior (n = 8), setting small, manageable objectives to stay focused, such as *"mastering one concept at a time"* (S3-Q2). These behaviors suggest an intentional and sustained approach to learning, aligning with findings by Eskreis-Winkler et al. (2014), who emphasize the importance of long-term goals in academic perseverance, as well as Locke and Latham's (2002) goal-setting theory.

Furthermore, the sub-theme Adaptive Problem-Solving (n = 16) illustrated how students manage stress and confusion through practical coping strategies. One participant noted, *"Taking short breaks helped refresh my* *mind"* (S3-Q1), highlighting the importance of self-awareness and cognitive flexibility in overcoming academic setbacks. These adaptive behaviors are essential for self-regulated learning and reflect a resilience-oriented mindset (Martin & Marsh, 2006), particularly the role of "academic buoyancy" in navigating daily challenges (Martin, 2013).

The second major theme, Motivational Foundations (*n* = 21), encompassed the internal and external forces that sustain students' grit in mathematics. Intrinsic Drivers (*n* = 7) included passion for the subject and personal fulfillment. For example, a student remarked, *"My love for mathematics helps me stay committed"* (S4-Q2), reflecting a deep-seated connection between identity and motivation. This aligns with research suggesting that intrinsic motivation enhances engagement and persistence (Ryan & Deci, 2000), particularly when students perceive mathematics as personally meaningful (Middleton et al., 2017).

In contrast, Extrinsic Drivers (*n* = 5) focused on obligations or rewards, such as familial expectations. One student shared, *"I want to pay off my parents' sacrifices"* (S1-Q2), demonstrating how external motivators can foster academic effort, especially in collectivist cultures where family support plays a pivotal role (King & McInerney, 2016). Such findings resonate with the cross-cultural literature on achievement motivation (Bernardo et al., 2018).

Moreover, Social Reinforcement (*n* = 9) highlighted the role of peer and teacher support in maintaining motivation. As one participant stated, *"The support of my classmates motivated me"* (S9-Q1). These findings support the view that academic grit is socially influenced and may be enhanced through positive educational environments (Credé et al., 2017), particularly via teacher-student relationships that foster belonging (Furrer & Skinner, 2003).

The final theme, Cognitive & Emotional Strategies (*n* = 16), reflected students' mental models and emotional regulation during mathematical challenges. The sub-theme Growth Mindset (*n* = 10) was evident in students who believed that effort leads to improvement. For instance, one student stated, *"Struggling is part of learning"* (S2-Q1), illustrating Dweck's (2006) assertion that growth-oriented beliefs foster resilience and motivation, particularly in STEM fields (Claro et al., 2016).

Additionally, Self-Regulation (*n* = 6) encompassed emotional management strategies such as self-reward systems. One student shared, *"I give myself rewards for small accomplishments"* (S15-Q1), indicating a high level of metacognitive control. These behaviors support Zimmerman's (2002) model of self-regulated learning, in which emotional regulation and self-monitoring are essential components of persistence, as well as broader theories of volitional strategy use (Wolters, 2003).

This study also investigated students' mathematical mindsets and their strategies for handling challenging mathematical tasks. Thematic analysis of qualitative responses revealed three main themes: Problem-Solving Approaches (*n* = 31), Mindset Toward Mathematics (*n* = 23), and Metacognitive Reflections (*n* = 20). These themes highlight the cognitive, affective, and reflective dimensions of students' engagement with mathematics, aligning with frameworks that emphasize self-regulated learning (Zimmerman, 2002) and sociocultural influences

(Vygotsky, 1978) (see Table 7).

Table 7. Emergent Themes, Sub-themes, Codes, and Exemplars from Students' Responses about Mathematical Mindset

Theme (Frequency)	**Theme Description**	**Sub-Theme (Frequency)**	**Sub-Theme Description**	**Codes (Frequency)**	**Exemplar Quotations (Student-Question)**
Problem-Solving Approaches (31)	Strategies and behaviors students use to tackle challenging math problems.	Strategic Methods (13)	Structured, self-directed techniques for problem decomposition and resource use.	Systematic Breakdown (8)	S3-Q1: "Broke it down step-by-step." S9-Q1: "Persistence and step-by-step approach."
				Resource Utilization (5)	S4-Q1: "Searched online." S13-Q1: "Used Excel tools."
		Collaborative Learning (9)	Reliance on social interactions to overcome challenges.	Peer/Instructor Support (9)	S5-Q1: "Asked teacher/classmates." S11-Q1: "Group study enhanced understanding."
		Adaptive Resilience (9)	Persistence and help-seeking behaviors in response to difficulty.	Persistence (7)	S10-Q1: "Never give up despite difficulties."
				Help-Seeking (6)	S6-Q1: "Asked professor for clarification." S14-Q1: "Peer assistance."
Mindset Toward Mathematics (23)	Students' beliefs and emotional responses about math learning, especially toward mistakes.	Growth Orientation (23)	Viewing challenges and errors as opportunities for mastery.	Mistakes as Learning Tools (14)	S1-Q2: "Mistakes as an opportunity to grow." S7-Q2: "Invaluable tools for growth."
				Self-Improvement	S4-Q2: "Strengthens understanding."

Theme (Frequency)	Theme Description	Sub-Theme (Frequency)	Sub-Theme Description	Codes (Frequency)	Exemplar Quotations (Student-Question)
				(9)	S10-Q2: "Mistakes motivate progress."
		Emotional Trajectories (9)	Shifts in affective states during problem-solving.	Frustration → Motivation (6)	S8-Q2: "Discouraged at first, then motivated." S9-Q2: "Shift from failure to learning."
				Enjoyment Despite Difficulty (3)	S15-Q2: "Enjoy math even when hard."
Metacognitive Reflections (20)	Students' awareness and evaluation of their learning processes.	Learned Insights (12)	Key takeaways about conceptual clarity and process-oriented learning.	Conceptual Clarity (7)	S1-Q1: "Relearned from the start." S5-Q1: "Active listening matters."
				Process Over Outcome (5)	S5-Q2: "Errors are hurdles, not failures." S13-Q1: "Tools matter as much as math."
		Behavioral Adjustments (8)	Intentional changes to future strategies based on reflection.	Strategy Refinement (8)	S2-Q2: "Checked steps to correct mistakes." S13-Q2: "Avoid repeating mistakes."

The most frequently occurring theme, Problem-Solving Approaches (*n* = 31), encompassed the various strategies and behaviors students employed to address difficult math problems. Within this theme, Strategic Methods (*n* = 13) emerged as a significant sub-theme, with students demonstrating structured and self-directed problem-solving techniques. For example, a student noted, *"I broke it down step-by-step"* (S3-Q1), reflecting a deliberate and organized approach consistent with Polya's (1945) heuristic model of problem-solving. The use of tools and resources was also prevalent, as seen in *"Used Excel tools"* (S13-Q1), showing students' inclination to utilize digital aids, which research suggests can enhance procedural fluency (Rittle-Johnson et al., 2015).

Another prominent sub-theme was Collaborative Learning (*n* = 9), where students described engaging with peers or instructors to overcome mathematical challenges. Statements such as *"Group study enhanced understanding"* (S11-Q1) illustrate the social nature of learning and are supported by Vygotsky's (1978) emphasis on the role of social interaction in cognitive development, as well as more recent work on collaborative problem-solving (Hmelo-Silver et al., 2013).

Additionally, the sub-theme Adaptive Resilience (n = 9) reflected students' persistence and help-seeking behaviors. *"Never give up despite difficulties"* (S10-Q1) was one such quote illustrating students' grit and adaptability. These findings are consistent with Duckworth et al.'s (2007) conceptualization of perseverance as a key contributor to academic success and Yeager and Dweck's (2012) research on resilience in academic contexts.

The second major theme, Mindset Toward Mathematics (n = 23), captured students' beliefs and emotional orientations, especially in relation to mistakes. The dominant sub-theme here was Growth Orientation (n = 23), with students viewing errors as stepping stones to improvement. One participant emphasized, *"Mistakes are an opportunity to grow"* (S1-Q2), reflecting Dweck's (2006) theory of a growth mindset, which has been linked to increased resilience and achievement in mathematics (Claro et al., 2016).

Within this growth-oriented perspective, students highlighted Mistakes as Learning Tools (n = 14) and Self-Improvement (n = 9). These responses suggest that students perceive errors not as failures but as valuable feedback mechanisms, a perspective supported by research on productive failure (Kapur, 2008). Another layer of this theme involved Emotional Trajectories (n = 9), revealing the dynamic affective responses students experience. For instance, a student shared, *"Discouraged at first, then motivated"* (S8-Q2), demonstrating how emotional responses can evolve positively through persistence and reflection, a process aligned with Pekrun's (2006) control-value theory of achievement emotions. Interestingly, even in the face of difficulty, a minority of students reported Enjoyment Despite Difficulty (n = 3), suggesting the presence of intrinsic motivation in learning mathematics (Boaler, 2016; Ryan & Deci, 2000).

The third major theme, Metacognitive Reflections (n = 20), emphasized students' awareness of their own learning processes. The sub-theme Learned Insights (n = 12) included reflections on conceptual clarity and the importance of understanding processes over merely obtaining correct answers. One student remarked, *"Relearned from the start"* (S1-Q1), signifying a reflective and conceptually grounded approach to learning, echoing Schoenfeld's (1992) work on metacognition in mathematics.

Another sub-theme, Behavioral Adjustments (n = 8), revealed that students made intentional changes to their learning strategies based on past experiences. For example, *"Checked steps to correct mistakes"* (S2-Q2) demonstrates an evaluative mindset and aligns with Zimmerman's (2002) model of self-regulated learning and Winne and Hadwin's (1998) COPES framework. These behaviors are indicative of higher-order thinking and metacognitive engagement, which are crucial for sustained learning success (Veenman et al., 2006).

The thematic analysis, based on students' responses to questions about the role of technology in learning mathematics, revealed four central themes, supported by a total of 87 coded quotations. These themes reflect students' perceptions of both the benefits and drawbacks of integrating technology in mathematical problem-solving, aligning with contemporary frameworks of digital pedagogy (Selwyn, 2016) and equitable access (Warschauer, 2004). The identified themes include Enhanced Learning Efficiency (n = 37), Interactive and Engaging Learning (n = 18), Dependency and Critical Thinking Erosion (n = 26), and Equity and Access Barriers (n = 6), where n refers to the number of supporting quotations (see Table 8).

Table 8. Emergent Themes, Sub-themes, Codes, and Exemplary Quotations on Students' Perceptions of Technology in Teaching and Learning

Theme (Frequency)	**Theme Description**	**Sub-Theme (Frequency)**	**Sub-Theme Description**	**Codes (Frequency)**	**Exemplar Quotations (Student-Question)**
Enhanced Learning Efficiency (37)	Technology improves speed, accessibility, and effectiveness of math learning.	Accelerated Problem-Solving (27)	Tools that streamline mathematical processes and reduce manual effort.	Faster Solutions (16)	"Solving mathematical problems has become now so easy unlike the traditional one." (S6-Q1)
				Accessibility (11)	"One can use a calculator in mobile devices... as I did not have any scientific calculator." (S5-Q1)
		Immediate Feedback (10)	Real-time corrections and learning reinforcement.	Real-Time Correction (10)	"Technology provides immediate feedback, helping me correct mistakes quickly." (S9-Q1)
		Resource Availability (8)	Diverse digital tools catering to varied learning needs.	Diverse Tools (8)	"Online tutorials and step-by-step video explanations help when I need extra practice." (S2-Q1)
Interactive and Engaging Learning (18)	Technology makes math dynamic through visual/gamified methods.	Visualization (10)	Tools that transform abstract concepts into tangible representations.	Visual Aids (10)	"Graphing calculators... help me visualize equations." (S2-Q1)
		Gamification (8)	Game-like elements increasing motivation and retention.	Interactive Methods (8)	"Online games and apps make practicing fun." (S13-Q1)
Dependency and Critical Thinking	Unintended consequences of over-reliance on technology.	Over-Reliance (21)	Dependence hindering independent	Reduced Critical Thinking (12)	"Students become too dependent on technology, always

Theme (Frequency)	Theme Description	Sub-Theme (Frequency)	Sub-Theme Description	Codes (Frequency)	Exemplar Quotations (Student-Question)
Erosion (26)			thinking.		relying on it." (S11-Q2)
				Skill Erosion (9)	"It can weaken my problem-solving skills." (S10-Q2)
		Distraction (5)	Technology diverting attention from deep learning.	Focus Loss (5)	"Sometimes technology can be distracting." (S13-Q2)
Equity and Access Barriers (6)	Systemic challenges in technology availability/reliability.	Inequity (6)	Disparities in access and technical limitations.	Access Disparities (3)	"Not everyone has access to technology, and that is a problem." (S11-Q1)
				Technical Issues (3)	"There are some misinformation in it." (S7-Q2)

Enhanced Learning Efficiency (*n* = 37) emerged as the most frequent theme. Students commonly expressed that technology improved the speed, accessibility, and overall effectiveness of learning mathematics. The sub-theme of Accelerated Problem-Solving (*n* = 27) was particularly dominant, with students appreciating the reduction in manual effort. For instance, one noted, *"Solving mathematical problems has become now so easy unlike the traditional one"* (S6-Q1), echoing research demonstrating how computational tools can streamline procedural tasks (Rittle-Johnson et al., 2015). Similarly, the Immediate Feedback sub-theme (*n* = 10) highlighted technology's capacity to provide real-time error correction, reinforcing learning through instant responses—*"Technology provides immediate feedback, helping me correct mistakes quickly"* (S9-Q1). These responses affirm prior findings that emphasize the role of digital tools in scaffolding efficient and autonomous learning (Kay et al., 2017; Hattie & Timperley, 2007), particularly when feedback is timely and actionable (Shute, 2008).

The theme of Interactive and Engaging Learning (*n* = 18) underscores how technology contributes to motivation and understanding through gamified and visual elements. The Visualization sub-theme (*n* = 10) included references to tools like graphing calculators that aid in conceptual comprehension, as reflected in the quote, *"Graphing calculators... help me visualize equations"* (S2-Q1), supporting theories of embodied cognition (Abrahamson & Trninic, 2015). Gamification (*n* = 8) was also evident, with one student stating, *"Online games and apps make practicing fun"* (S13-Q1). These insights support previous research showing that technology can enhance engagement and deepen understanding, especially when abstract concepts are made more tangible (Boaler, 2016; Papastergiou, 2009), and when game mechanics align with learning objectives (Plass et al., 2015).

Conversely, Dependency and Critical Thinking Erosion (*n* = 26) captured students' concerns about over-reliance on technology. The sub-theme of Over-Reliance (*n* = 21) included quotations suggesting that students may default to technological solutions without engaging in independent problem-solving—*"Students become too dependent on technology, always relying on it"* (S11-Q2), a phenomenon critiqued in studies of "cognitive offloading" (Risko & Gilbert, 2016). Similarly, Skill Erosion (*n* = 9) and Reduced Critical Thinking (*n* = 12) appeared in statements like, *"It can weaken my problem-solving skills"* (S10-Q2), resonating with warnings about the decline of manual computation skills (Pape & Tchoshanov, 2001). A smaller subset addressed Distraction (*n* = 5), referring to the risk of diverted attention—*"Sometimes technology can be distracting"* (S13-Q2). These findings align with concerns in the literature about potential cognitive passivity resulting from excessive technology use (Heitin, 2016; Postman, 1992), particularly when tools are used uncritically (Carr, 2014).

Finally, the theme of Equity and Access Barriers (*n* = 6) reflects broader systemic issues. Students cited limited access to devices and inconsistent digital infrastructure. The sub-theme of Inequity (*n* = 6) was captured in remarks such as, *"Not everyone has access to technology, and that is a problem"* (S11-Q1), underscoring the persistent "second-level digital divide" in skills and usage (Van Deursen & Van Dijk, 2019). Technical Issues (*n* = 3) included concerns over misinformation or functional limitations—*"There are some misinformation in it"* (S7-Q2), highlighting the need for digital literacy alongside access (Winegar & Abbott, 2022). These concerns emphasize the intersectional nature of the digital divide (Robinson et al., 2015) and its impact on learning equity (Van Dijk, 2020).

Integration of Findings in the Context of Technology-Integrated Problem-Based Learning (TIPBL) Strategy

Academic Grit

Quantitative data revealed that students exhibit a high overall level of academic grit (M = 4.12, SD = 0.60), suggesting a strong general tendency to persevere and remain passionate about long-term academic goals. Particularly noteworthy were items reflecting persistence during difficulties (e.g., "Even if I am struggling in school, I keep trying my best" with M = 4.47) and determination to complete schoolwork regardless of difficulty. These results suggest that students are highly committed to overcoming academic challenges, consistent with Duckworth et al.'s (2007) conceptualization of grit as sustained effort and interest over time.

However, some items received slightly lower (though still high) ratings, such as balancing schoolwork with personal interests (M = 3.82) and maintaining motivation across prolonged challenges (M = 3.88). These may represent potential areas for further support or intervention, especially in helping students sustain grit in contexts requiring long-term focus and task management.

To explain and expand on the quantitative results, qualitative data were gathered and analyzed, revealing three key themes: Resilience in Learning, Motivational Foundations, and Cognitive & Emotional Strategies. These themes provided nuanced insights into how grit manifests in students' day-to-day academic lives, particularly in mathematics.

The theme Resilience in Learning reflected students' determination and adaptability, often through persistence despite challenges and goal-directed behavior—mirroring the high scores in quantitative items on perseverance and hard work. One student illustrated this by stating, "I kept trying different methods, like breaking the problem into smaller parts," reinforcing the behavioral aspects of grit observed in the survey.

The Motivational Foundations theme further clarified students' sources of persistence, revealing that both intrinsic (e.g., love for math) and extrinsic (e.g., family expectations) drivers sustain effort. This qualitative evidence complements the high self-ratings on items related to working toward goals, as it reveals the why behind the what—students' motivation is deeply personal, social, and culturally grounded.

Additionally, the theme Cognitive & Emotional Strategies uncovered how students regulate emotions and shift mindsets to maintain their effort, echoing items in the quantitative instrument related to perseverance during difficulties. Students emphasized growth mindset beliefs (e.g., "Struggling is part of learning") and self-regulation tactics like rewarding themselves—both essential components for sustaining grit in mathematics learning, especially under the demands of rigorous coursework.

The findings collectively suggest that academic grit among BSEd-Math 1 students is not only high but also complex, multifaceted, and influenced by both personal and contextual factors. Students draw upon a mixture of determination, goal-setting, emotional regulation, and social reinforcement to persevere in mathematical learning. These insights align with Martin's (2013) model of academic resilience and Zimmerman's (2002) self-regulated learning theory, both of which view persistence as embedded in dynamic learning environments.

In the context of the Technology-Integrated Problem-Based Learning (TIPBL) intervention, the findings underscore the importance of designing learning environments that not only develop mathematical thinking but also nurture grit-related skills such as goal-setting, emotional regulation, and strategic help-seeking. The grit demonstrated by students suggests they are well-positioned to benefit from problem-based learning tasks that are complex and extended over time—especially when combined with supportive technologies that promote autonomy, feedback, and collaboration.

The relatively lower scores on balancing academics with personal life also suggest that TIPBL interventions should consider scaffolding time-management and self-regulation strategies, perhaps through features like digital planners, embedded reflections, or peer-support modules. These could help students maintain grit during long-term, open-ended problem-solving processes.

Mathematical Mindset

The results from both the quantitative and qualitative strands of this study indicate that BSEd-Math 1 students hold a predominantly growth-oriented mathematical mindset, which played a crucial role in their engagement with the Technology-Integrated Problem-Based Learning (TIPBL) approach. The quantitative data show an overall high level of mathematical mindset (M = 4.17, SD = 0.61), with particularly strong agreement on items related to effort, persistence, and belief in gradual improvement. These findings suggest that students are inclined to view mathematics as a domain where competence can be developed rather than fixed—a core tenet of Dweck's (2006) growth mindset theory.

The qualitative findings offered rich elaboration of these beliefs and illustrated how students enact and reflect on their mindsets in real learning situations. The most frequently cited theme, Problem-Solving Approaches, highlights the behavioral dimension of mindset—how students strategically approach challenges, seek support, and demonstrate persistence in mathematical problem-solving. For example, students reported "breaking problems down step-by-step" (S3-Q1) and using online tools or Excel (S13-Q1), behaviors aligned with Polya's (1945) heuristic model and modern conceptions of technologically supported problem-solving (Rittle-Johnson et al., 2015). This strategic behavior reinforces the idea that a growth mindset not only shapes beliefs but also guides effective learning behaviors.

The sub-theme of Collaborative Learning showed that students valued peer and instructor support—consistent with Vygotsky's (1978) sociocultural theory, which emphasizes the importance of social interactions in cognitive development. These interactions appeared to buffer against discouragement and reinforced students' commitment to learning, even when the mathematical content was challenging.

The second main theme, Mindset Toward Mathematics, provided insight into the emotional and cognitive orientations students held toward learning. Nearly all students expressed growth-oriented responses to mistakes, framing them as valuable learning tools rather than signs of failure. This finding directly supports quantitative results like the high agreement with the item, "Even though I've been told I'm not intelligent many times, I will keep asking questions until I finally understand mathematics" ($M = 4.24$). Students shared quotes like, "Mistakes are an opportunity to grow" (S1-Q2), demonstrating the productive failure mindset described by Kapur (2008) and the resilience highlighted by Yeager and Dweck (2012).

Additionally, the sub-theme Emotional Trajectories revealed how students' affect shifted from frustration to motivation—indicating that the TIPBL environment may have served as a catalyst for transformative emotional experiences. For instance, one student noted, "Discouraged at first, then motivated" (S8-Q2), reflecting how persistence and a supportive learning structure can enhance emotional resilience (Pekrun, 2006).

The third major theme, Metacognitive Reflections, added a reflective layer to students' mindsets. Sub-themes like Learned Insights and Behavioral Adjustments highlighted students' awareness of their own learning processes and their capacity to change ineffective strategies—an important marker of self-regulated learning (Zimmerman, 2002). For example, students mentioned "relearning from the start" (S1-Q1) and "checking steps to correct mistakes" (S2-Q2), showing not only a growth mindset but also metacognitive control and intentional learning regulation (Winne & Hadwin, 1998; Veenman et al., 2006).

These integrated findings suggest that the TIPBL approach not only fostered cognitive engagement but also created opportunities for students to develop more resilient, reflective, and socially supported mathematical mindsets. The slight variation in quantitative responses—such as lower agreement on resisting peer discouragement (M = 3.59)—was illuminated by qualitative data emphasizing the importance of peer support and social influence in shaping mindset beliefs. This underscores the value of explanatory sequential mixed-methods in capturing the nuanced interplay between belief, behavior, and context.

Perception of Technology in Teaching and Learning

The study also provides a comprehensive understanding of BSEd-Mathematics 1 students' perceptions of technology in teaching and learning, as influenced by the Technology-Integrated Problem-Based Learning (TIPBL) strategy. The quantitative results revealed an overall positive perception (M = 4.05, SD = 0.52), with the highest ratings attributed to technology's role in enhancing learning experiences, increasing access to resources, and preparing students for future careers. These findings were further explained and enriched by the qualitative phase, consistent with the modified explanatory sequential mixed-methods approach (Creswell & Plano Clark, 2018).

The theme of Enhanced Learning Efficiency, which emerged as the most prominent in the qualitative phase (n = 37), provides insight into why students rated items related to resource availability and learning enhancement so highly. The highest-rated item in the survey—"Technology provides access to additional learning resources that improve my understanding" (M = 4.47)—is consistent with qualitative reports of improved speed, accessibility, and effectiveness. Sub-themes such as Accelerated Problem-Solving and Immediate Feedback reflect students' appreciation of digital tools that streamline complex computations and offer real-time correction, thereby reinforcing autonomous learning. These findings are consistent with the literature on digital scaffolding and feedback systems (Hattie & Timperley, 2007; Shute, 2008). Furthermore, students reported that technology facilitated individualized learning at their own pace (M = 4.06), and improved conceptual understanding, aligning with prior studies on personalized learning through educational technology (Kay et al., 2017).

Quantitative results also showed strong agreement with statements such as "Technology makes lessons more engaging and interactive" (M = 4.06). This is supported by the qualitative theme Interactive and Engaging Learning, which highlighted the use of visual tools and gamified applications. Sub-themes of Visualization and Gamification illustrated how technology transformed abstract mathematical concepts into more tangible and motivating experiences. For instance, students cited the usefulness of graphing calculators and educational games in enhancing their learning engagement. These findings align with theories of embodied cognition (Abrahamson & Trninic, 2015) and research showing increased motivation and retention through game-based learning (Papastergiou, 2009; Plass et al., 2015).

The alignment between the quantitative and qualitative phases affirms that the TIPBL strategy effectively fosters active and engaging learning environments—one of the core goals of technology integration in modern pedagogical frameworks (Boaler, 2016; Trilling & Fadel, 2009). While the quantitative results were generally positive, the qualitative theme Dependency and Critical Thinking Erosion offers a cautionary perspective. Students expressed concerns about over-reliance on technology, reporting reduced problem-solving and critical thinking skills. Although confidence in using technology (M = 3.94) and its effect on knowledge retention (M = 3.71) were rated positively, the qualitative data reveal nuanced reservations. Statements such as "Students become too dependent on technology" and "It can weaken my problem-solving skills" point to the phenomenon of cognitive offloading, where learners defer too readily to technological tools (Risko & Gilbert, 2016).

These insights emphasize the importance of integrating technology in ways that still encourage independent reasoning and critical engagement—essential goals of the TIPBL framework. Without mindful use, technology may inadvertently hinder the development of deeper cognitive skills (Carr, 2014; Postman, 1992).

Although the item "I find it easy to use technology in classroom activities" (M = 4.12) was positively rated, the qualitative theme Equity and Access Barriers revealed underlying disparities. Some students reported lacking access to reliable devices or internet connections, highlighting issues of digital inequality. The sub-themes Inequity and Technical Issues support the notion of a "second-level digital divide," where students have unequal opportunities not only in access but also in meaningful usage of technology (Van Deursen & Van Dijk, 2019; Warschauer, 2004). These findings underscore the necessity of equitable implementation strategies, particularly in diverse learning contexts.

The divergence between quantitative and qualitative data in this theme exemplifies the value of explanatory sequential design, as the follow-up qualitative phase uncovered systemic issues masked by averaged numerical results. Aligned with the action research framework, the integrated findings provide actionable insights for improving the TIPBL strategy. First, technology-enhanced tools that promote individualized and engaging learning should be sustained and refined. Second, instructional practices should aim to balance technological support with opportunities for developing critical thinking. Finally, issues of access and equity must be addressed to ensure inclusive implementation of technology-integrated strategies.

Conclusions

This study aimed to investigate the influence of Technology-Integrated Problem-Based Learning (TIPBL) on the engagement, academic grit, mathematical mindset, and perception of technology in teaching and learning among first-year BSEd-Mathematics students at Biliran Province State University. The findings demonstrate that students exhibited high levels of academic grit, characterized by perseverance and resilience, even in the face of academic challenges. Furthermore, students maintained a growth-oriented mathematical mindset, showing a strong belief in their ability to improve their mathematical competence through effort and persistence. The study also revealed that students held a generally positive perception of technology's role in enhancing their learning experiences, although concerns about technology dependency and digital inequities emerged.

In line with these findings, TIPBL proved to be an effective strategy for developing engagement, supporting their academic resilience and development of critical thinking skills. The integration of technology in the learning process provided students with the tools to engage more deeply with mathematical content, while also enhancing their problem-solving abilities and access to learning resources. In addition to academic grit and mathematical mindset, the study highlighted the students' positive perceptions of technology in teaching and learning, emphasizing how TIPBL effectively integrated technological tools to support learning and problem-solving.

The high levels of academic grit observed suggest that students are well-equipped to navigate the challenges of TIPBL environments, leveraging both intrinsic and extrinsic motivation. Similarly, students' growth-oriented mindset in mathematics played a significant role in their engagement with the TIPBL strategy, developing persistence and strategic problem-solving behaviors. However, despite positive perceptions of technology's role in enhancing learning experiences, concerns regarding over-reliance on technology and unequal access to resources point to areas that require further attention to ensure the equitable and effective implementation of TIPBL.

Recommendations

Based on the findings of this study, several recommendations can be made to enhance the effectiveness of the Technology-Integrated Problem-Based Learning (TIPBL) strategy. These recommendations aim to build upon the strengths observed in students' academic grit, mathematical mindset, and perceptions of technology, while addressing areas that could benefit from further improvement:

1. *Enhance Technology Integration for Critical Thinking:* Although the technology proved beneficial in the TIPBL strategy, it's important to take it a step further by using digital tools that develop critical thinking and problem-solving skills. Instead of relying on technology for quick answers, educators can design tasks that encourage students to use technology in ways that promote deeper understanding and independent reasoning. For instance, digital tools can be used to guide students through problem-solving steps, while leaving room for them to make decisions and think through solutions on their own.
2. *Support Time Management and Self-Regulation:* Many students faced difficulties in balancing academic work with their personal lives. To help students maintain their focus and perseverance, TIPBL interventions should incorporate strategies for better time management and self-regulation.
3. *Address Digital Inequities:* The study revealed that some students struggled with access to reliable technology and the internet, which could limit their participation in TIPBL. To create a truly inclusive environment, it's essential that institutions provide students with access to the resources they need. This could include lending programs for devices or offering hybrid learning models where not all content relies on digital tools, ensuring that every student can fully engage in the learning process.
4. *Develop Collaborative Learning and Peer Support:* The study highlighted the importance of peer and instructor support in helping students develop a growth-oriented mindset toward mathematics. Moving forward, TIPBL should continue to provide opportunities for collaborative learning, where students can work together, share strategies, and encourage each other.
5. *Further Research on the Long-Term Impact of TIPBL:* Although this study showed promising results, further research is needed to explore the long-term effects of TIPBL on students' academic grit, mindset, and technology perceptions. Longitudinal studies can offer deeper insights into how these factors evolve as students' progress in their academic journeys. This could inform the refinement of TIPBL strategies to better support students as they advance through their educational careers.

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Trends in Professional Development of Mathematics Teachers Using Topic Modeling: A Scoping Review

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Abstract

Professional development for mathematics teachers is a prerequisite for effective student learning. This study conducted a topic modeling analysis of 1,330 articles on the professional development of mathematics teachers published over 20 years from 2004 to 2024. As a result, ten topics related to the professional development of mathematics teachers were identified. These topics are popular research areas that have received a lot of attention from researchers during this period. To track trends in the field, a time-series regression analysis and annual trends in topic proportion were also examined. The 10 topics exhibited different research trends, including increasing, decreasing, and stable trends. The three topics Assessment, Technology, and Lesson reflection and Noticing emerged as hot topics that showed a significant increase in research interest during the period. The interest of researchers focused on the 10 topics varied depending on the year, but the studies were continuously conducted on most of them as time progressed. Based on these findings, this study suggested the current state and future directions in this field.

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Introduction

The preparation of pre-service teachers (PSTs) and the ongoing professional development of in-service teachers have attracted substantial attention from researchers (Hollebrands & Lee, 2020; Scher & O'Reilly, 2009). At the heart of these initiatives lies the fundamental belief that the expertise of mathematics teachers plays a pivotal role in enhancing teaching and fostering student growth (Goldsmith et al., 2014). This process unfolds within a specific educational policy context or school culture, and the tools implemented for development vary according to the goals and needs of both the teachers and students (Avalos, 2011). Given the complexities associated with the professional development of mathematics teachers, extensive literature reviews have been conducted to synthesize previous research. The studies included mathematics professional development interventions (Scher & O'Reilly, 2009), conceptual frameworks for professional development (Goldsmith et al., 2014), and the trends in thinking and practice (Zaslavsky et al., 2003). However, these literature studies have notable limitations. Firstly, existing research tends to concentrate on specific aspects, such as interventions, frameworks, or programs, resulting in a relatively limited number of papers reviewed. Second, manual coding, which is the main approach adopted in the studies, involves a tedious coding process and can be inaccurate as it largely reflects the researcher's subjectivity (Chen et al., 2020). Therefore, there is a pressing need to employ review methods that are suited for large datasets, to overcome the limitations of existing review studies, and to provide a comprehensive overview of the trends and future directions in the professional development of mathematics teachers.

Topic modeling is a statistical method used to analyze collections of text and extract latent topics (Blei, 2012; Blei et al., 2003; Griffiths & Steyvers, 2004). Researchers can employ topic modeling to identify various underlying components that form the foundation of their study (Copur-Gencturk et al., 2023). Recently, extensive research has been conducted in applying topic modeling to the field of mathematics teacher education (e.g., Copur-Gencturk et al., 2023; Hwang et al., 2023; Lutovac & Kaasila, 2019). These studies provided insights into specific factors related to mathematics teachers (e.g., understanding, technology, identity) and implications for future research directions. However, information on research topics related to the professional development of mathematics teachers and how they have evolved remains limited. This study aims to use topic modeling to review all articles related to the professional development of mathematics teachers over the past two decades. Four main research questions guide the present study.

RQ1. How have the overall research trends in the professional development of mathematics teachers changed over time?

RQ2. What are the major research topics in the professional development of mathematics teachers?

RQ3. How have individual research topics evolved over time?

RQ4. How have the principal topics of interest among researchers changed over time?

Literature Review

Professional Development of Teachers in Mathematics Education

Professional development of teacher is an intensive, continuous, and systematic process aimed at improving education, learning, and the school environment (Elmore, 2002; Fenstermacher & Berliner, 1985). Teachers are regarded as playing a central role in mathematics instruction. "Teachers are necessarily at the center of reform, for they must carry out the demands of high standards in the classroom" (Garet et al., 2001: 916). The professional knowledge and skills of mathematics teachers have a significant impact on the quality of teaching and learning in the classroom, and consequently, on student achievement (Hill et al., 2005). Therefore, professional development for teachers has been recognized as a crucial component of policy aimed at improving the quality of teaching and learning in schools (Ingvarson et al., 2005).

Although achieving meaningful improvements in student achievement requires substantial, extended, and continuous professional development for teacher, this process is resource-intensive in terms of time, effort, and cost (Yoon et al., 2007). Teacher professional development is a gradual, nonlinear, and iterative process that involves repeated cycles of inquiry outside the classroom and experimentation within it (Goldsmith et al., 2014). Therefore, it is necessary to conduct an extensive investigation of teachers' professional development and explore the underlying factors that shape the beliefs and practices of mathematics teachers over the long term (Bernack-Schüler et al., 2015).

For this reason, numerous researchers have synthesized studies in mathematics education to examine research trends and uncover hidden factors. For example, Inglis and Foster (2018) used topic modeling to investigate articles published in two major mathematics education journals, Educational Studies in Mathematics and the Journal for Research in Mathematics Education, between 1968 and 2015, identifying 28 topics across four domains. Teacher knowledge and beliefs emerged as one of the key topics. Foster and Inglis (2019) conducted topic modeling on articles published in two major mathematics teacher professional journals in the UK (Mathematics Teaching and Mathematics in School). They identified 15 topics across three domains: mathematical content, pedagogical issues and resources, and administrative matters. Similarly, Gökçe and Güner (2021) examined 1,021 mathematics education articles published between 1980 and 2019, identifying four research domains: foundation, implementation, association, and evaluation. Previous studies provided valuable insights into understanding broader research trends and offering a comprehensive picture of mathematics education and teacher professionalism. However, there has been little extensive research reviewing which topics related to mathematics teacher professional development have been investigated and how these topics have evolved over time.

This study, rather than focusing on specific journals, included broaden the scope of the entirety of mathematics education. This study investigated research trends related to mathematics teacher professional development Using topic modeling. The following section provides a detailed explanation of the topic modeling approach used for data analysis in this study.

Topic Modeling

Topic modeling is a text mining method used to automatically organize large volumes of text into clusters, allowing researchers to explore hidden patterns in unstructured data (Papadimitriou et al., 2000). Researchers have employed topic modeling to analyze trends in large bibliographic datasets (e.g., Foster & Inglis, 2019; Inglis &

Foster, 2018; Son & Lee, 2020). Various topic modeling methods exist, including pLSA (probabilistic Latent Semantic Analysis) and LSI (Latent Semantic Indexing), but the most widely used and oldest method is LDA (Latent Dirichlet Allocation). LDA operates on a hierarchical Bayesian model with three levels—words, topics, and documents—to identify hidden topics in the collected data (Blei et al., 2003).

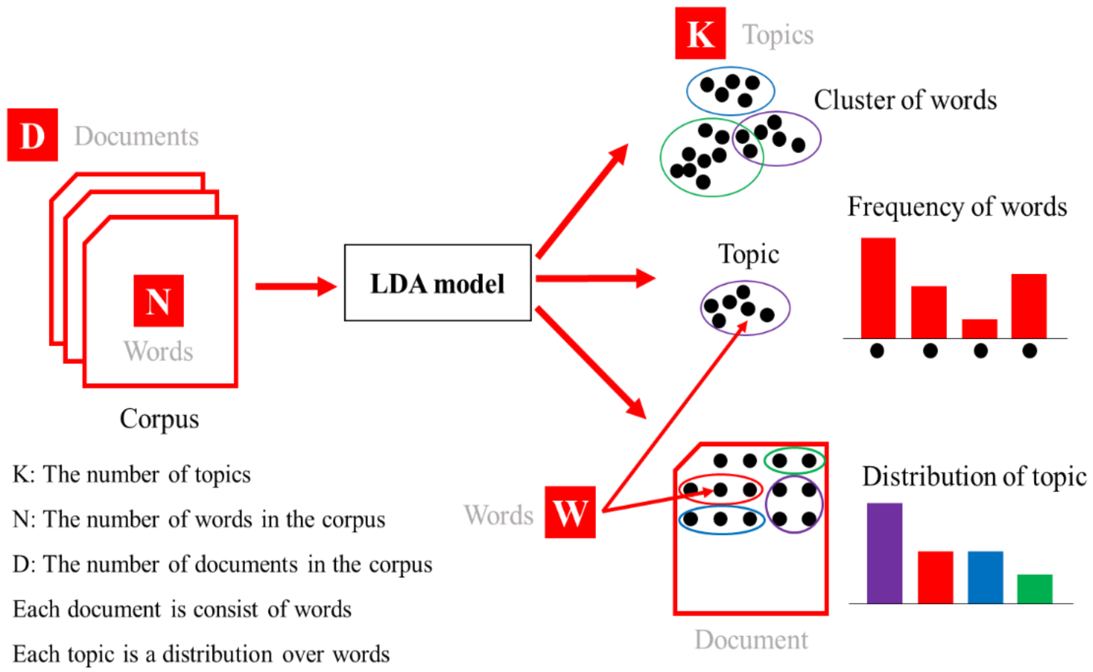

Figure 1. Visualization Model Representing the Topic Modeling Process (adapted from Bernack-Schüler et al., 2015)

Methods

Data Collection and Retrieving Process

The data collection process was conducted in five stages, following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines proposed by (Page et al., 2021). First, electronic databases of Web of Science, Education Resources Information Center (ERIC), and EBSCO Education Source were used for searching articles. The search strings were systematically formulated as shown in Table 1: (“teacher* OR teaching) AND (professional OR skill OR competence) AND (development OR improvement OR learning) AND (math OR maths OR mathematics). This search was carried out on March 1, 2024, yielding an initial result of 21,642 articles.

Table 1. Searching Strings

A	B	C	D
1. teacher*	1. professional	1. development	1. math
2. teaching	2. skill	2. improvement	2. maths
	3. competence	3. learning	3. mathematics

Note. The asterisk (*) was used to broaden a search.

Second, the collected articles were processed using EndNote reference management software to eliminate duplicates, resulting in a corpus of 15,293 articles. Third, these articles were screened based on inclusion criteria. Studies not in English or published before 2004 were excluded. To ensure academic rigor, dissertations, conference proceedings, review articles, and commentaries were eliminated, focusing on peer-reviewed articles. Fourth, articles without accessible abstracts or full texts were excluded. The primary data for topic modeling in this study were the abstracts of the papers. Abstracts are generally suitable for conceptual review as they summarize the research purposes, questions, and key findings (Cretchley et al., 2010; Yan, 2015; Zhong et al., 2016). This process yielded 2,138 articles. Fifth, a thorough review of each paper's title, abstract, and full text was conducted to exclude those not related to the professional development of mathematics teachers (e.g., articles focusing on the use of professional development programs in science education) were excluded. Consequently, this rigorous screening process resulted in the selection of 1,330 articles. Figure 2 provides a visual representation of the data collection and retrieval process, grounded in the PRISMA framework. This figure aids in illustrating the systematic approach adopted for data screening and selection.

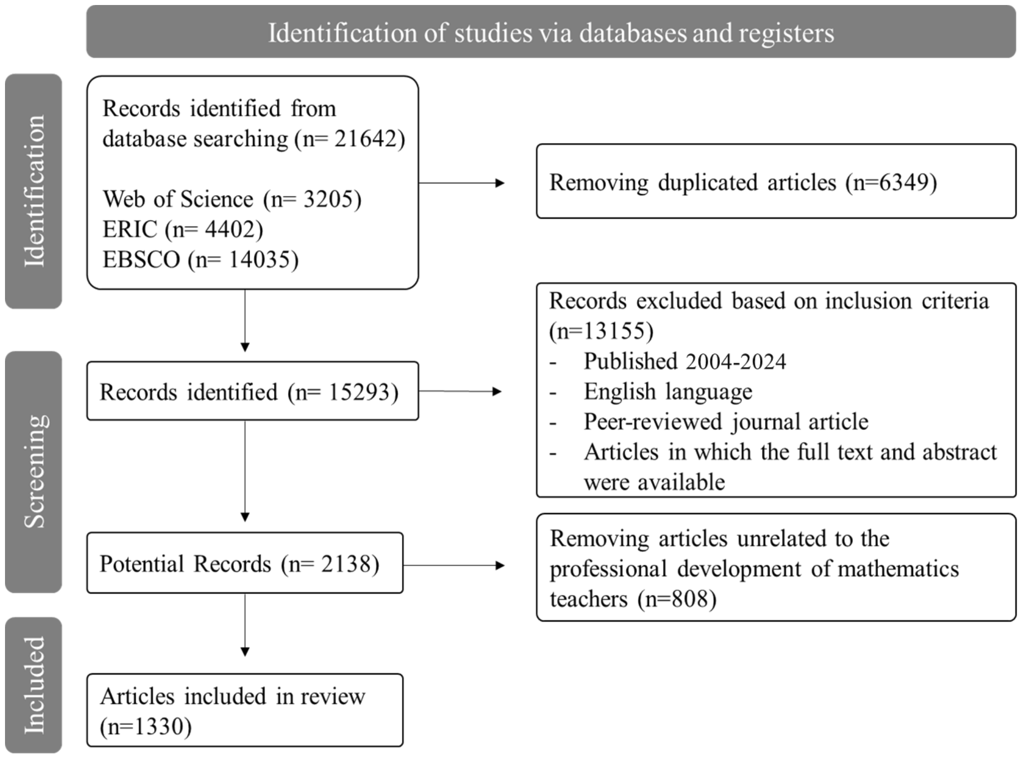

Figure 1. Data Retrieval Process Based on a PRISMA Guideline

Data Analysis

Preprocessing

Data preprocessing was carried out to enhance data quality before conducting topic modeling. First, punctuation, symbols, and stop words (e.g., in, the, and, or, I, we) were removed to increase consistency in the analysis and reduce computational loading (Boyd-graber & Blei, 2008; Hoffman et al., 2010). Second, terms were converted to their singular form and lowercase (e.g., Teachers → teacher). Third, words used with similar meanings were standardized (e.g., prospective teacher → preservice teacher). Fourth, words commonly found in all abstracts of articles, which could potentially confound the analysis, such as 'math', 'mathematics', 'author', 'journal', 'article', 'paper', 'study', were eliminated. Through these preprocessing steps, a total of 86,927 words were included in the analysis.

Determine the Optimal Number of Topics

This study employed the LDA model to identify topics within 1,330 articles related to the professional development of mathematics teachers (Blei et al., 2003). The 'topicmodels' package in R was used for conducting LDA. To determine the optimal number of topics in a dataset, researchers have widely employed statistical analysis methods such as perplexity (Inglis & Foster, 2018), harmonic mean (Griffiths & Steyvers, 2004), cosine similarity (Cao et al., 2009), and coherence (Blair et al., 2020). The number of topics, denoted as K, was set as ranging from 2 to 30, and examined the trend of the perplexity index which indicates an internal index for assessing model fit. Perplexity, which serves as an indicator of how distinct the topics are from each other, suggests that a smaller value indicates a more suitable model (Blei et al., 2003). However, perplexity index has the nature of tends to decrease the value as the number of topics increases. Therefore, it is generally advisable to select the point where there is a sharp change in the gradient (Inglis & Foster, 2018). Figure 3 demonstrates that the perplexity index is the smallest and the gradient change is most abrupt when K is 10. It indicated optimal performance at this point. Consequently, 10 topics were selected to categorize the collected data.

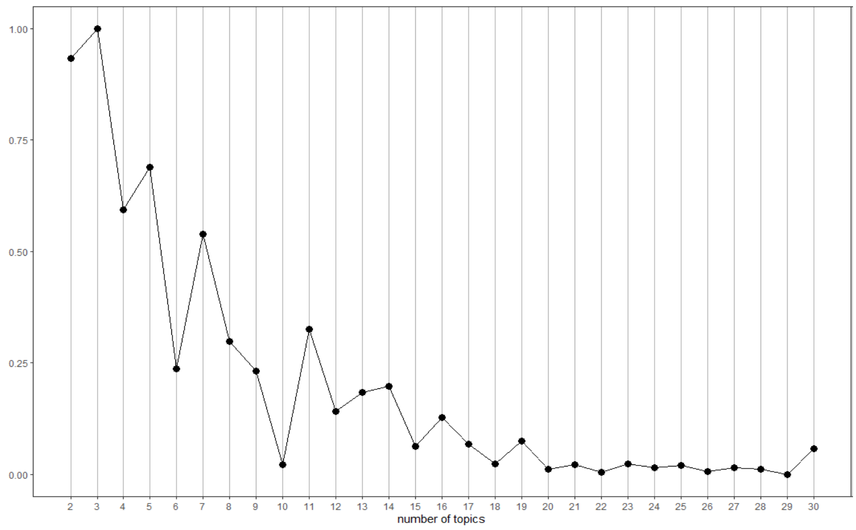

Figure 2. The Perplexity for Determining Optimal Number of Topics

Topic Labeling

Based on the identification of the number of topics, LDA was conducted on the collected data and labeled each topic. The labeling of the topics was determined by examining the top 10 representative words for each topic and the three most representative papers with the highest probability of belonging to each topic. For example, the topic *Assessment* included a set of the top 10 words: {assessment, belief, level, efficacy, test, performance, modeling, competence, attitude, view}. The three representative papers for this topic were as follows. First, Hudson et al.

(Hudson et al., 2012) assessed the beliefs of PSTs in the teaching and learning of mathematics and science. Second, Burgos and Godino (2022) analyzed and assessed the perceptions and competencies of PSTs on proportion tasks. Third, Kusaeri and Aditomo (2019) assessed the pedagogical beliefs of Indonesian mathematics PSTs regarding critical thinking and explored the potential relationship between these pedagogical beliefs and educational experiences. The topic was labeled *Assessment* based on the analysis of the top 10 words and the content of the representative papers. Labels were assigned to the other nine topics following the same strategy.

Trends Analysis

Three analysis methods were implemented to examine the research trends of the topics. First, the trend of the number of papers published each year was examined to assess the popularity and diffusion of professional development of mathematics teachers. Second, the topics that showed significant trends of increase or decrease over the years were examined. To evaluate the validity of these trends for each topic, a time-series regression analysis was conducted. The independent variable was publication year and the dependent variable was the annual proportion of each topic. Topics were labeled as 'Hot topic' when the regression coefficient was positive (+) and statistically significant ($p < 0.05$), or 'Cold topic' when it was negative (-) (Griffiths & Steyvers, 2004). Third, the distribution of topic proportions by year was visualized to investigate which topics received the most attention by year and how the topics of interest to researchers have evolved over time. This approach allows for an in-depth examination of the shifting focus on research topics within the specified time frame.

Results

Overall Research Trends

To examine the overall trends in research on the professional development of mathematics teachers, the number of published papers by publication year was visualized since 2004 (see Figure 4).

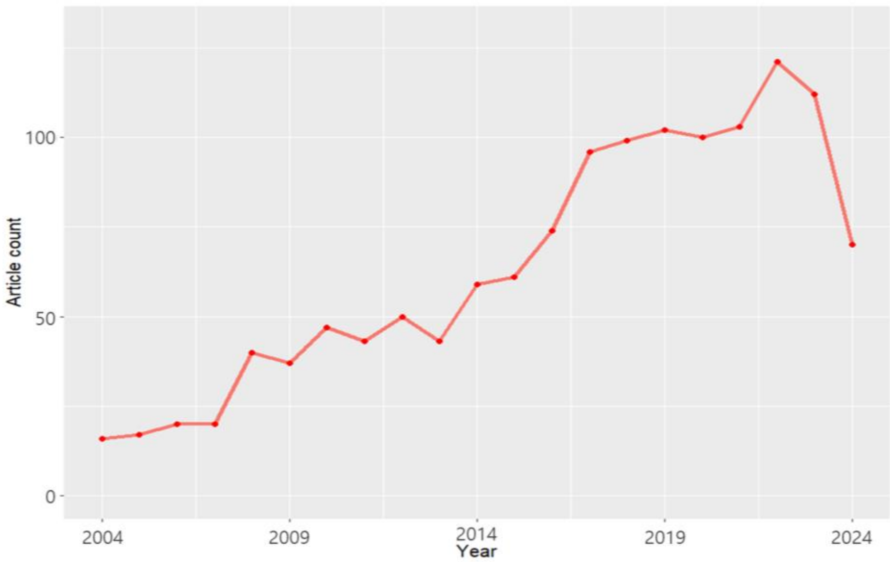

Figure 3. The Count of Articles by Publication Years

Figure 4 illustrates a progressive increase in the number of published articles over time. Table 2 shows the number of papers published in decade intervals (2004-2014 and 2015-2024). Research published between 2004 and 2014 represented only 29.5% of the total (n=392), whereas studies published between 2015 and 2024 accounted for 70.5% (n=938).

Table 2. Number of Publication Articles Per Decade

Period	The Number of Article
2004-2014	392 (29.5%)
2015-2024	938 (70.5%)
Total	1330 (100%)

Topic Identification

Table 3 presents the 10 topics derived from the implementation of LDA, along with the proportion of each topic across all articles. It is important to note that only articles related to the professional development of mathematics teachers were selected during the screening process, the topics were closely related to this field.

Table 3. Top 10 Keywords, Their Proportions in the Whole Corpus, Suggested Topic Labels

Top 10 Keywords	%	Label
assessment, belief, level, efficacy, test, performance, modeling, competence, attitude, view	11.6	Assessment
student, thinking, understanding, reasoning, problem, solving, practice, strategy, ability, response	11.9	Student thinking and understanding
teacher, identity, teaching, primary, change, secondary, experience, reform, educator, report	8.9	Identity
knowledge, content, pedagogical, curriculum, teaching, meta, cognitive, subject, PCK, resource	10.4	Pedagogical Content Knowledge (PCK)
preservice, technology, teaching, skills, training, integration, design, ICT, elementary, qualitative	9.8	Technology
learning, task, design, process, approach, context, role, theory, activity, explore	8.3	Tasks design
lesson, noticing, teacher, video, practice, framework, evidence, reflection, opportunity, develop,	10.2	Lesson reflection and Noticing
student, achievement, grade, quality, academic, school, skill, classroom, quality, children	8.3	Achievement
support, practice, teaching, training, challenge, online, community, barrier, material, context	10.1	Support and challenges
professional, development, program, effect, project, model, inquiry, design, support, implementation	10.6	Program

The topic *Assessment* included articles assessing teacher's factors influencing professional development (e.g., belief, efficacy, attitudes). The topic *Student's thinking and understanding* examined teachers' abilities to assess and foster students' mathematical thinking and understanding. The topic *Identity* included studies on the development and growth of teachers' identity. The topic *PCK* examined various aspects of teacher knowledge, such as content knowledge, knowledge of tools, and conceptual and procedural knowledge. The topic *Technology* covered research on the integration of various technologies, including ICT, multimedia, mobile, and games. The topic *Tasks design* deals with teachers' ability to design tasks for students' mathematics learning and teacher professional development. The topic *Lesson reflection and Noticing* included studies on lesson reflection for teacher professional development and teachers' abilities to attend, interpret, and decide how to respond to students' thinking. The topic *Achievement* covered the impact of teachers' professional development on students' mathematical achievements. The topic *Support and Challenges* included studies focusing on support, challenges, and barriers in professional development of mathematics teachers. The topic *Program* examined the development and application of programs for teacher professional development and their effectiveness. The top five most discussed topics were *Student's thinking and understanding* (11.9%), *Assessment* (11.6%), *Program* (10.6%), *PCK* (10.4%), and *Lesson reflection and Noticing* (10.2%).

Topic Trends

Topic Trends Change over Time

Figure 5 shows the annual proportion (weight) of each topic. Given the nonlinear trends observed in some topics, the visualization includes scatter plots along with curve trend lines.

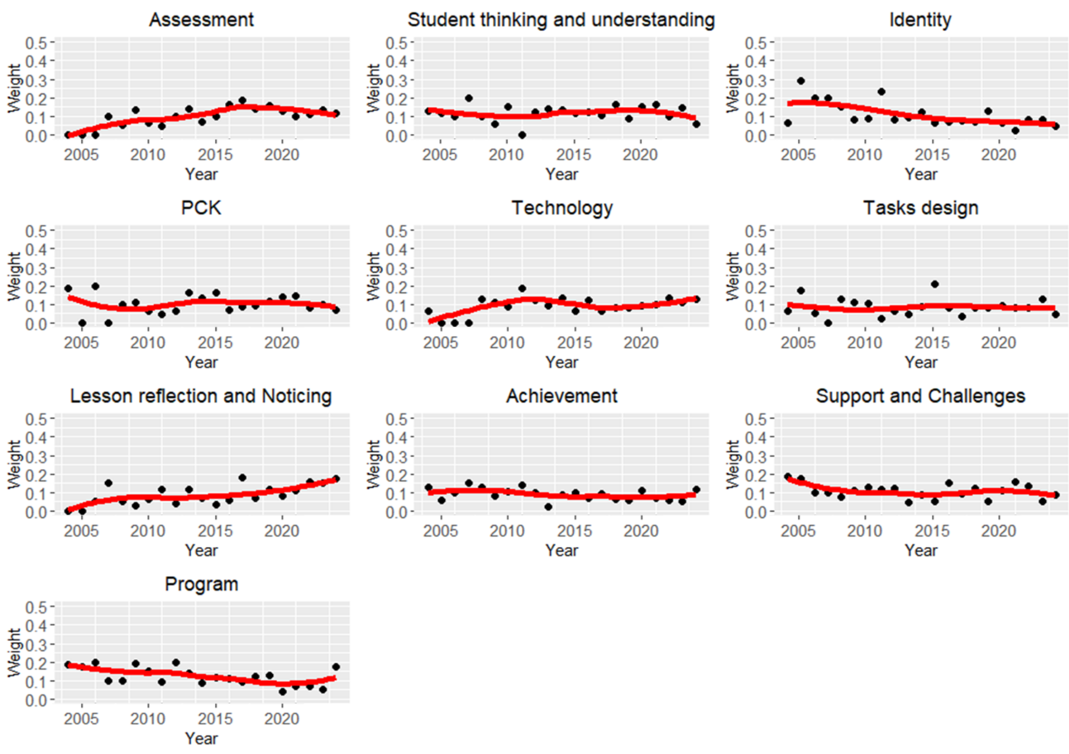

Figure 4. The Change of Annual Topic Proportion Within the Entire Corpus for the 10 Topics

Topics such as *Assessment*, *Technology*, and *Lesson reflection and Noticing* showed increasing trends. In contrast, the topic *Identity*, *Support and Challenges*, and *Program* showed decreasing trends. The remaining topics *Student thinking and understanding*, *PCK*, *Tasks design*, and *Achievement* did not exhibit trends of either substantial increase or decrease.

Hot and Cold Topic

A time-series regression analysis was conducted to examine the significant trend changes in topics over time and identify Hot and Cold topics. Table 4 shows the statistically significant hot and cold topics from the time series regression analysis. Out of a total of 10 topics, three were identified as hot topics: *Assessment, Technology, and Lesson reflection and Noticing*. Conversely, the topic *Identity* and *Program* were identified as Cold topics. The remaining five topics did not show statistically significant results ($p > .05$).

Table 4. Hot and Cold Topics

Topic	Regression Coefficient	p	Trends	Hot/Cold
Assessment	.681	.001	↑↑	Hot
Student thinking and understanding	.020	.932	↑	-
Identity	-.609	.003	↓↓	Cold
PCK	.048	.210	↑	-
Technology	.440	.046	↑↑	Hot
Tasks design	-.014	.951	↓	-
Lesson reflection and noticing	.649	.001	↑↑	Hot
Achievement	-.395	.076	↓	-
Support and Challenges	-.320	.158	↓	-
Program	-.577	.006	↓↓	Cold

Note. ↑(↓): increasing (decreasing) trend but not significant ($p > .05$); ↑↑(↓↓) Significantly increasing (decreasing) trend ($p < .05$).

Research Interests by Year

Figure 6 presents the visualization of the distribution of topic proportions by year. The result clearly shows prominent research interest in each year. For example, the topic *Identity* was the most prominent topic of interest in 2005.

The topic *Tasks design* garnered the most attention in 2015. The topic *Assessment* and *Lesson reflection and Noticing* received attention from researchers in 2017. In 2024, *Lesson reflection and Noticing* stood out as the most prominent area of interest. In the early stages, some topics did not emerge, and there was a tendency for researchers to focus their attention on specific topics. However, as time progressed, research on almost all topics was continuously conducted.

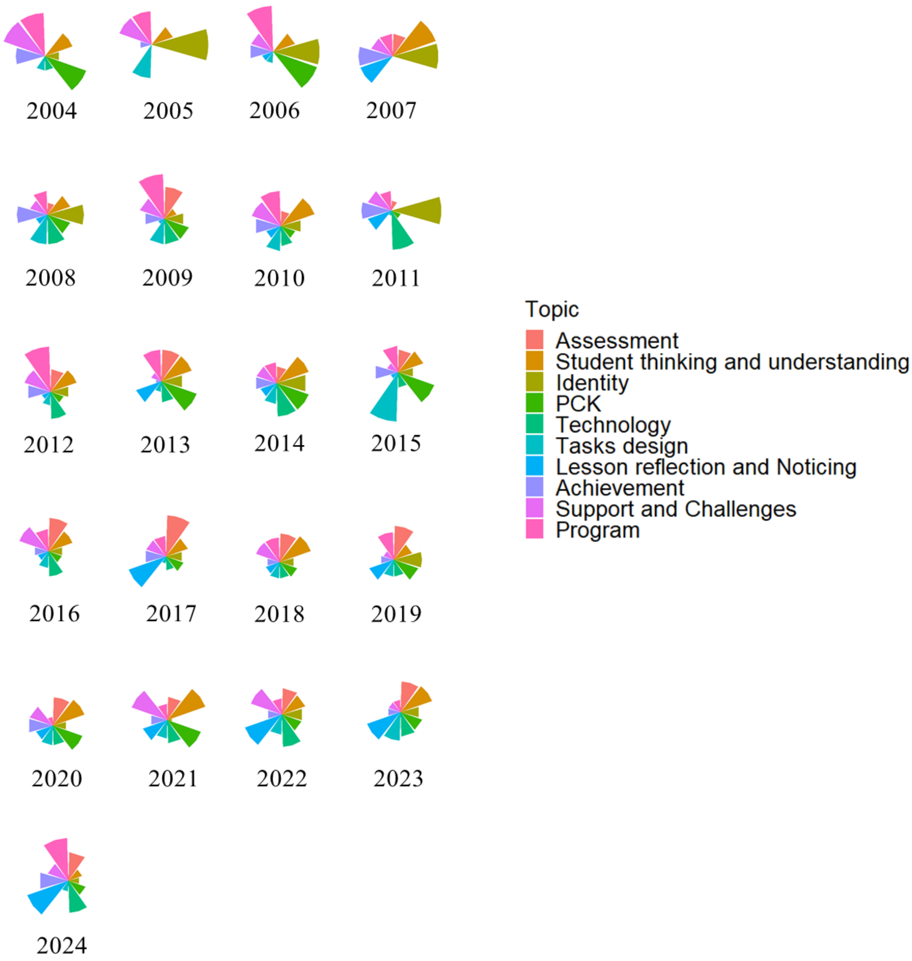

Figure 5. The Distribution of Topic Proportion by Year

Discussion

This study conducted a topic modeling analysis on 1,330 articles published between 2004 and 2024 concerning the professional development of mathematics teachers. The research aimed to identify topics related to mathematics teacher professional development and track trends in each topic over time. The findings of this study provide an overview of the current state and a comprehensive picture of teacher professional development in mathematics education. The results of the first research question showed a steady increase in the number of published articles on mathematics teacher professional development. The number of articles published between 2015 and 2024 was approximately three times greater than those published between 2004 and 2014. This finding aligns with Inglis and Foster (2018), which reported a continuous increase in research on mathematics teachers in mathematics education. Research on mathematics teacher of professional development remains a field of consistent interest among researchers, and it has rapidly grown within the mathematics education community over time.

Regarding the second research question, the topic modeling analysis identified ten topics: *Assessment, Student thinking and understanding, Identity, PCK, Technology, Tasks design, Lesson reflection and Noticing, Achievement, Support and Challenges,* and *Program.* These identified topics refine the potential areas of research on mathematics teacher professional development, expanding on the findings of previous studies that identified general topics in mathematics education (e.g., Gökçe & Güner, 2021; Inglis & Foster, 2018). Furthermore, the identified topics do not neatly align with the categorization of research topics on teacher professionalism by Foster and Inglis (2019). Notably, the present study did not reveal topics related to mathematical content or administrative matters. This difference may be attributed to the type and scope of the used data. While the current study included articles that investigated teacher professional development in mathematics education, Foster and Inglis (2019) only examined articles from two mathematics teacher professional journals.

The topics *Student thinking and understanding*, *Assessment*, *Program*, *PCK*, and *Lesson reflection and Noticing* emerged as the most prominent. These topics represent the most extensively researched areas within the field of mathematics teacher professional development. They are closely related to the development of teacher professionalism in mathematics and hold significant importance in this field. The results for the third research question showed significant increasing trends were observed over time for the hot topics of *Assessment, Technology,* and *Lesson reflection and Noticing*. The topic *Assessment* included studies of teachers' factors such as teachers' beliefs (Lau, 2022), attitudes (Panero et al., 2023), competencies (Kaiser et al., 2017), and views (Dreher et al., 2016). This topic showed continuous growth over time. However, assessing teachers' expertise is included in most studies in this field. Therefore, it is reasonable to interpret the increasing interest in 'assessment' as a result of the cumulative research on the professional development of mathematics teachers. The topic *Technology* emerged as a prominent topic in this field, indicating a growing interest in the use of technology for professional development. For example, Çelik and Pektaş (2017) investigated PSTs' graphic comprehension and interpretation skills in technology-aided learning environments. Hansen et al. (2016) explored how co-designing a virtual manipulative for teaching fractions impacted professional development. Integrating technology into mathematics education has the potential to fundamentally transform teaching and learning (Bray & Tangney, 2017; Zawacki-Richter et al., 2019). Therefore, it can be predicted that using technology for professional development of mathematics teachers will be a promising research area. Research on *Lesson reflection and Noticing* also showed a significant increasing trend. Leavy and Hourigan (2016) reported that ‘Lesson Study' supported PSTs' reflection and enhanced their noticing abilities. van den Kieboom (2021) examined PSTs' noticing skills using reflective journals. This topic still holds research potential and is likely to remain a central focus of studies on professional development of mathematics teachers.

On the other hand, the topics *Identity, Support and Challenges,* and *Program* showed a decreasing trend. Among these topics, *Identity* and *Program* were cold topics that showed a significant decreasing trend. These two topics showed a decrease in research output compared to previous periods, suggesting that they may lose popularity in the near future. Finally, the topics *Student thinking and understanding, PCK, Tasks design,* and *Achievement* showed consistent trends without significant increases or decreases. These topics have matured sufficiently in this field, and while continuous research will likely take place in the future, they may not attract significantly more attention in the near term.

The results of the fourth research question, which analyzed the annual topic distribution, revealed changing trends in researchers' focus within this field. For example, in the early stages, researchers concentrated more on topics such as *Identity*, *Program*, and *PCK.* Over time, the focus shifted, with the topic *Technology* becoming prominent from 2008 onward, and *Lesson reflection and Noticing* gaining significant popularity after 2011. These findings indicate that, in the early 2000s, researchers primarily focused on personal characteristics and capacities, such as teachers' knowledge, beliefs, and identity. After the early 2000s, there was growing interest in teacher's professional development related to the use of technology in mathematics education, as well as reflection on teaching practices and noticing that drives teaching moves.

Limitations

This study has several limitations. First, the used data in this study stemmed from specific databases (i.e., Web of Science, ERIC, EBSCO). Different results may be obtained when articles from other databases are included. Therefore, depending on the research purpose, future studies can choose to use a single database or incorporate data from different databases to conduct similar research. Second, it is important to note that while topic modeling can capture meaningful signals regarding unexplored potential areas, it does not reach the same level as a systematic re-view. Topic modeling is suitable for summarizing and grouping large-scale data but may miss significant aspects of topics compared to a systematic literature review. For example, the result of this study did not reveal which content areas (e.g., arithmetic, algebra) in mathematics education have been the focus of professional development of mathematics teachers. This does not necessarily imply a lack of research in those areas rather than suggests that there may not be enough studies to identify them as independent topics. Therefore, to connect researchers' areas of interest with topic modeling, additional reviews are needed to expand the results. Lastly, considering the results of this study, an in-depth analysis of the most abundant topics and emerging hot topics can contribute to the field by shedding further light on these areas.

Conclusion

Teacher's professional development is essential for ensuring the quality of mathematics teaching and learning. This study synthesizes research published over the past 20 years, from 2004 to 2024, and investigates trends in the field using topic modeling. The results identified overall research trends in the professional development of teachers in mathematics education and highlighted topics that diverged from those identified in previous studies (Foster & Inglis, 2019; Gökçe & Güner, 2021; Inglis & Foster, 2018). The findings of this study offer guidance for further research on teacher professional development. The topic modeling analysis provides a comprehensive overview that can contribute to mathematics teacher education. The exploration of identified topics and their developmental directions serves as a foundation for identifying and comparing strengths in research on the professional development of mathematics teachers, both in the present and in future research.

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A Bibliometric Study on Science, Technology, Engineering, and Mathematics (STEM)

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Abstract

This article presents a synthesis of current trends in STEM research, concentrating on how professional development affects teachers' opinions and involvement using bibliometric analysis. The main focus of education and technical growth is STEM, or science, technology, engineering, and mathematics. This article provides an in-depth review of the latest research and innovative developments. The study of STEM's influence on government policy gives insight into government responses to STEM trends through changes in education policy and the support of stakeholders. The bibliometric study starts by firstly reviewing publications on STEM in journals indexed by Scopus by examining patterns of fluctuation and balance every year for the last ten years. Second, The Sustainability journal has published the most articles on STEM. Third, with a total of 287 citations, the majority of citations are focused on papers released in 2018. Fourth, student, learning, and STEM are the author keywords that are most frequently employed. The necessity of education policy congruence and the significance of ongoing support and training for STEM teachers' professional growth are emphasized. and adequate support from the Indonesian perspective. Recommendations include enhancing teacher training programs, promoting interdisciplinary approaches, and strengthening partnerships between academia, industry, and government to advance STEM education in Indonesia.

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Introduction

STEM, which stands for science, technology, engineering, and mathematics, is regarded as the main area of attention in the fields of technology development and education. This field's skills are seen to be crucial for overcoming the difficulties of the twenty-first century. (Bartels, 2019; Henry, 2021; López, 2022; Nurtanto, 2020; Shaby, 2021). STEM forms the foundation for innovation, enables the solving of complex problems, and drives technological advances that will shape the global future (Chakraverty, 2019; Fuesting, 2019; Grinis, 2019; Wang et al., n.d.).

Educators' views of STEM education in grades K-12 are influenced by their experience and the role of learning professionals. (Falloon et al., 2020a). Interdisciplinary linkages, ambitious teaching strategies, and practical problem-solving skills are common themes that show up. Regarding STEM advancements, STEM instruction, and the advantages of integrating STEM, the importance of incorporating these elements into educational practices (Bryan & Guzey, 2020; Belfield & Brock, 2023). There needs to be a framework to advance STEM literacy in grades K-12 (Falloon et al., 2020b). There is a need to give greater focus to STEM integration, especially in the context of mathematical and engineering disciplines. (English, 2016).

The article titled "STEM" in-depth reviews recent research and innovative developments. By outlining key trends and presenting a synthesis of data from relevant articles, the central role of STEM in addressing the complex challenges of the 21st century can be understood. Studies show that integrating STEM into the ed. Jamaludin education system can improve students' skills and knowledge. Through citation analysis, Additionally, this essay will talk about the extent to which research and contributions in STEM have influenced the global outlook on science and technology. From here, it can be seen to what extent the influence of STEM penetrates various sectors, including industry, education, and government policies. A series of meta-analyses and syntheses have consistently demonstrated the positive impact of Computer-Aided Collaborative Education (CSCL) in STEM education. (Jeong et al., 2019; McKeown et al., 2017). Furthermore, there is a need for different strategies to build learning, based on a combination of technology, pedagogy, and types of collaboration. By digging deeper into the trends and citations of the article titled "STEM," insights into the future direction of research and innovation can be gained. This article becomes a window into the dynamic world of STEM, highlighting current challenges and new emerging opportunities. Let's dive together into the journey of STEM in carving its mark in the evolution of knowledge and guiding us towards a more sophisticated future.

Based on some of the research outlined earlier, there is a great opportunity for further research on STEM, especially in the context of mathematics. With rapid technological advancements, this development can inspire researchers and practitioners from various disciplines to explore the role of mathematics as a whole, starting from 2014 to 2023. The research aims to address the following questions related to STEM publications between 2014 and 2023: What trends are observed in the publication of STEM articles during this period? Which journals have been the most prolific in publishing STEM articles? What is the total number of citations received by STEM articles published between 2014 and 2023? Which keywords are most frequently used by authors of STEM articles? during this timeframe?

Literature Review

An in-depth literature review of "STEM" Articles provide insight into a number of significant topics. For instance, a number of studies have examined how science instructors see STEM education, emphasizing both its advantages and disadvantages. The need for a professional development model to support teachers in enacting STEM education (El-Deghaidy & Mansour, 2015; Bohrnstedt et al., 2023). Although teachers in the United Arab Emirates (UAE) have a positive attitude towards STEM, they face challenges such as documentation and lack of time. (Hamad et al., 2022). Primary school teachers noted their initial aversion to STEM and the need for support in overcoming barriers. (Samara & Kotsis, 2023). The importance of teacher preparation for integrated STEM education, focusing on concept knowledge, curriculum knowledge, and implementation knowledge (Fırat, 2020). These studies collectively underscore the necessity of continual assistance and professional growth for educators to successfully execute STEM instruction.

Various studies have explored the use of tablets and applications Regarding early childhood education, especially in the domains of robotics, mathematics, STEM, and literacy. (Yang et al., 2024). This technology has the capacity to enhance kids' educational experiences. There are benefits to using tablets in math learning, including increased collaboration and engagement. (Kaggwa et al., 2023; Svela et al., 2019). Tablets and apps have the opportunity to engage children with disabilities and pre-service teachers in robotics-based activities, respectively (Howard & Park, 2014). Overall, these studies emphasize the positive impact of tablet use and apps in early childhood education, especially in STEM and literacy contexts. Numerous research has looked into how professional growth affects teachers' views on STEM education. Teachers' understanding of integrated STEM education develops throughout a 3-week professional development program, with their conceptual models becoming more complex. (Ring et al., 2017). Improved perceptions of science teachers regarding E-STEM, especially in disadvantaged schools, after they attend professional development programs (Amoa-Danquah, 2023; Aydogdu et al., 2020). Professional development has a beneficial effect on teachers' perceptions, efficacy, and confidence. of STEM. (George et al., 2020). The significance of successful professional development in STEM teaching and pointed out the necessity of many formats in addition to consideration of contextual factors. (Goodenough et al., 2014).

Meanwhile, the study of the influence of STEM on government policy provides a perspective on government responses to STEM trends through changes in education policy and industry support. This literature review provides a strong theoretical foundation for "STEM" articles, helping to form an in-depth understanding of the developments, influences, and ramifications of STEM trends across several domains.

Method

This study uses bibliographic research methodology and makes use of explicit and methodical mapping procedures that are drawn from. (Andrade-Arenas et al., 2023a; Angraini et al., 2024; Cansız Aktaş, 2022; Gusteti et al., 2024; Julius et al., 2021; Karampelas, 2023; Kartika et al., 2023; Rafiq et al., 2023; Triyono et al., 2023; Utami et al., 2023a, 2023b). This study applied bibliographic design using systematic and explicit attribution methods (Andrade-Arenas et al., 2023b;; Sofwan et al., 2024). The literature review stage follows four steps, along with research conducted (Huan et al., 2022; Julia et al., 2020). These stages involve (1) search steps, (2) bibliographic filters, (3) complete bibliographies, and (4) bibliographic evaluation. The Publish or Perish (PoP) program is used in this study's search strategy to go through bibliographic databases. Because Scopus is one of the largest databases offering peer-reviewed literature, it was selected as a database source for reference searches using PoP apps (Khusna et al., 2024; Suseelan et al., 2022). Therefore, Scopus became the only database used in this study. Certain criteria were set for all bibliographies to be included in the analysis, involving three main aspects: (1) Bibliography-type journals only, (2) Article titles containing the phrase "STEM", and (3) Search year ranges were limited from 2014 to 2023 (last 10 years).

Search Procedure

The software tool Bibliographic databases were explored using Publish or Perish (PoP)., particularly focusing on Scopus. These databases are recognized as the leading sources of peer-reviewed scholarly works. The preference for Scopus is attributed to its wider range of content compared to other databases (Andrade-Arenas et al., 2023b). Remarkably, they hold about 70% more publications than the Web of Science (Julia et al., 2020). In this study, specific criteria were set for including bibliographies, such as the inclusion of only journal types, article titles featuring "STEM Education," and a search period limited to the last decade, from 2014 to 2023. Figure 1 shows how to use the PoP program for a bibliographic search.

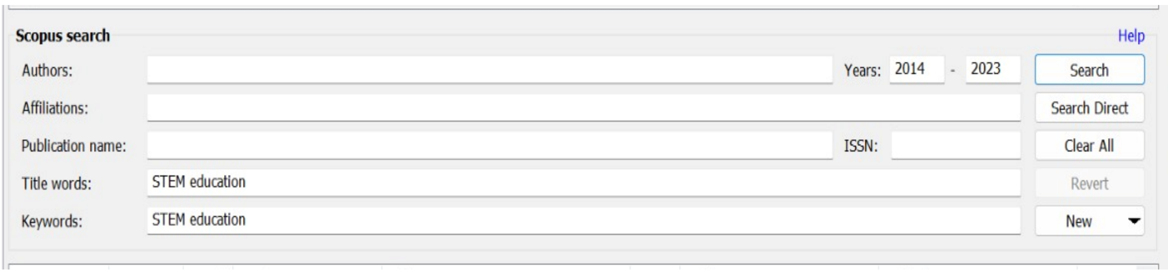

Figure 1. Search for the PoP Application Bibliography

Bibliographic reference search results are saved in the app and exported into CSV file format, which is then opened in the Excel application. Files that have been saved are checked and given additional metadata.

Filter Bibliography

Three criteria are used to choose a bibliography:

(1) it must include the context of STEM education;

(2) it must be written in English; and

(3) it must be published by a publisher of a recognized bibliographic database.

The Scopus database, which is taken from the PoP program, is used to monitor each bibliography that is to be included or removed from the bibliographic analysis process. The article type is the sole reference type selected. Because they are conference papers, mistakes, notes, editorials, reviews, clones, or publications without abstracts attached, some of the reference lists that are shown during the PoP application search process are not chosen. The

PoP application's first search yielded 1,730 reference lists, which were then divided into 869 chosen reference lists. Because they did not meet the requirements, 861 reference lists weren't chosen. The total number of referrals produced by searches using PoP apps each year is displayed in Table 1.

Table 1. Bibliographic Selection Results

Year of Publication	Inclusion	%	Exclusion	%	Total
2014	32	28.8	79	71.2	111
2015	46	33.8	90	66.2	136
2016	50	35.2	92	64.8	142
2017	45	31.9	96	68.1	141
2018	90	45.0	110	55.0	200
2019	93	46.5	107	53.5	200
2020	125	62.5	75	37.5	200
2021	130	65.0	70	35.0	200
2022	145	72.5	55	27.5	200
2023	113	56.5	87	43.5	200
Total	**869**		**861**		**1,730**

As seen in Table 1, the quantity of article publications peaked between 2018 to 2023 with each year publishing 200 articles on STEM, and the lowest number occurred in 2014, with only 111 articles. From the visualization, it can be seen that from 2014 to 2016 the number of articles about STEM always increased. However, in 2017, there was a decline in article publications, and from 2018 to 2023 there was another increase in the publication of articles about STEM. From the table, it can be seen that the number of Exclusion is higher than Inclusion, with a total of 861 articles, while Inclusion is 869 articles. It can be concluded that the number of inclusions and exclusions has only a small comparison.

Bibliography Completeness

To perform filtered bibliographic analysis, metadata is reviewed and finalized. Aspects like the paper title, author name, publishing country and institution, abstract, author keywords, article link, publisher, and year of publication are all examined in the review. A bibliographic analysis is carried out following the completion of the metadata.

Bibliometric Analysis

The following four criteria served as the foundation for the bibliographic analysis: (1) publication patterns; (2) top STEM article publishing journals; (3) top STEM article citations; and (4) most often used keywords in STEM author publications. Bibliographic analysis is carried out and the findings are seen using the VOS viewer tool. Large data sets may be processed quickly and effectively using VOSviewer, which also offers a variety of visualizations, analysis, and observations. Furthermore, VOSviewer may generate publication, author, and journal maps using distributed channel-centric keyword maps or shared citation systems. The EndNote bibliographic file is the sort of file that is loaded into the VOSviewer program for examination.

Results and Discussion

Publication Trend-Based Analysis

More research is required to examine the patterns of STEM-related journal publications from 2014 to 2023. There has been a rise and fall in the quantity of publications across the time frame. There was an increase from 2014 to 2016, a decrease from 2017, and again increase from 2018 to 2023. The years 2018 to 2023 recorded the highest number of publications. Therefore, it can be concluded that the interest and popularity of research on STEM topics will reach its peak in 2018 to 2023.

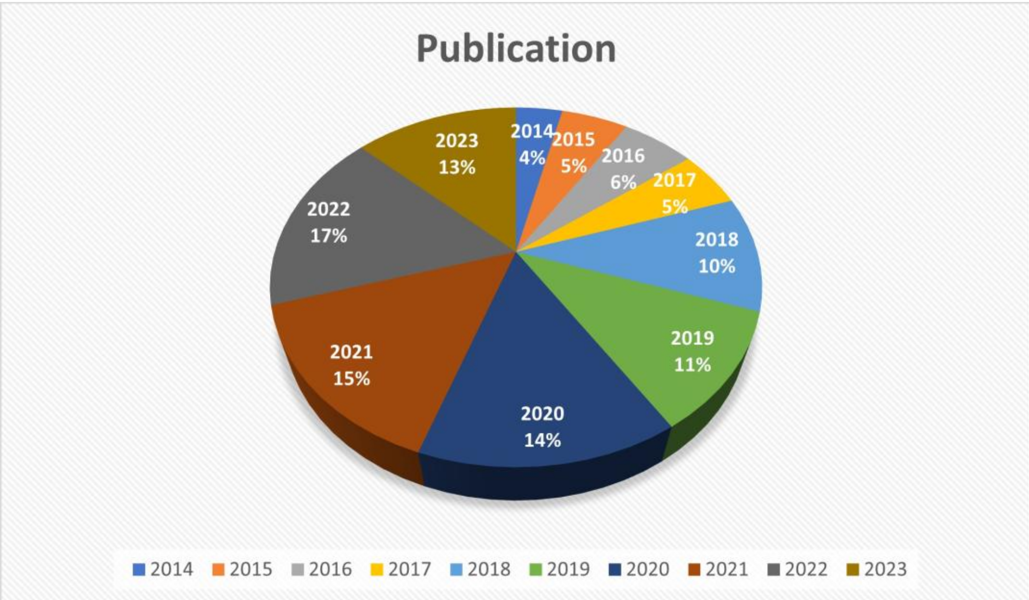

Figure 2. Publication Trends per Year

The following details may be inferred from Figure 2. The number of publications increased from 4 percent in 2014 to 6 percent in 2016. 2017 had a little decline of 5%, however beginning in 2018, this trend flipped and there was a notable gain. There was a steady increase from 2018 to 2022, with 2022 having the most publications (17%). In 2023, it dropped to 13% from its highest point the year before. This suggests that, although there has been some yearly variation, there has been a general rising trend in the publication of STEM-related journal papers over this time. The period from 2018 to 2022 marks a striking increase in publication numbers, indicating a growing interest and prominence in STEM research during these years.

Subsequent data showcase the top 10 journals that published articles on STEM research from 2014 to 2023. This research highlights a widespread ambition to understand and advance STEM competencies across various aspects of life. Table 2 indicates that the top 10 journals are as follows: Sustainability (Switzerland) has the most articles (33 total), followed by Education Sciences (32 total), the Eurasian Journal of Mathematics, Science and Technology Education (20 total), and the International Journal of Science and Mathematics Education (11 total).

Table 2. The STEM-related journals with the highest number of papers published between 2014 and 2023

Journal	Number of articles
Sustainability (Switzerland)	33
Education Sciences	32
Eurasia Journal of Mathematics, Science and Technology Education	20
International Journal of STEM Education	19
International Journal of Technology and Design Education	16
International Journal of Science Education	15
Journal of Turkish Science Education	13
Journal of Science Education and Technology	12
Journal of Baltic Science Education	11
International Journal of Science and Mathematics Education	11

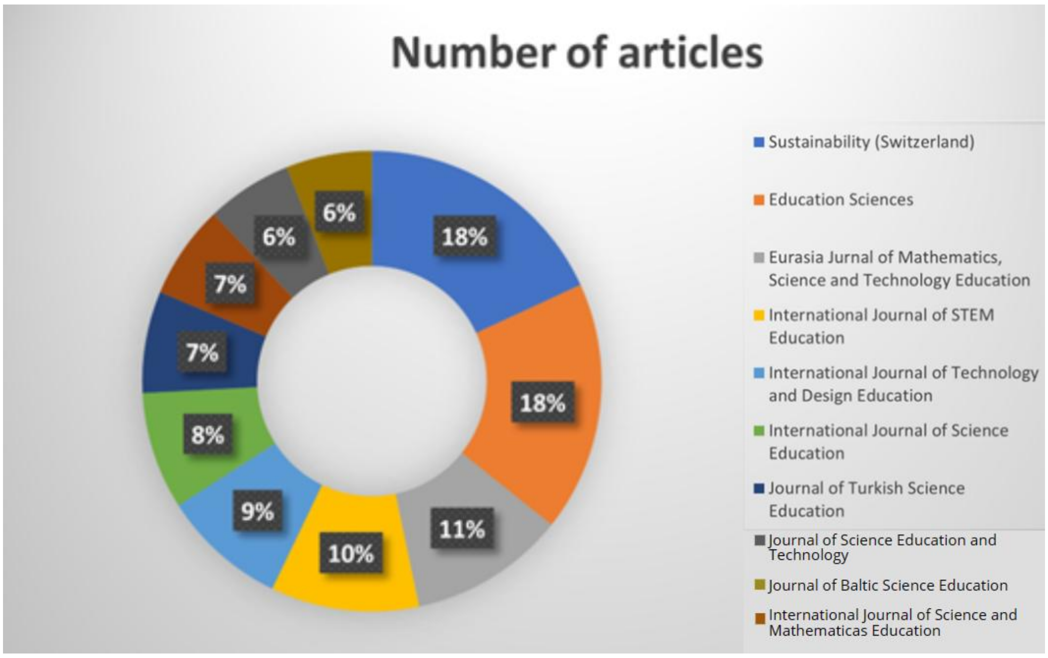

Figure 3. The Proportion of Journals That Have Published the Most Articles on STEM

Figure 3 visualizes the distribution of articles among the leading 10 journals that have featured research on STEM from 2014 to 2023. This chart demonstrates academic interest and efforts directed towards understanding and promoting STEM competencies, as seen in the percentages of published articles across these notable journals:

1. "Sustainability (Switzerland)" and "Education Sciences" are leading the chart, each with 18% of the published articles, indicating a significant contribution to STEM research in their respective domains.
2. With 11% and 10%, respectively, the "Eurasia Journal of Mathematics, Science and Technology Education" and the "International Journal of STEM Education" come in second and third, respectively, demonstrating their contributions to the dissemination of research that advances STEM education.
3. Other noteworthy journals that contribute to the wider discussion and investigation of STEM subjects are the "International Journal of Technology and Design Education," "International Journal of Science Education," and the "Journal of Turkish Science Education," with 9%, 8%, and 6% of the articles, respectively.

This distribution underscores the collective endeavor of these journals in advancing STEM research, reflecting a global ambition to integrate and enhance STEM skills in education and various sectors.

Citation Count Analysis (Annual Citations)

Here's the data detailing annual citation counts spanning from 2014 to 2023.

Table 3. The Annual Number of Citations

Publication Year	The quantity of references	The quantity of articles
2014	1,557	32
2015	1,441	46
2016	1,660	50
2017	1,771	45
2018	2,189	90
2019	1,939	93
2020	2,259	125
2021	1,089	130
2022	810	145
2023	124	113
Total	**14,839**	**869**

Table 3, which shows the number of articles produced year and the number of citations from 2014 to 2023, provides numerous important insights. Initially, there is a general increasing trend in citations, peaking in 2020 with 2,259 citations, suggesting that research in this field has been gaining more attention over the years. However, there was a noticeable decline in citations in the subsequent years, particularly in 2023 when citations significantly dropped to 124. This decline could be attributed to various factors, such as the recency of publications or shifts in research focus. Concurrently, there is a general rising tendency in the quantity of papers produced annually., indicating growing interest and research activity in this field. The ratio of citations to articles varies across the years, highlighting the varying impact of research over time. Overall, the table reflects a vibrant and active research community with a substantial impact, as evidenced by the total of 14,839 citations across 869 articles over the ten years.

The Top 10 Articles with the Most Cited

The 10 most quoted STEM articles are listed in Figure 4. First place goes to the article with the most citations, which was written by Ong et al. in 2018 and has 287 citations. Borrego came in second with 283 citations. In Figure 4, the highest number of citations first appeared in 2018 with 287 citations, which are related to writing (Ong et al., 2018). Meanwhile, the second-highest citation was recorded in 2014, attributed to works written by Borrego and Henderson (2014). On the other hand, there was the first lowest number of citations in 2017, which was related to publications by Blackburn (2017) with the number of citations of 162, the second lowest number of citations published by Belland et al. (2017) with the number of citations of 167.

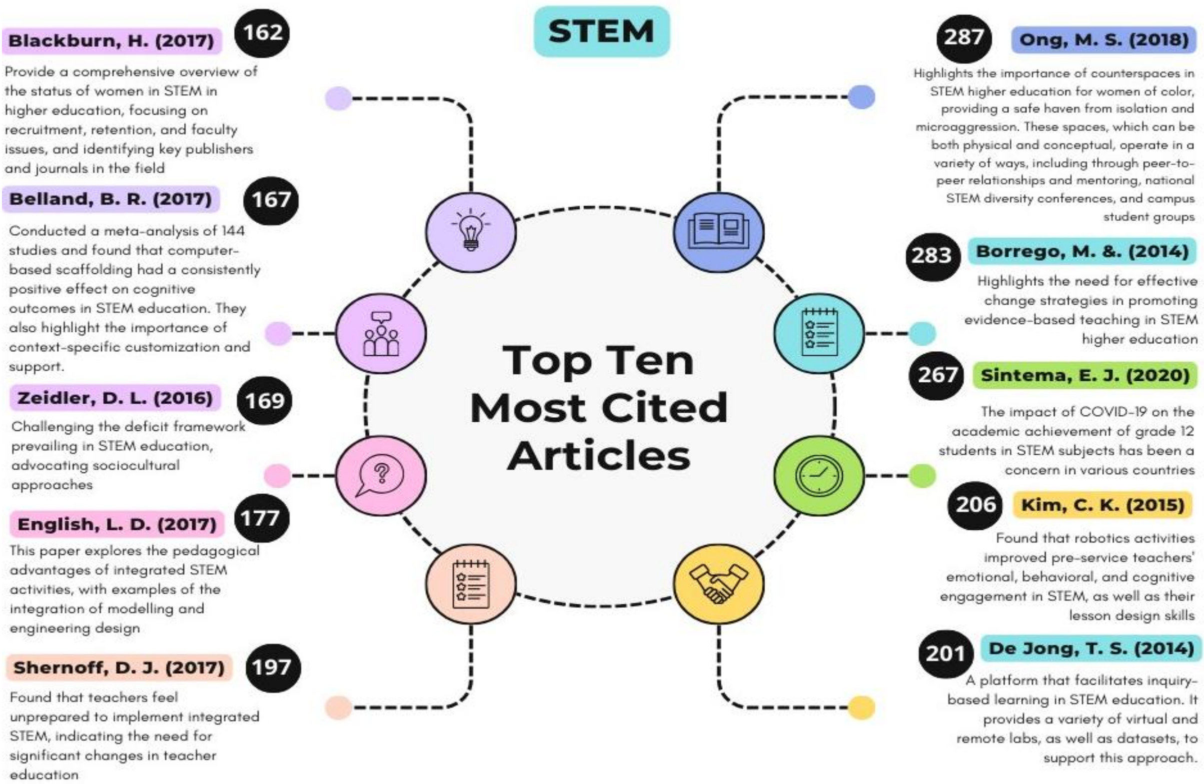

Figure 4. Most Cited Articles on STEM from 2014 to 2023

Author Keyword Based Analysis

Based on the author's keywords, an analysis was performed using the VOSviewer tool. By visualizing the interconnections between commonly used terms in publications, this tool provides insight into the primary topics and how they relate to one another within the study environment.

VOSviewer is a tool for creating network-based maps from scientific data. These maps are commonly used to visualize relationships between various entities, such as journals, researchers, articles, or keywords. In Figure 3, VOSviewer is used to create a keyword map of literature related to STEM education. Keywords shown on the map, such as "stem", "education", "technology", "engineering", and "science", are terms that often appear in the literature analyzed.

The lines between the nodes indicate relationships or connections between these themes. For instance, "student" is strongly connected to "learning", indicating that many discussions or publications involve the relationship between students and their learning processes within STEM fields.

The density of nodes and the thickness of the lines could represent the strength or frequency of the connections. Areas with more nodes and thicker lines suggest well-established research areas with many connections.

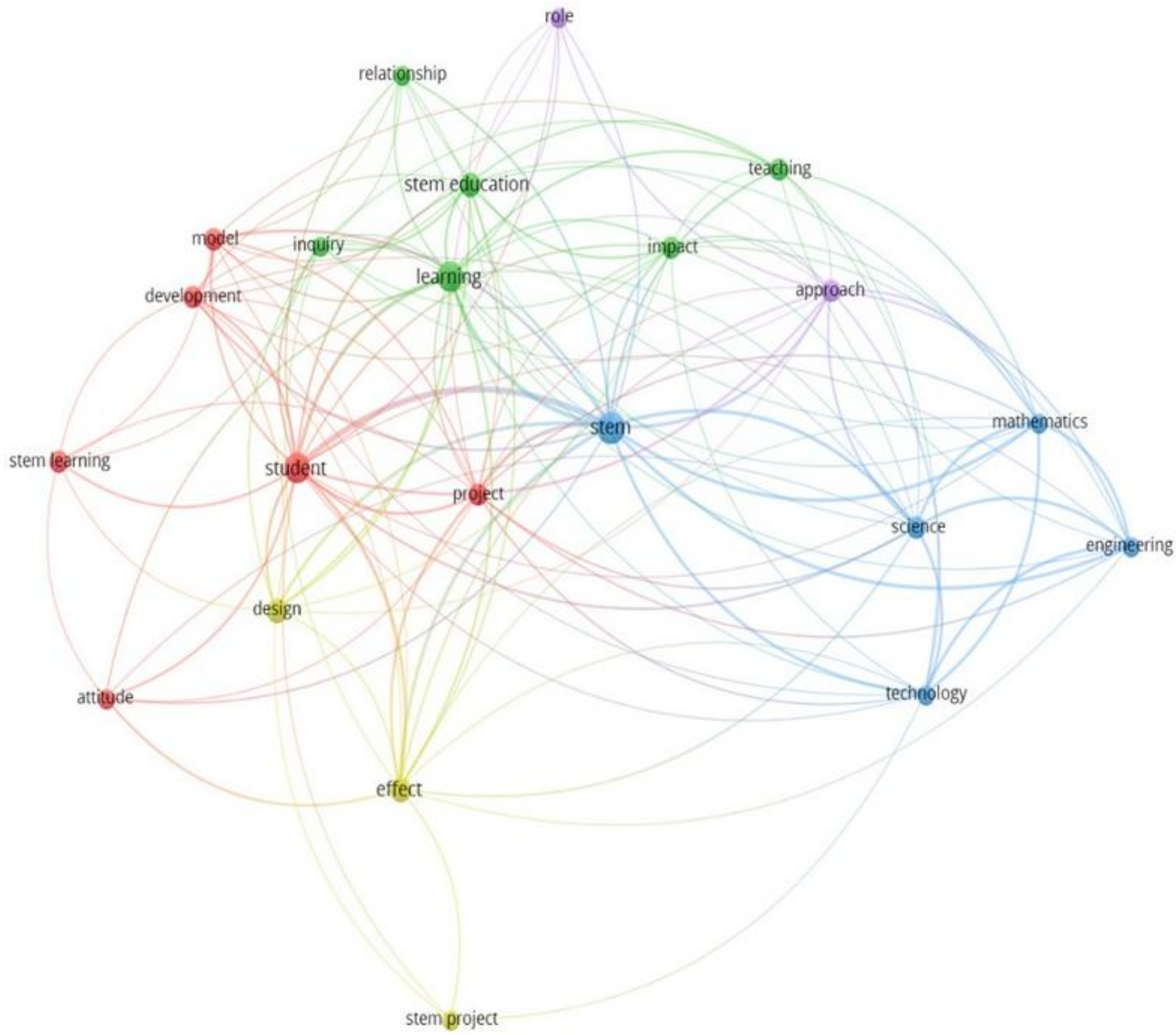

Figure 5. Author Keyword Network Visualization

Recommendations for Follow-Up Research

1. *Gap Analysis:* Identify areas with fewer connections to explore under-researched aspects or to find unique intersections between topics that could benefit from further study.
2. *Emerging Trends:* Look for emerging trends by examining the peripheral nodes that are beginning to form connections to the central clusters.
3. *Impact Studies:* The node "impact" connected to "STEM" and "education" suggests potential for studies that measure the impact of different STEM educational approaches or technologies.
4. *Curriculum Design:* The connection between "design" and "STEM education" could be explored to develop innovative STEM curricula that incorporate the latest findings in pedagogy and technology.
5. *Educational Technology:* Given the presence of "technology" and its connection to "STEM", there may be room for research into how emerging technologies are influencing STEM education.
6. *Interdisciplinary Projects:* The map suggests a relationship between subjects like "science" and "engineering". Research could explore interdisciplinary educational projects that bridge these subjects.
7. *Teacher Training and Development:* Since "teaching" is a visible node, investigating the professional

development of STEM teachers and how they can be better equipped to teach in a rapidly evolving educational landscape could be valuable.

In the last ten years, research on STEM in education only began in 2014 and was published in journals that are indexed by Scopus. Since then, there have been changes in STEM research, as seen by variations in the quantity of publications in 2023. Even Nevertheless, the overall number of published papers has increased, decreased, and increased again, reaching 869. This demonstrates that STEM education has not yet reached its full potential in recent years. Between 2017 and 2018, there was the most rise in publications throughout that period, with 45 papers. The trend pattern of this publication shows that the discussion about STEM needs to be increased again because it has not yet reached the expected level of popularity.

Although related articles are not as well-known, several journals have contributed to mapping research in STEM fields. In the last ten years, according to Table 2, the 869 journals that are listed on Scopus have made the most contributions to the publication of STEM-related papers. Researchers' choice of journals for publishing also reflects their reputation and credibility, including the publisher's trustworthiness (Julia et al., 2020). However, some journals cannot be controlled by management, causing dissatisfaction among those who use the Scopus index.

Of all the publications available, it can be identified which article has had the greatest impact on other research. The use of quotes is one of the parameters for evaluating the achievements of a scientist. As seen in Figure 3, the most impactful STEM articles were published in 2018, with 287 out of 200 papers receiving citations overall. Based on the article titles listed in Table 3, research in STEM fields has also delved quite deeply into STEM concepts in the context of education.

Certain keywords are most often utilized by authors when publishing STEM research findings; these keywords capture the spirit of the author and the sentence's overall meaning. (Julia et al., 2020). Certain keywords (author keywords) that the researcher uses in a research article indicate that they capture the core of the subject matter being examined. The phrase 'Student' from cluster 1 with six elements is the author's most utilized keyword in STEM study, as seen in Figure 4. The phrase 'Learning' from cluster 2 has six entries, making it the second biggest order. The phrase 'STEM' from cluster 3 has five elements and is the third highest order. It is evident from these three author keyword words that STEM education in his study is intimately tied to learning and the function that instructors play in the educational and technological worlds.

Conclusion

To summarize, the four questions asked at the beginning can be answered as follows. First, publications on STEM in Scopus-indexed journals show patterns of fluctuation and equilibrium every year for the last ten years. Second, The Sustainability journal has published the most articles on STEM. The top-ranked journal published 33 articles, while the tenth-ranked journal published only 11 articles. Third, many citations are concentrated on articles published in 2018, with a total of 287 citations. The most frequently cited articles are works (Ong et al., 2018).

With 287 citations. Fourth, the author keywords most used by the top three writers are student, learning, and STEM.

Limitations and Recommendations

The use of a single application for bibliometric analysis and restrictions on the range of other apps utilized are the study's limitations. Additionally, there are limitations on bibliographic data sources that are only sourced from Scopus. The breadth of study in this area is currently restricted, but it may be broadened by enhancing bibliometric mapping in the context of STEM research using apps or other techniques in addition to different bibliographic databases. Thus, there is need for additional development or enrichment of STEM bibliometric mapping. STEM research may hold the key to increasing the efficacy of the educational process. To uncover understudied topics and investigate new developments in STEM education, future research should concentrate on gap analysis. Research on the effects of different teaching strategies, including the use of AI technology, is required. It is crucial to create cutting-edge curriculum that includes the newest pedagogical and technical developments, such as artificial intelligence. Examining multidisciplinary initiatives and the use of instructional technology in STEM education might yield insightful information. Finally, to adjust to the changing educational landscape, research on teacher training and development with an emphasis on using AI tools is essential.

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Experimental Self-Efficacy in Biology Education: A Systematic Literature Review

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Abstract

The aim of this study was to examine the status of experimental self-efficacy in biology education in national and international literature. The research was designed using a systematic literature review as a qualitative method. The PRISMA statement was taken into account to ensure reliability and validity in the research. The keywords “experiment self-efficacy, experimental self-efficacy, lab self-efficacy and laboratory self-efficacy” were determined as search terms and all results were reduced to biology and science. The searches were conducted on 6 databases [Web of Science, Scopus, Science Direct, ERIC (Education Resources Information Center), Google Scholar and National Thesis Center] without any limitations such as time period or language preference. 19 studies were included in the research. Content analysis was used in data analysis. As a result of the research, it was determined that the studies were mostly conducted in 2020-2021, in international publications and in Türkiye on a country basis, in the field of science, with quantitative methods and through scales. It is recommended to focus on qualitative, scale development and intervention-based research in the field of biology education.

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Introduction

Science and technology follow developments in biology to keep pace with the times. Biology experiments and observations offer solutions to various problems, big and small, in our lives, from biological warfare to nutrigenetics. Biology, which is of vital importance, should fill its place in education by using field and laboratory studies. According to research, when biology is approached in an applied way, learning is meaningful, complete and useful (Kırpık & Engin, 2009).

Although critical, the application of biology to practice is not easy in many respects. The first reason that comes to mind for this is the lack of appropriate environment and materials (Akgün, 2005; İnce & Kutlu, 2017; Koç Ünal & Şeker 2020). However, it can be said that in addition to such financial inadequacies, the low level of experimental self-efficacy, plays a significant role in characterizing biology as theoretical, rote, boring and difficult (Şimşek et al., 2012; Aydın Gürler, 2023). Damerau (2013) defined the experiment self-efficacy as the belief that a person can successfully conduct an experiment. In fact Bandura argues in Self-Efficacy Theory (1995) that beliefs are decisive on behavior. This context can be explained by Gandhi's words too, “People generally become what they believe they are. If I believe I can't do something, that belief takes away my power to do it. If I believe I can, I find within myself the power to do it, even if I don't have it at first” (Arseven, 2016). From this perspective, that Dameraus' (2013) found individuals with low experimental self-efficacy approach experiments more hesitantly, which is very important for biology education.

The literature has various studies on this topic in the fields of biology and science education. Some of these are the chemistry laboratory self-efficacy scale study developed by Alkan (2016), the study of Akkış (2024) to increase laboratory self-efficacy in science education, the study of Cramman et al. (2024) revealing the negative impact of the COVID-19 period on experiment self-efficacy, and the study of Reinboth et al. (2017) revealing that high school students who gained experience with low-cost, simple experiments improved their biology experiment self-efficacy.

Studies generally appear to progress within the framework of chemistry discipline and laboratory self-efficacy. However, when biology is put into action, it penetrates into areas much wider than the confines of the laboratory. At the same time, it is evident that the skill based new Biology Curriculum (2024) in Türkiye focuses heavily on field skills. In order for biology skills to develop, teachers and students must be empowered to believe that they will successfully demonstrate these skills (Atik & Doğan, 2020). For this purpose, the literature on biology education is expected to be a guide. However, there are not enough studies in the literature on belief in biology experiment skills, and accessing such studies is sometimes difficult.

Purpose and Importance of the Research

The aim of this study was to examine the status and place of experimental self-efficacy in biology education in Türkiye and the world. In addition, it is thought that evaluating related studies together will contribute to the literature and future studies by providing a holistic, systematic and detailed perspective that will improve experiment self-efficacy.

Problem Statement

What is the current status of experimental self-efficacy in biology education in terms of literature?

Sub Problem

What is the status of experimental self-efficacy in biology education in national and international literature?

Method

In this research, which will be conducted with qualitative method, the situation of experimental self-efficacy in Türkiye and the world was examined by systematic literature review. Systematic literature review is a method that presents relevant information, terms, methods and problem frameworks; provides information about useful and useless methods; enables awareness of new problems and puts forward suggestions for the future (Gall et al., 1996). However, the increase in the number of articles and the frequent use of this method with the development of technology have led to concerns about its quality (Toker, 2022). As a solution to this, it was decided to use the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) statement recommended by Moher et al. (2010) for meta-analyses and systematic reviews in this study. The PRISMA statement is a set of recommendations that researchers are advised to follow, which helps in the complete reporting of reviews based on evidence (Sarkis-Onofre et al., 2021).

Data Collection Process

Considering the PRISMA flow chart (Moher et al., 2010) for the systematic literature review method, national and international scientific publications were selected according to the following steps. This research has been carried out taking into account research and publication ethics; since it was carried out on openly available written documents and using the document review method, it is not one of the studies requiring an ethics committee decision; however, since it is part of the thesis study, it has an ethics permit from the Hacettepe University commission with the E-82474949-300-00003698264 number and 09.08.2024 date.

Study Selection Stages According to the PRISMA Flowchart

Stage 1: Identification

At this stage, the research problem was determined as "What is the status of experimental self-efficacy studies in biology education in Türkiye and the world?" and a research was conducted in this direction. The keywords "experiment self-efficacy, experimental self-efficacy, lab self-efficacy and laboratory self-efficacy" were determined as the search term and all results were reduced to biology education and science education. It was preferred to conduct searches on 6 databases [Web of Science, Scopus, Science Direct, Education Resources

Information Center (ERIC), Google Scholar and National Thesis Center] without any limitations such as time interval or language preference.

Stage 2: Screening

At this stage, the search terms were scanned starting from 15.10.2024 and continuing on dates such as 31.10.2024, 07.11.2024 and 13.11.2024, and a total of 743 records were identified, 739 from the specified databases and 4 from other sources.

Stage 3: Eligibility

At this stage, the criteria for the research problem were determined. First, the studies were checked for compliance with the criteria in terms of titles, keywords, and abstracts. The studies were then rechecked based on their full texts. The selected studies were submitted to expert evaluation and the studies were included in the research after consensus was reached on the opinions. The eligibility criteria determined at this stage are as follows:

- it should only be related to experiment/laboratory self-efficacy in terms of biology education and science education,
- it should not be a study in a non-target field such as chemistry laboratory self-efficacy or laboratory self-efficacy belonging to engineering,
- the scale used in the study, if any, should measure experiment/laboratory self-efficacy,
- it should not be limited to the scale only for classroom-laboratory management,
- it should be an article and national thesis study, not an (unpublished) presentation or international thesis study, and
- it should be open access, and it should not be a duplicate publication.

Thus, after removing the duplicates, it was determined that only 130 full texts out of the remaining 712 records met the biology and science education criteria, but approximately 110 of these were found to be outside the criteria.

Stage 4: Inclusion of Studies in the Systematic Review

It was observed that there were 19 studies remaining that met the specified criteria. The search strategy followed while reaching the 19 studies that were decided to be examined with the PRISMA method suggested by Moher et al. (2010) is shown in Table 1 and Figure 1.

Stage 5: Data Evaluation and Analysis

Studies that were confirmed to be examined for systematic literature review were subjected to content analysis.

The table below shows the evaluation of the number of studies considered according to the search terms and databases, depending on the PRISMA stages.

Table 1. Number of Studies by Search Terms and Databases

Search Terms	WOS			Scopus			Science direct			Google Scholar			ERIC			National Thesis Center		TOTAL	
	R	I	E	R	I	E	R	I	E	R	I	E	R	I	E	N	O	R	E
Laboratory self-efficacy	7	7	0	6	6	0	3	3	0	176	55	121	7	7	0	2	1		
Experiment self-efficacy	2	0	2	3	1	2	8	7	1	91	2	89	23	6	17				
Experimental self-efficacy	4	4	0	6	6	0	7	7	0	262	28	234	81	9	72				
Lab self- efficacy	0	0	0	0	0	0	3	3	0	46	2	44	1	1	0				
Total Record	13	11	2	15	13	2	21	20	1	575	87	488	112	23	89	3		739	582

R: Result, I: Included, E: Excluded, N: Thesis obtained from the National Thesis Center, O: Thesis obtained from other sources.

Of the 739 results, 582 studies were excluded from the systematic literature search. Figure 1 shows the number of studies included in the research and the reasons for their inclusion according to the PRISMA flow chart.

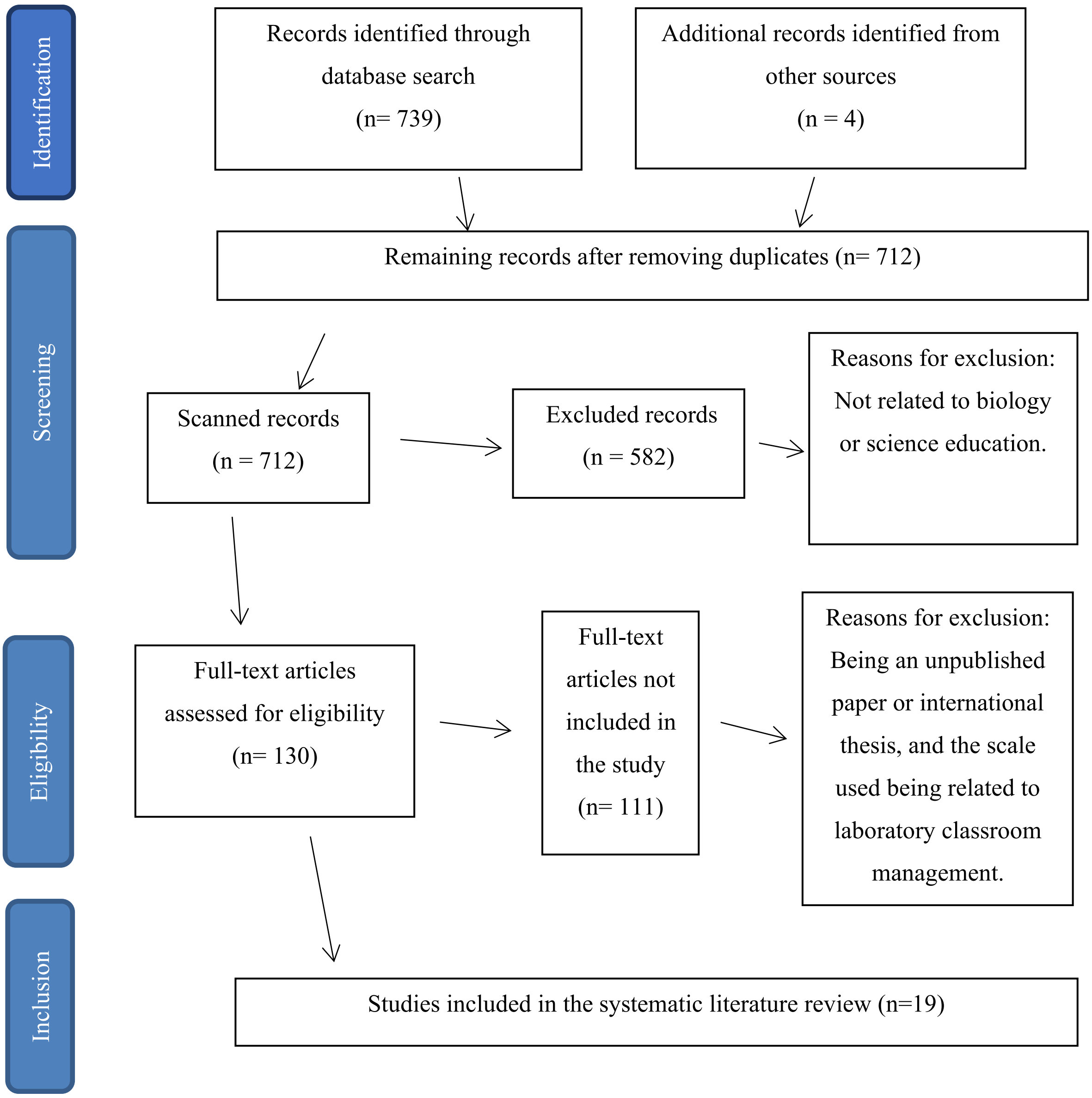

Figure 1. Number and Reasons for Inclusion of Studies

Data Analysis

The data obtained through systematic literature review was examined with content analysis, compared, and separated into themes, codes, and categories. Content analysis was conducted using a Microsoft Excel spreadsheet, focusing on the publication years, countries, methods and patterns, objectives, participants, and data collection tools of the studies.

Reliability

To minimize bias in the analysis of the qualitative data obtained, the data set was analyzed by two researchers. Using Miles and Huberman's (1994) intercoder reliability formula, the intercoder consistency in our study was determined to be 93% ([Consensus/(Agreement + Disagreement)]x100). In addition, research methods, research stages and the entire process are clearly explained and the list of reviewed publications is added in detail to the last part of the study (APPENDIX).

Findings

In this part of the research, the findings obtained from 19 studies included in the systematic literature review are explained in detail and national and international studies are tabulated within the framework of certain characteristics (Appendix). The 19 studies included in the research through systematic literature review were analyzed through content analysis in terms of publication years, national and international origins, countries, participants, study areas, aims, method types, method patterns, data collection tools, and the findings are explained in the tables below.

Table 2. Distribution of the 19 Studies Reviewed by Year

Themes	Codes	Frequency	Percentage(%)
Year	2024	2	10%
	2023	2	10%
	2022	1	5%
	2021	3	15%
	2020	3	15%
	2019	1	5%
	2018	1	5%
	2017	1	5%
	2016	1	5%
	2015	1	5%
	2014	1	5%
	2009	1	5%
	1994	1	5%
	Total	19	100%

According to the data in Table 2, it is clear that the studies were most concentrated in 2020 and 2021 and remained at the lowest level in 2022. The studies cover the years 1994–2024.

The 19 studies included in the research through systematic literature review were analyzed with content analysis in terms of their national and international origins and the findings are explained in Table 3. According to the table, the majority of studies are international publications. National publications were published especially in 2020 and later.

Table 3. Distribution of the 19 Studies Reviewed by Origin

Themes	Alt Themes	Codes		Frequency	Percentage (%)
Origin	National	2024		1	
		2021		2	
		2020		1	
		2018		1	
		2014		1	
		2009		1	
			Total	7	36.84%
	International	2024		1	
		2023		2	
		2022		1	
		2021		1	
		2020		2	
		2019		1	
		2017		1	
		2016		1	
		2015		1	
		1994		1	
			Total	12	63.16%
			General Total	19	100%

The 19 studies included in the research through a systematic literature review were analyzed using content analysis based on their countries, and the findings are presented in Table 4. According to this distribution, although international publications on experimental self-efficacy outnumber national publications, Türkiye is the country where the most studies have been conducted.

The 19 studies included in the research through systematic literature review were analyzed with content analysis in terms of their participants and the findings are explained in Table 5. An examination of the table reveals that the majority of participants in studies on experimental self-efficacy are pre-service teachers. This group consists of pre-service teachers from various fields, including primary school teaching, science, and biology. Studies are also conducted with high school and university students.

Table 4. Distribution of the 19 Studies Reviewed by Country

Themes	Alt Themes	Codes		Frequency	Percentage (%)
Country	National	Türkiye		7	
			Total	7	36.84%
	International	United States		4	
		Canada		1	
		India		2	
		Indonesia		1	
		Philippines		1	
		Germany		2	
		United Kingdom		1	
			Total	12	63.16%
			General Total	19	100%

Table 5. Distribution of Participants in the 19 Studies Reviewed

Themes	Alt Themes	Codes		Frequency	Percentage (%)
Participants	Teacher	-		4	
			Total	4	14.81%
	Pre-service	Primary School		2	
	Teacher	Science		7	
		Biology		3	
			Total	12	44.44%
	Student	University		4	
		High School		6	
		Middle School		1	
			Total	11	40.74%
			General Total	27	100%

The 19 studies included in the research through systematic literature review were analyzed with content analysis in terms of study areas and the findings are explained in Table 6. An examination of the table reveals that the majority of the experimental self-efficacy studies were conducted in the field of science, followed by biology and pre-service primary teacher education programs. It has been determined that various sub-fields such as physics and chemistry are included in the field of science, and different areas of expertise (microbiology, molecular biology, cell biology, etc.) are taken into account in the field of biology.

The 19 studies included in the research through systematic literature review were analyzed with content analysis in terms of their aims and the findings are explained in Table 7. As shown in the table, the studies demonstrate that the most common research aim is to examine the variables that affect or are affected by experimental self-efficacy, followed by scale development and adaptation, examining relationships, analyzing opinions, and investigating predictor variables.

Table 6. Distribution of the 19 Studies by Field

Themes	Alt Themes	Codes	Frequency	Percentage (%)
Field of Study	Primary School	Pre-service Primary Teacher Education Program – (Science Laboratory Course)		
		Total	2	7.69%
	Science	Physics		
		Chemistry		
		Science		
	Biology	Total	15	57.69%
		Microbiology		
		Molecular Biology		
		Medicine		
		Biodiversity, Evolution, and Ecology		
		Introduction to Cells, Molecules, and Genes Curriculum for Agricultural Science Education (CASE)		
		Total	9	34.62%
		General Total	26	100%

Table 7. Distribution of the 19 Studies by Purpose

Themes	Codes	Frequency	Percentage (%)
Purpose	Examining Variables Affected by and Affecting Experimental Self-Efficacy	11	52.36%
	Developing and Adapting an Experimental Self-Efficacy Scale	5	23.81%
	Examining Relationships with Experimental Self-Efficacy	3	14.29%
	Examining Views on Experimental Self-Efficacy	1	4.76%
	Examining Predictors of Experimental Self-Efficacy	1	4.76%
	Total	21	100%

The 19 studies included in the research through systematic literature review were analyzed with content analysis in terms of method types and the findings are explained in Table 8. According to the data in the table, the findings indicate that quantitative methods were used most in the studies examined, followed by mixed and qualitative methods, respectively.

Table 8. Distribution of the 19 Studies Reviewed by Method

Themes	Codes	Frequency	Percentage (%)
Method Types	Qualitative	4	20%
	Quantitative	10	50%
	Mixed	6	30%
	Total	20	100%

The 19 studies included in the research through systematic literature review were analyzed with content analysis in terms of method patterns and the findings are explained in Table 9. The results suggest that the most commonly used method design in the studies is the experimental design (f:9), followed by the predictive design (f:5), scale development and adaptation studies (f:5), case study (f:3) and other designs.

Table 9. Distribution of the 19 Studies by Method Designs

Themes	Codes	Frequency	Percentage (%)
Method Designs	Experimental Design	9	36%
	Predictive Design	5	20%
	Case Study	3	12%
	Total	17	68%
	Scale Development (International 2)	2	8%
	Scale Adaptation (National 2, International 1)	3	12%
	Total	5	20%
	Correlational Pattern	2	8%
	Descriptive Pattern	1	4%
	Total	3	12%
	General Total	25	100%

The 19 studies included in the research through systematic literature review were analyzed through content analysis in terms of data collection tools and the findings are explained in Table 10.

Table 10. Distribution of Studies by Data Collection Tools

Themes	Codes	Frequency	Percentage (%)
Data Collection Tools	Scale	19	73.15%
	Survey	3	11.55%
	Document	2	7.70%
	Interview Form	1	3.85%
	Experiment Reports	1	3.85%
	General Total	26	100%

As seen in Table 10, scales (f: 19) were the most common data collection tools used in the reviewed studies. Other tools included surveys (f: 3), documents (f: 2), interview forms (f: 1), and experiment reports (f: 1).

Discussion and Conclusion

When the results of the systematic literature review on experiment self-efficacy were examined, the 19 publications included in the study demonstrated the highest study rate in 2020 (15%) and 2021 (15%). However, after Covid-19, a significant decrease in studies can be observed in 2022 (5%), and publications started to rise again in the following years (see Table 2). This situation is hopeful because it suggests that awareness of the importance of belief in the ability to experiment will become widespread. In fact, it can be said that the value of experimental self-efficacy will be exalted thanks to the frequent mention of experimental activities in the Biology Curricula. This suggests that the new biology curriculum in Türkiye, which strongly includes field skills, will support experiment self-efficacy (MEB TYMM BÖP, 2024).

It is seen that publications specific to experimental self-efficacy lag behind the international literature in terms of quantity at the national level in Türkiye (see Table 3). However, when examined on a country basis, the national publication rate is higher than the individual studies on experimental self-efficacy of other countries (see Table 4). When the increasing number of national studies in recent years are examined, it is thought that biology education will develop further in the future in terms of experiment self-efficacy studies that will increase experimentation (see Table 3). In addition, the fact that there have been recent studies reporting that experimental studies will not only remain within the school boundaries but will also gain importance in out-of-school learning environments (Kirchhoff et al., 2024), and that experimental environments are supported by Science and Art Education Centers, strengthens the belief that experimental self-efficacy studies will develop.

It is noteworthy that among the countries where these 19 studies were conducted, Türkiye is the country that publishes most frequently on experimental self-efficacy, followed by the USA and other countries in terms of publication frequency (see Table 4). This situation may have been shaped by the fact that scale adaptation studies have been conducted in our country, making it possible to use the scale in the native language (Ekici, 2009; Yılmaz, 2018). Then, the publication frequencies are ranked from most to least as America, Asia and Europe (Table 4). When evaluated according to the participants, nineteen studies included in the analysis were mostly conducted with pre-service teacher (see Table 5). This result is consistent with the results of studies emphasizing the importance of developing experimental self-efficacy in the training of teachers who create permanent behavioral changes in students (Gezer, 2014). Additionally, some studies indicate that experimental self-efficacy has an impact on success, performance, and motivation in high school and university students. This may also explain the high number of studies on these groups (Ekici, 2009; Kolil, 2020).

It is evident that the studies were mostly conducted in the field of science (f:15), and at the same time, the number of experimental self-efficacy studies in the field of science is twice as much as the number of experimental self-efficacy studies in the field of biology (f:9) (see Table 6). This result reflects the need to increase the number of experimental self-efficacy studies in the field of biology. This need is also compatible with studies emphasizing the importance of experimentation in biological sciences (Yılmaz, 2018; Ekici 2009). According to research, no other teaching method is as effective as experiments on scientific process skills (Yılmaz, 2018).

The aims of the study are mostly focused on examining the variables affected by experimental self-efficacy and examining the variables that affect experimental self-efficacy (f:11) (see Table 7). Apart from this, it was determined that the number of studies aiming at scale development-application and examining the relationships was also high (see Table 7). This result demonstrates the rarity of studies aiming to investigate the causes of situations related to experimental self-efficacy and suggests that there is a need for investigation and intervention studies specifically aimed at increasing experimental self-efficacy. Intervention studies are important for the development of experimental self-efficacy, as they not only identify the data but also make it possible to try and evaluate the methods designed to change it in a positive and meaningful way (Büyüköztürk et al., 2021).

When the studies are examined according to their methods, it is seen that quantitative studies are the most intense (50%) and qualitative studies are the least intense (20%) (see Table 8). However, it can be said that qualitative research methods should be used more frequently, as the qualitative method will make it easier to intervene in the negative variables that affect experimental self-efficacy while examining the causes of events and phenomena (Yıldırım & Şimşek, 2018). Büyüköztürk (2021) states that more meaningful results can be obtained by examining variables that can be classified, such as teaching method and gender, from a qualitative perspective. However, the information that studies were conducted intensively with mixed methods (30%) shows that quantitative and qualitative method data are evaluated together from a broader perspective in the literature. Because experimental self-efficacy is a structure that requires not only determining the level but also examining the variables related to experimental self-efficacy in depth and increasing its level, and since it involves multidimensional and complex problems, the use of mixed methods, which benefit from the complementarity of more than one method, which also increases reliability and validity, is parallel to the emphasis of the publications (Akkış, 2024; Atik & Doğan, 2020). It is seen that the studies used the experimental design extensively (f: 9, 36%), which reported the effectiveness of experiment self-efficacy (see Table 9). However, the lack of action research aimed at improving experimental self-efficacy is noteworthy. However, in order to carry out experimental activities in a more healthy way at the frequency required by the new biology curriculum, experimental self-efficacy needs to be strengthened (MEB TYMM BÖP, 2024). Therefore, it is pleasing that beyond descriptive detection studies, there are also a high number of publications that predict and explain (f:9+5=14, 56%). However, the fact that qualified scale development and adaptation studies on experimental self-efficacy are few in our country compared to international publications and that there are only two adaptation studies may be important in indicating the need for new scale studies to be developed on this subject (see Table 9).

Finally, it was determined that 19 studies (f: 19) used the scale data collection tool the most (see Table 10). In addition, it is seen that interview forms are used in relatively low numbers (f:1). However, research emphasizes the need for studies that involve deep inquiry to identify and solve students' problems related to the experiment and research emphasizes the need for studies to develop an experimental self-efficacy scale that can be a determinant on professional choices (Damerau, 2013; Yılmaz, 2018).

Recommendations

In this section, several important recommendations are presented to strengthen the literature based on data obtained from national and international studies on experimental self-efficacy in biology education:

- Experimental self-efficacy, which has been studied extensively in science education in the literature, should be studied more specifically for biology education.
- Experimental self-efficacy scales should be developed (in Turkish and the other languages) that will address the problems related to experimentation from different and broader perspectives, have diversified scope and content, and are suitable for different target groups.

- The use of qualitative data collection tools such as open-ended interviews, focus group studies, and observation forms, which can provide more in-depth information about experiment self-efficacy, should be expanded.
- In order to contribute to the development of experimental teaching strategies, the number of qualitative research and intervention-based studies focusing on the reasons and development processes of experimental self-efficacy should be increased.
- For future research, it is recommended that the search options of the National Thesis Center in Türkiye be improved. This will make it possible to access more resources on the subject.

Statements and Declarations

Data Availability/Ethics Statement: This research has been carried out taking into account research and publication ethics; since it was carried out on openly available written documents and using the document review method, it is not one of the studies requiring an ethics committee decision; however, since it is part of the thesis study, it has an ethics permit from the Hacettepe University commission with the E-82474949-300-00003698264 number and 09.08.2024 date.

Notes: This study was presented as an oral presentation at Gazi University International Turkish World Educational Sciences Congress-IV (12-13 December 2024) in Ankara; this article is an expanded, developed version of the relevant paper and is also derived from the first author's master's thesis on supervision of the second author’s completed in 2025.

Disclosure Statement: The authors declare no conflicts of interest. There is no conflict of interest in this study.

Turnitin Result: Turnitin result is 12%.

Limitations: The research was conducted only on general experiment self-efficacy in science and biology education, and studies on sub-fields of experiment self-efficacy (such as microscope use self-efficacy, chemistry laboratory self-efficacy) were excluded from the research within the scope of the systematic literature review. In this study, some studies could not be accessed and the data coverage remained limited due to the inadequacy of filtering in the search infrastructure of the National Thesis Center.

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Appendix. Studies Included in the Systematic Literature Review

No	Publication	Purpose	Participant	Method	Data Collection Tools
1.	Akkış, (2024)	Investigation of Variables Affecting Biology Laboratory Self-Efficacy.	Pre-service Science Teacher (N=40)	Quantitative Research (Pre-Post Test Control Group Experimental Design)	Biology Self-Efficacy Scale Biology Laboratory Anxiety Scale
2.	Cramman et al. (2024)	An Examination of Their Views on Practical Science Experiences.	From students who started their education in the fields of Biological Sciences, Chemistry, Physics and Natural Sciences at two universities (N=275)	Mixed Method (Exploratory Sequential)	Focus groups (Qualitative) Online survey (Quantitative)
3.	Kolil et al. (2023)	Examining the Relationship between Experimental Self-Efficacy and Laboratory Performance	Chemistry Students (N = 684), Physics And Biology Chemistry Students (N = 439)	Quantitative Method (Correlation)	Experimental Self-Efficacy Scale
4.	Robledo et al. (2023)	Examining the Effect of Performance on Knowledge and Self-Efficacy	Teacher (N=10) Student (N=836)	Mixed Method (Pre-Post-Test Quasi-Experimental Design)	Self-Efficacy Scale Survey
5.	Larry & Wendt (2022)	Examining Variables Predicting Experimental Self-Efficacy	High School Students (N=388)	Quantitative Method (Regression)	Science Self-Efficacy Questionnaire - Questionnaire on Teacher Interaction
6.	Çeliker (2021)	Examining the Effect of the Scenario Method on Experiment Performance	Pre-service Science Teacher (N=108)	Quantitative Method (Pre-Post-Test Experimental Design)	Biology Self-Efficacy Scale Critical Thinking Disposition Scale
7.	Yılmaz et al. (2021)	Examining the Effect of Performance on	Pre-service Biology Teacher (N=26)	Qualitative Method (Single-	Survey Interview Form

No	Publication	Purpose	Participant	Method	Data Collection Tools
		Experimental Self-Efficacy		Case Holistic Case Study)	
8.	Martin et al. (2021)	Adaptation of Self-Efficacy Scale, Examination of Variables Affecting Laboratory Self-Efficacy	Biology Student	Quantitative Method (Pre-Post-Test Experimental Design, Factor Analysis)	Self-Efficacy Scale Survey
9.	Kolil et al. (2020)	Development of an Experimental Self-Efficacy Scale	Chemistry Students (N=1225)	Quantitative Method (Scale Development)	Experimental Self-Efficacy Scale
10.	Atik & Doğan, (2020)	Examining the Effect of Experiment Process Management on Experiment Self-Efficacy	Pre-service Primary School Teacher (N=44)	Mixed Research (Single-Group Pre-Post-Test Experimental Design, Interview)	Experimental Self-Efficacy Scale Interview Form Focus Group Interview
11.	McLean et al. (2020)	Examining the effects of online decision tree on self-efficacy and motivation	Medical sciences students (N=120)	Mixed method interview	Scale Survey
12.	Yılmaz (2018)	Adaptation of the Experimental Self-Efficacy Scale	Pre-service Biology Teacher and Pre-service Science Teacher (N=333)	Quantitative Method (EFA-CFA Factor Analysis)	Experimental Self-Efficacy Scale
13.	Randler et al. (2016)	Examining the Effect of Performance on Experimental Self-Efficacy	Pre-service Biology Teacher (N=135)	Quantitative Method (Pre-Post-Test Experimental Design)	Self-Efficacy Scale Emotional Schedule Anxiety Inventory
14.	Reinboth et al. (2016)	Examining the Effect of Performance on Experimental Self-Efficacy	High School Students (N=18)	Quantitative Method (Pre-Post-Test Experimental Design)	Scale Survey
15.	Widiyawati & Sari, (2019)	Examining the Relationship between Laboratory Self-	Pre-service Science Teacher (N=12)	Quantitative Method (Scale Development,	Laboratory Self-Efficacy Scale

No	Publication	Purpose	Participant	Method	Data Collection Tools
		Efficacy and Science Process Skills		Correlation)	
16.	Velez et al. (2015)	Examining Variables Affecting Science Laboratory Self-Efficacy	High School Students (N=173)	Quantitative Method (Longitudinal Correlation)	Science Laboratory Self-Efficacy Scale Motivated Strategies for Learning Questionnaire (MSLQ Learning Climate Questionnaire (LCQ)
17.	Gezer (2014)	Examining the Effect of Laboratory Use on Skills	Pre-service Science Teacher (N=66)	Mixed Method (Scale, Interview)	Self-Efficacy Perception Scale, Laboratory Anxiety Scale, Scientific Process Skills Test, Reflection Skills Questions
18.	Ekici (2009)	Adaptation Study of the Biology Self-Efficacy Scale	High School Students (N=465)	Quantitative Method (Scale Adaptation)	Biology Self-Efficacy Scale
19.	Smist & Owen, (1994)	Examining the Relationships Between Attitude and Achievement in Science Self-Efficacy	High School Students (N=500)	Quantitative Method (Correlation, Use of Scale)	Science Attitude Scale Science Self-Efficacy Scale

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Digital Technologies and Calculus: Students' Peaks and Pits

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Abstract

Understanding calculus students' perspectives can provide valuable insights into their learning needs and help develop strategies to enhance persistence in STEM programs. Numerous studies have shown that the use of digital technologies (DT) influences student engagement, motivation, and mathematics achievement. In this project, we explored students' perspectives on using DT in calculus. We interviewed eight calculus students from a midwestern doctorate-granting institution in the United States and used thematic analysis informed by the didactical tetrahedron, accounting for internal and external factors that may influence the teaching and learning process. Students reflected on their use of technology, identifying various benefits, including looking for similar problems, checking their work, and visualizing concepts. They also identified challenges, particularly with online feedback. Additionally, students shared their perceptions of how instructors utilized DT in calculus, recognizing benefits when they provided relevant course material or solved mathematical problems, and highlighted challenges related to the misalignment between course content and online homework. Finally, students described how external factors, such as classroom environments, facilities, and accessibility, impacted their use of technology. These findings offer valuable insights for faculty and institutions regarding effective DT implementation and highlight the importance of considering the specific instructional context in calculus courses.

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Introduction

Given the pivotal role of calculus in STEM retention (Ellis et al., 2016; Rasmussen & Ellis, 2013; Riegle-Crumb et al., 2019; Sithole et al., 2017), there has been growing interest among United States (US) institutions to investigate the teaching and learning of calculus. Recent research in calculus education has focused on examining how students learn calculus concepts and on understanding teachers' knowledge, beliefs, and practices (Bressoud et al., 2016; Rasmussen et al., 2014). Despite numerous individual and coordinated efforts to support students' learning experiences in calculus classes, students continue to retain misconceptions and struggle with the conceptual understanding of limits, derivatives, and integrals (e.g., Blaisdell, 2012; Bezuidenhout, 2001; Carlson et al., 2003; Denbel, 2014; Habre & Abboud, 2006; Hall, 2010; Orhun, 2012; Rasslan & Tall, 2002; Sealey, 2014; Serhan, 2015; Thompson, 1994; Wagner, 2018).

Extensive scholarly literature highlights the potential of using digital technologies (DT) to enhance mathematics learning and student motivation (Drijvers & Sinclair, 2024; Higgins et al., 2019). Nonetheless, the mere presence of technology does not guarantee an enhancement in students' learning and motivation (Cohen et al., 2003). Regarding the teaching and learning of calculus, numerous studies have focused on leveraging specific technological tools like GeoGebra or Desmos and sophisticated computer algebra systems (CAS) to foster students' conceptual understanding, visualization skills, and mathematical representation (e.g., Hunter, 2011; Takači et al., 2015; Yu, 2023). Less research has focused on understanding students' perspectives regarding technology integration within calculus classes (e.g., Boz & Adnan, 2017; Esparza Puga & Sánchez Aguilar, 2021; Sevimli, 2016). These studies have focused on the students' perspectives about specific DT such as YouTube or CAS (e.g., Esparza Puga & Sánchez Aguilar, 2021; Sevimli, 2016) and have included the perspectives of college students from different courses rather than focusing exclusively on calculus courses (e.g., Esparza Puga & Sánchez Aguilar, 2021), or only consider a specific subpopulation of students such as engineering majors (e.g., Boz & Adnan, 2017). Though some studies focus on specific technologies, we could not find any studies that explore students' perspectives on the overall use of DT in calculus courses.

Investigating students' perspectives can provide valuable insights into their experiences and help design targeted strategies to overcome challenges. Additionally, there is a significant relationship between students' perspectives, their mathematics achievement, and their motivation for learning (Muis, 2004). Understanding these perspectives is essential for creating a meaningful and impactful learning experience in calculus classes.

This gap in the literature prompts an exploration of students' perspectives on the general use of technology, aiming to acknowledge their concerns, preferences, and recommendations. Such insights hold significant promise for guiding instructors in anticipating and addressing students' apprehensions, thereby fostering a more supportive and effective learning environment for calculus classes. Thus, the primary objective of this study is not to determine the extent of technology usage or which technologies students use but rather to consider students' perceptions of the effective use of technology to enhance the teaching and learning of calculus.

The research questions that guide our study are:

(1) How do students perceive the benefit of using technology in calculus classes?
(2) What challenges do students face when using technology in calculus classes?

Digital Technology

We refer to DT as any technology that supports, facilitates, and enhances mathematical learning processes, including hardware, software, and digital resources. Crisan et al. (2023) classify mathematics education technology as digital technology devices, applications (apps), and tools. They also specify whether apps and tools are generic or specific for teaching or learning mathematics. In this paper, we refer to generic DT apps and tools and mathematics–specific DT apps and tools. The generic DT apps and tools category compiles all apps and tools that enable mathematics communication through reading or writing (Crisan et al., 2023), such as PowerPoint, PDF notes, Blackboard, Zoom, and e-books. Mathematics–specific DT apps and tools are used to support, enhance, and facilitate the learning and teaching of mathematics (Crisan et al., 2023). While the generic DT apps can present content, we consider mathematics–specific apps and tools created to learn and teach mathematics–related content, such as calculators or graphing software.

We are interested in the benefits or challenges perceived by calculus students when interacting with generic or mathematics-specific DT apps and tools in the following ways: (1) as tools used by students to learn course content, (2) as mediums utilized by instructors to teach, share class material, or assess students, or (3) as a means for students to communicate with instructors regarding course content. However, the mere presence of technology, without its use as described above or without explicit interaction with it for learning, falls outside the scope of our study.

Literature Review

In this section, we build on existing literature concerning the integration of DT in calculus classes. The students' use of online resources in mathematics classes has been studied at the college level (e.g., Gueudet & Pepin, 2016; Pepin & Kock, 2021). Pepin and Kock (2021) explain that students who are more advanced in their undergraduate degrees use mathematics DT tools such as Mathlab, Simulink, and JavaScript to solve mathematical questions in their courses. Regarding calculus courses, the effective integration of DT enhances conceptual understanding through visualization, multiple representations, and exploration of key calculus concepts like limits, derivatives, and integrals (e.g., Bressoud et al., 2016; Ferrara et al., 2006; Rasslan & Tall, 2002). To delve deeper into the utilization of technology in calculus classes, we explore relevant literature addressing efforts to improve the teaching and learning of calculus by examining both the instructors' and students' use of technology (Drijvers, 2015; Ferrara et al., 2006; Takači et al., 2015).

Instructors Using Technology in Calculus Classes

Calculus instructors utilize DT for several purposes, primarily to introduce or explore calculus concepts. Examples of class activities incorporating DT have been extensively shared as resources for other teachers to implement in their classrooms (e.g., Hohenwarter et al., 2008; Liang, 2016; Yu, 2023). For example, Yu (2023) used Desmos, an advanced graphing calculator, to create an animation of the rate of change concept to help students who were not necessarily familiar with Desmos understand its relationship with derivatives. Other instructors have used technology to share class materials (e.g., Maciejewski, 2016). Maciejewski (2016) found that using online videos in a flipped calculus teaching model increased student performance and understanding of calculus.

Research on how instructors perceive DT has been studied at the school level. Researchers have found that school teachers are not confident in their proficiency in using mathematics-specific DT that are new to them and are concerned regarding accessibility, lack of training, and lack of alignment with the curriculum (e.g., Hudson et al., 2008; Muhazir & Retnawati, 2020; Sacristán, 2017). Less research has focused on instructors' use and perspectives of mathematics-specific DT at the calculus college level (e.g., Martínez-Planell et al., 2023; Serkan, 2013; VanDieren et al., 2020). Martínez-Planell et al. (2023) found that calculus instructors use the dynamic Java applet CalcPlot3D for teaching multivariable calculus, and they perceive these DT help students visualize multivariable calculus concepts and are convinced this will help with building conceptual understanding. Additionally, Serkan (2013) found that instructors use DT to facilitate students discovering and solving calculus problems. They also reported difficulties using DT. Specifically, they perceived its use as distracting and were skeptical of using it when students had not yet mastered basic mathematical skills and concepts.

Extensive research has examined students' perceptions of instructors' use of DT for teaching calculus. However, they have focused on using generic DT apps and tools and have found that students have positive experiences with this type of DT in their calculus courses (Loch, 2005; Othman et al., 2017; Vajravelu & Muhs, 2016). For example, Othman et al. (2017) found that most students perceived as positive the use of PowerPoint as considering mobility and learning satisfaction. Some research has examined how the use of DT impacts calculus students' attitudes toward mathematics (e.g., Sonnert et al., 2014). We also found limited research examining students' perception of instructor use of mathematics DT apps and tools (Bedada & Machaba, 2022). Bedada and Machaba (2022) found that students liked learning calculus using GeoGebra classroom-oriented approaches. Specifically, this quantitative study found that students agreed that scaffolding activities offered better learning opportunities than traditional classroom ones.

Students Using Technology in Calculus Classes

Researchers have examined how the use of different DT can benefit calculus students' learning experiences and how the use of DT can support the doing of mathematics by doing quick arithmetic computations or visualizing concepts (e.g., Hunter, 2011; Takači et al., 2015). Using DT enhances learning (e.g., Hunter, 2011; Takači et al., 2015). Hunter (2011) investigated the impact of graphing calculators on calculus students' reasoning in solving problems on definite integrals and their applications and found that using graphing calculators was more effective in monitoring progress than traditional methods without graphing calculators. Takači et al. (2015) conducted a study that compared two groups of calculus students in a collaborative environment while examining functions and drawing their graphs. One group used GeoGebra as a tool, and the other completed the task without using it. The results showed that the students who used GeoGebra had higher scores in the calculus post-test.

Extensive research has explored the use of DT to assist with visualizing concepts (Nongharnpituk et al., 2022; Takači et al., 2015), getting immediate feedback (Dorko, 2020; Lampe & White, 2023), and seeing similar examples (Dorko, 2021; Esparza Puga & Sánchez Aguilar, 2021). For example, some DT facilitate the visualization of mathematical concepts by allowing multiple representations, thus enhancing a complete visualization of calculus concepts (e.g., Nongharnpituk et al., 2022; Takači et al., 2015). Dorko (2021) discusses that students use similar examples to troubleshoot, to check if they are on the right track, and to see the form of the answer. Dorko (2020) discusses how online homework provides intermediate feedback, allowing students to work on multiple homework trials when they get an incorrect answer.

In mathematics college courses, Ní Shé (2023) conducted a meta-analysis and reported that accessibility issues of DT may be explained by the lack of familiarity, financial limitations, and ability to find DT resources. We did not find studies examining these specific limitations in calculus courses. While extensive research has examined the uses of technology and its benefits to teaching calculus, few studies have focused on students' perspectives on using technology in calculus courses.

Some studies have focused on how students perceive the use of technology (Lampe & White, 2023; Nongharnpituk et al., 2022; Pepin & Kock, 2019; Sevimli, 2016). Lampe and White (2023) found that calculus students like online homework because they find it accessible and adaptable and can get immediate feedback compared to written homework; however, students also share that online homework does not allow them to keep track of their progress. Nongharnpituk et al. (2022) found that future teachers in a calculus class perceived the use of GeoGebra as a tool for providing visualization and conceptual understanding. Sevimli (2016) found that calculus students with an analytical thinking style were likelier to limit CAS use than those with more visual thinking skills. Additionally, students who used CAS developed a stronger preference for conceptual understanding, while those who did not tended to favor procedural understanding. Pepin and Kock (2019) examined the use of resources in calculus and linear algebra. While focusing on resources for learning calculus, they found that students reported using digital resources such as YouTube and Khan Academy.

Many of the existing studies are narrowly focused on specific digital tools, such as online homework systems, Geogebra, or CAS (Lampe & White, 2023; Nongharnpituk et al., 2022; Sevimli, 2016), while others take a broader, more inclusive approach to the use of digital resources (Pepin & Kock, 2019). As these studies do not examine students' perspectives on the overall use of DT in the context of calculus learning, this exposes a gap in the literature. A more comprehensive examination is needed to fully capture how students engage with and perceive DT in calculus education.

Theoretical Perspective

To shed light on our investigation, we draw from the didactical tetrahedron perspective. The didactical tetrahedron is an extension of the instructional triangle, which considers the interaction among student, teacher, and mathematical concepts and adds an extra vertex to include technology (e.g., Olive et al., 2009; Tall, 1986). The tetrahedron redefines the learning space where mathematical knowledge emerges by considering how mathematics interacts with teachers, students, and technology. Our research is rooted in analyzing the faces of this tetrahedron, and we enclose a tetrahedron inside a sphere to represent the context. Tall (1986) first proposed the idea of a tetrahedron inside a sphere and considered the context of using inquiry and cooperation as components that contribute to students' learning with technology.

The didactical tetrahedron has four vertices representing the learner, the teacher, the mathematics content, and the technology. As an extension of the didactic triangle, the idea expands on the interactions among these four vertices for emerging mathematical knowledge and practices (Olive et al., 2009). Tall (1986) used the vertices of pupils, teachers, content, and computers in an enhanced Socratic mode, starting with a demonstration on one computer to show students a concept followed by teacher and pupil discussion, encouraging cooperation in a whole group setting. Tall illustrated the context of these classroom practices as a sphere enclosing the tetrahedron.

The idea of including technology as one of the tetrahedron's vertices has been developed further in studies like Olive et al. (2009), which positioned students, teachers, tasks, and technology as vertices. They also emphasize using faces as a lens to illustrate the possible inter-relationships among the four vertices.

Our Study: Didactical Tetrahedron in a Sphere

In our study, we adapted the didactical tetrahedron, as shown in Figure 1, to have four vertices—calculus content, instructors, students, and DT (CIST)—that form four faces: calculus content, instructor, and DT (CIT); calculus content, students, and DT (CST); instructor, students, DT (IST); and calculus content, instructor, students (CIS).

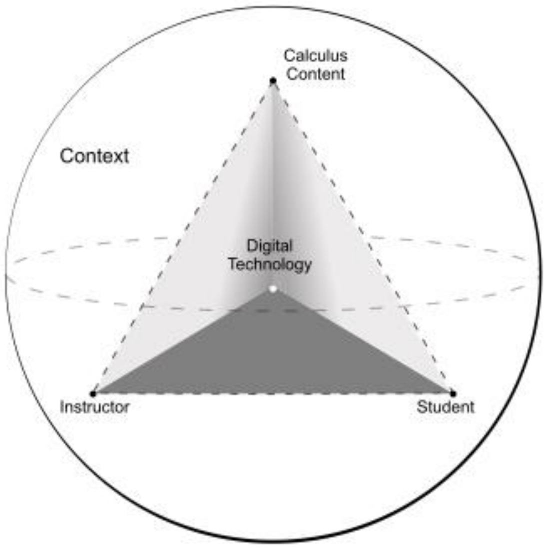

Figure 1. Calculus Content, DT, Instructor, Student (CIST) Didactical Tetrahedron in a Sphere

We kept the idea of using student, teacher, content, and technology, but we modified these to ensure alignment in our study. First, following Crisan et al. (2023), we use DT to disambiguate the term technology. We also refer to the calculus content to emphasize what we mean by content. Using instructors instead of teachers is not related to classroom practice but to a typical language to refer to a college educator. The word *instructor* includes professors, part-time and full-time instructors, and graduate teaching assistants who may teach calculus.

As we need to analyze three vertices to visualize the interrelationships among one face, let us start by considering two vertices: the calculus content and the DT. DT can be used as generic tools to deliver calculus content (Crisan et al., 2023), which serves as a mediator, or as a mathematics–specific tool (Crisan et al., 2023) to facilitate visualization and manipulation. The CIT face shows up when instructors use technology to teach calculus content, influencing the student learning experience. This includes, for example, an instructor using technology to solve a problem in class, selecting problems on a computer for homework, and sharing course materials.

While these scenarios would only make sense with the presence of students, students play a secondary role as they do not interact directly in this triangle. In this scenario, students may or may not engage in the graphing software activity shown by the instructor. If, in this scenario, the student is the one utilizing the graphing software to learn calculus content, that is a moment when the CST face will show up.

Let us now consider the vertices of the student and the instructor. Without content to teach or learn, the student-instructor interaction is just an interaction between two human beings. When adding DT to this relationship, it works as a mediator of this relationship to facilitate communication to discuss course content. For example, a virtual office hour or an email exchange represents the IST face, where the student seeks help to understand specific class content. This is indeed an example of the CIST didactical tetrahedron in action. The instructor-student relationship with the content and without DT, CIS face, would be the traditional didactic triangle. In other words, when considering this face, DT does not play a central role in the didactic process as in a discussion between teachers and students about content. The DT might be present in the background to support the discussions, such as a presentation, but in this case, the content plays the main role in producing those discussions. Since the CIS face did not provide insights to address our research questions and was not a result gained from our interview questions, it will not be included in this investigation.

Methods

Eight calculus students volunteered to participate in this study. At the beginning of the spring 2023 semester, the students completed a demographic survey and were interviewed during the subsequent summer. The audio of the interviews was recorded, transcribed, and then de-identified for analysis.

Research Context

This study was conducted at a US midwestern PhD-granting institution serving approximately 15,000 students. Around 400 students take calculus per the 14-week semester, and roughly half are from the College of Engineering and Engineering Technology. The remaining students belong to the Colleges of Liberal Arts and Sciences, Business, Education, and Health and Human Sciences.

Calculus classes are coordinated. This coordination consists of common midterm and final exams, common online homework, and the optional implementation of collaborative group work at least once a week to complete weekly worksheets, which act like written homework. Calculus classrooms usually have a computer, a projector, a whiteboard, a webcam, and a traditional lecture setup consisting of rows and fixed seating. When the study was conducted, instructors were encouraged but not required to have small group activities once a week, and the Department of Mathematics transitioned to open resources for textbooks and online homework in calculus classes.

Participants

Eight calculus students consented to participate in this study and completed a survey at the beginning of the Spring 2023 semester to collect demographic information. The reference number for this study is HS23_0150, approved by the Institutional Review Board. During the subsequent summer, the participants took part in follow-up interviews. In this study, we report on their responses during the follow-up interviews. We assigned pseudonyms to participants to protect their identities.

Alejandro was a sophomore first-generation student from the Department of Computer Science enrolled in Calculus I and reported having financial struggles, a part-time job, and a long commute. Bria was a junior first-generation student from the College of Engineering enrolled in Calculus III and reported having transportation issues, financial struggles, and a part-time job. Diana was a senior first-generation student from the School of Music in the mathematics teaching preparation program and reported having a part-time job and a long commute. Grace was a sophomore student from the College of Engineering enrolled in Calculus III and reported having financial struggles and a part-time job. José was a sophomore transfer student from the Department of Earth, Atmosphere, and Environment enrolled in Calculus II and reported having financial struggles. Nathan was a sophomore student from the College of Engineering enrolled in Calculus III. Said was a sophomore student from the Department of Computer Science enrolled in Calculus II and reported having a long commute. Sarah was a sophomore transfer student from the College of Engineering enrolled in Calculus I and reported having a full-time job and a long commute.

Data Collection

We collected data through a demographic survey and one individual semi-structured one-hour interview. Students in all Calculus I, II, and III courses completed the demographic survey within the first four weeks of the Spring 2023 semester. The demographic survey questions are included in the appendix. Each student had three points added to their total point value on the first exam as an incentive to complete it. We strategically selected students to conduct the interviews in ways that students were enrolled in different calculus sections and be representative of all three calculus sequence sections. The eight students who agreed to meet via Zoom during the subsequent summer received a $25 Amazon gift card as compensation.

The first and second authors conducted four interviews each. The interview questions focused on documenting students' perspectives about using technology in the teaching and learning of calculus. We asked participants about the type of technology that they used to learn calculus, the type of technology they would like to see in the instruction of calculus, and their perspectives about the benefits, if any, of using technology in calculus classes. We also asked questions about their experiences with assessments and their suggestions for having an ideal calculus classroom to teach and learn mathematics. The interview questions are included in the appendix.

Data Analysis

The semi-structured interviews were conducted via Zoom, audio recorded, and transcribed for analysis. To ensure the confidentiality of participants, we then de-identified the data by assigning pseudonyms. We used thematic analysis to analyze the data (Braun & Clarke, 2012). The three authors read the transcripts of four interviews separately to familiarize themselves with the data and generate initial codes (Saldaña, 2021).

The initial codes in the data were related to the type and use of technology reported by students. The authors met to discuss the initial codes, analyze the proposed codes, refine existing ones, and introduce new ones. The final codebook was framed on the interactions that resulted from the four faces of the CIST didactical tetrahedron. The three authors then used the final codebook to code the eight interviews and met until a 100% consensus was reached. The agreement of the coding was recorded using MAXQDA during weekly meetings.

Results

While asking questions about technology, students described their experiences using DT in calculus classes. We framed their responses using the faces of the didactic tetrahedron. Specifically, we found broader mentions of the CST and CIT faces. The IST face is the CIST didactical tetrahedron, as all the interactions in this face were explicitly related to calculus content. We finalize this section by reporting on factors related to the sphere, which provides insights into the classroom context when using DT.

The CST Face

For the calculus content, students, and DT (CST) face, we report on activities where students interact with both technology and calculus content, aiming to learn the course material. As shown in Table 1, students discussed CST interactions in their calculus classes by reviewing concepts, visualizing or exploring calculus content, doing online homework, looking for similar examples, checking work, and speeding up the process.

Table 1. Participants Who Mentioned the CST Face

The CST Face	Participants
Reviewing concepts	Alejandro, Bria, Diana, Georgia, José, Nathan, Said, Sarah
Visualizing and exploring calculus content	Bria, Diana, Georgia, José, Nathan, Said, Sarah
Doing online homework	Alejandro, Bria, Georgia, José, Sarah
Looking for similar examples	Alejandro, Diana, Georgia, José, Sarah
Checking work	Bria, Diana, José, Nathan, Said
Speeding up process	Alejandro, Diana, José, Nathan, Said

Reviewing Concepts

Students' most common use of DT was for reviewing concepts. For example, they used it to review notes when they missed classes and needed to catch up or to understand concepts they were learning in class. Some participants found that DT helped them review calculus concepts when they did not attend a class or struggled to understand a concept. For example, Sarah noted:

> It [DT] gives me more time or more options if I can't make it to class that day, or if I just need extra time to the class than provided. I can sit and review, or even go online and just even look up videos or if there's a link in class to expound on an idea until I can understand it fully.

Sarah explained that DT provides access to content even when she cannot attend classes. In class, Sarah used webpage links likely shared by her instructor. Additionally, Sarah searched for videos to understand the concepts she struggled with in class or did not understand well because she could not attend class. Sarah shows persistence in understanding the calculus concepts and perceives DT as a good resource, as they provide "more time or more options" for reviewing concepts.

Students also used DT to review class content, even when attending classes. This was commonly done by reviewing instructors' online notes or watching videos. For example, when solving a calculus problem, José used different resources:

> I would watch YouTube a lot for like a lot of my topics and then kind of just see how they work through the problem. And then if I'm still lost or I want further clarification that I'm not able to ask the YouTuber, right? Then I would go to the tutoring center, or even if it's a quick question, I'll ask at the end of my math class to my instructor.

By using different resources, José acknowledges DT as a preferred resource, however, it has its limitations as one cannot ask one-on-one questions to the YouTuber. The preference for using DT as a first resource when having a question was a typical response from other students. Despite the students being aware of different resources like their instructor or the learning center, they found DT was convenient as a first step when struggling with a calculus problem.

Visualizing and Exploring Calculus Content

Seven students mentioned that DT were useful for visualizing or exploring concepts. Calculus students explained that dynamic mathematics software like CalcPlot3D and Desmos facilitated both visualization and exploration of calculus content. For example, José explained the usefulness of a three-dimensional system like CalcPlot3D:

> If I'm doing a problem and I'm kind of confused on how it's really working out, I can put it on my 3D plot and say "Oh, okay, I see this shape, so now this makes sense. So the surface does make sense, and what I'm finding, and my limit bound should be." and then it kind of helps us tie everything together.

On this note, the visual representation José used not only clarified his confusion but also provided a concrete way to connect the surface of the graph to its limit bound. The dynamic software serves as a powerful tool, enabling the student to explore relationships between variables and reinforcing the importance of visualization in understanding calculus concepts. Such insights underscore how integrating DT can foster a more robust conceptual understanding, especially when students face challenges in traditional problem-solving approaches.

Doing Online Homework

Students highlighted issues in the process of doing calculus online homework. Specifically, students expressed concerns regarding the feedback provided in online assessments, identifying it as a significant issue in their learning experience. The feedback typically lacks the detail necessary for meaningful understanding, hindering their ability to grasp calculus concepts effectively. For example, Bria noted:

> I feel like I've put way more effort into math when technology is used versus, like, a professor like you, and a professor doing a one-on-one, or when a professor is lecturing in the class and is telling you, like, "You're here and you're seeing it real-time. Okay, this step is this step because of this." You know what I'm saying? Versus a computer giving you a big fat red X, like, "No, that's not right." And even if they do give you steps, I don't know. It just doesn't work out for me. Yeah, it just doesn't work out for me.

Bria's remarks underscore a critical distinction between traditional instructional methods and technology-enhanced learning. While technology can facilitate engagement, the lack of personalized feedback diminishes its effectiveness. Bria, like other students, expresses a preference for real-time guidance from instructors, emphasizing the importance of understanding each step in the problem-solving process rather than simply receiving feedback on whether the answers are correct or incorrect when completing online homework. This reveals a deeper need for formative feedback that addresses the cognitive processes involved in mathematics. Without such support, students feel frustrated and disconnected, highlighting the necessity for DT to not only assess correctness but also to nurture a more comprehensive understanding of calculus concepts.

Looking for Similar Examples

Students mentioned going online and browsing similar examples so they could use them as resources for learning course content. Diana noted:

> I'll also google the problem and see if there's similar problems that pop up and see how other people on the internet solved them. Although it's just people on the internet so I don't know if I can trust that. I do look sometimes if I really don't understand a problem, I go to Google as my last resource.

Here, Diana used similar examples online as a resource but is aware of the limitations regarding the accuracy of the approaches and solutions seen online. This shows that Diana used her understanding of calculus concepts to solve problems but may look for ideas and approaches while solving them. Students also discussed wanting to have examples to see step by step solutions and mentioned this could be created or provided by the instructor by posting these solutions online. This practice showed students value the use of learning management systems for accessing similar examples that can support them when struggling with a concept. For example, when discussing how DT could be good for the calculus learning experience, José noted:

> It would be nice if, like, you know, not every instructor has to do this, but maybe just the math department where they went through all the lessons and just hand-wrote all the answers, like working through the problem, and then kind of just uploaded that to Blackboard. [...] So it would be nice to say, okay, I stumbled, I'm stuck, I can look online, see how they've been through it, get it right, and then keep it moving.

José's comments, in particular, underscore a reliance on such examples for self-directed learning. His reference to being "stumbled" or "stuck" reveals a critical moment in the learning process where immediate access to similar problems can serve as a form of academic support. This reliance on online resources reflects a broader trend where students are increasingly turning to digital platforms to resolve cognitive obstacles independently.

Checking Work

Students mentioned using DT to check their work. Specifically, they discussed using graphing software or Chegg to check if their graphs were accurate or the correctness of their solutions. For example, Said noted:

> When I was going through homework and things like that, I was building the graph on the application, and then I was kind of converting it over doing the work in person as well to kind of help me through just to kind of double check my work and verify that I was building the right graph.

Said's use of graphing software illustrates how DT can support learning by allowing students to visualize concepts while working on homework. By transitioning from the application to manual graphing, Said uses DT as a complementary resource to check accuracy, thereby enhancing his understanding through constructive feedback.

Speeding Up Process

Students discussed using DT as a good support for computing simple calculations. For example, Nathan explains that using this resource helped him to "speed it up and even take on more complicated problems." Another student, Diana, explained this further:

> Instead of spending all my time multiplying and dividing and adding in my head or on the paper I could just do it in the calculator and know that the way the process that I took to get there was what I spent the most time on, if that makes sense. So it felt like I was allocating more time [to] learning the material than computing because of the calculator.

Diana's positive perspective about using DT in calculus classes relies on allowing time and energy to learn the calculus content rather than redoing arithmetic computations. This shows how DT can shift the focus from manual computation to deeper engagement with the problem-solving process and understanding of calculus concepts.

The CIT Face

The calculus content, instructor, and DT (CIT) face highlights how students perceive the instructors' interaction with both technology and calculus content, shaping the overall learning experience and influencing their understanding of the course material. The results of this face are shown in Table 2. Students reported instructors sharing course materials, doing mathematics, and selecting online homework problems.

Table 2. Participants Who Mentioned the CIT Face

The CIT Face	Participants
Instructors sharing course materials	Bria, Georgia, Nathan, Said
Instructors selecting online homework problems	Bria, José, Said
Instructors doing mathematics	Diana, José, Nathan

Instructors Sharing Course Materials

A common student perception of how instructors use DT was as a tool for sharing course materials with them. Students reported their instructors posted materials online or used DT to teach in the classroom. For example, Said noted, "So, the material that we had for the class was mostly posted online through Blackboard." In this note, Said explains the instructor used Blackboard to share class materials such as notes and worksheets. Said explains how this instructor's practice helped with reviewing concepts:

> [...] If you didn't understand a certain topic and you felt like you could use a little bit more help or a little more practice on that problem, you could go back into the notes, see how he would approach and how he did a certain problem.

This shows that instructors sharing course materials helped students learn calculus concepts. Said used these posted materials when he needed help understanding a topic or to practice problems.

Additionally, other students highlighted that instructors use DT for teaching. These included using a projector, incomplete notes to fill in class, and presentation software. For example, Bria mentioned: "she [the instructor] will also upload the PowerPoint as well as the notes." This is a way Bria's instructor was using presentation software. However, the use of presentation software limited Bria to follow the class explanations while attending class:

> [The instructor] tried to do the PowerPoint one day, like really clicking through the slides, and it was horrible. Like, it was, it was horrible, because there was no, like, working out any example for us or anything. It was just like the steps, but you know sometimes in math, each step sometimes has a step, kind of in between.

Bria explains that using slides for teaching calculus classes might not be ideal as it provides a fixed setting to focus on only one solution, and it does not show all the steps. What Bria describes is a perception of a teacher-centered practice where students are probably less active in providing strategies for solving the calculus problems, and the instructor is just "clicking through the slides" to present their solution.

Instructors Selecting Online Homework Problems

Students referred to working on problems that lacked alignment with what they were learning in their calculus classes. This aligns with the CIT face as these were choices from their instructors while using DT to assess calculus content. For example, Said noted, “Some questions weren't taking the approach of what the teacher may have taught us in class.” Another student, José, noted:

> We do online homework and some of the lessons where it's like the, like, partial derivatives. It's like finding volumes and stuff like that. He would do homework where like a word problem, like one question out of the 10. And that last one, I'm just like, just writing it and I was like, “Why is this word problem in here?” I don't know. Honestly, I'm really, I've never been the biggest fan of the word problems. I do think they can be good, but I also will say that in the test, he does not use word problems at all.

Said and José discuss a disconnection between the type of problems taught in class and the concepts assessed in the online homework. While José acknowledges the potential value of word problems, his frustration is rooted in the inconsistency in class and homework.

Instructors Doing Mathematics

Students perceived DT as useful for doing mathematics. In this case, students described how instructors used dynamic software like Desmos, three-dimensional software, and Wolfram Alpha to solve mathematical problems in class. Diana exemplifies this:

> I had never used Desmos before college or even before last academic year. I had never known that Desmos existed. But then our teacher in Calc 2 last spring showed us Desmos and I was like, “Oh, this is really cool!” And I liked using that. I'm really glad I found that resource. I actually use it all the time now. And it's good for teaching too. And Wolfram Alpha, my Calc I professor showed us Wolfram Alpha if we ever needed help with the problem. Or if we wanted to learn more about a problem we could plug it into Wolfram Alpha. And I thought that was really cool. I still use it.

Diana, who is also a future teacher, appreciated the teacher working through problems using Desmos and Wolfram Alpha. She sees these tools as helpful for students' mathematics learning experience and her future teaching experience.

The IST Face - The CIST Didactic Tetrahedron

The instructor, students, and DT (IST) face considers students using DT as tools for communicating with their instructor regarding course content, thus, completing the CIST didactic tetrahedron. Students mentioned that DT was useful for online meetings or emailing instructors, as shown in Table 3.

Table 3. Participants Who Mentioned the IST Face

The IST Face	Participants
Online meetings	Alejandro, Sara
Emailing instructors	Said, Sara

For example, when we asked Sarah the question, “When you need help for the class, what do you typically do?” she mentioned:

> I'm not on campus a lot, so it's hard for me to go to things like office hours or tutoring centers. So, it's more of a, I'm doing it, like, you know, 10 o 'clock at night or something. So it's easier sometimes if I'll just Google part of it, or I'll just send an email to the instructor and table it for the day.

Sarah noted that emailing an instructor is convenient when not having other resources available outside regular business hours.

When we asked the same question about what they did when needing help in calculus class, Alejandro mentioned, “One-on-one teacher meetings are just better, just cause you don't have the pressure of the whole class listening to your questions.” Alejandro used this context to explain the need for online office hours.

> Sometimes teachers’ office hours are in the classroom only. And I think, um, maybe having one in the classroom and, like, one online where you could join like a, like a, Blackboard Collaborate. I think that would be good also just for, like people commute and stuff, like me ‘cause I have a 40 minute commute. And if I don't, if it's some, if a teacher's office hours is one day that I don't have classes, I'm not going to drive 40 minutes to go to their office hours. You know, it's like a really big hassle and it's kind of a lot of money also on gas and the mileage on your car. So I think making office hours also available online at least once a week would be pretty beneficial.

Alejandro’s comments highlight a critical gap in accessibility, especially for students with long commutes or financial constraints. By suggesting that instructors offer online office hours through platforms like Blackboard Collaborate, he emphasizes the importance of flexibility in supporting students who cannot attend in-person sessions. This situation points to a broader issue of equity in education, where logistical barriers like transportation and cost can disproportionately affect certain student groups.

The Sphere: Students Describe the Context While Using Technology

In addition to the faces of the CIST didactical tetrahedron, we found that students also described external factors already present in their calculus classes or ones they wished they had. The results of the sphere, which represents the context, include classroom environment, facilities, and accessibility. These results are shown in Table 4.

Table 4. Participants Who Mentioned the Sphere

The Sphere	**Participants**
Classroom environment	Alejandro, Bria, Diana, Georgia, José, Nathan, Said, Sarah
Facilities and accessibility	Alejandro, Bria, Diana, José, Nathan, Said, Sarah

Classroom Environment

Students discussed the classroom environment while using technology. Some students described how DT should be used in their calculus classes. For example, Nathan described a wish list for a calculus classroom with technology and active learning:

> I think they were called smart boards that we had in, I think it was, either at high school or middle school, and they were kind of experimenting with them at the time. But you could go up, and you could just, like, kind of draw on like the projector screen in a way. And it would take an input like that. But maybe something that's more laid flat out and everybody can kind of gather around and see that way.

Nathan's reflection on smart boards reveals both the potential and limitations of DT. While interactive tools like smart boards offer opportunities for engagement, the student's suggestion for a more accessible, flat interface indicates that current setups may not always promote inclusive, collaborative learning. This critique highlights the importance of designing classroom technologies prioritizing visibility and group interaction rather than just individual use to enhance collective learning experiences.

Facilities and Accessibility

Students discussed facilities and accessibility to DT. In this category, students described their access to the online textbook, the institutional facilities, and the access to several DT. For example, Bria explained there was no financial burden in buying all calculus textbooks because she "found them online free." However, when prompted, she revealed the source of these free textbooks, but it was not a legitimate distributor of the textbook used at the institution. Other "free textbook" practices were also found, such as taking pictures of the physical textbook to access the content. Diana described this practice, noting how if she "couldn't see the book online, [she] could ask someone to take pictures of their book and [she] could read it there with the pictures." These practices indicate that students may face financial challenges in purchasing course materials.

In several opportunities, Alejandro mentioned that using DT in calculus classes would be beneficial but may cause issues with access to the content if someone has internet or computer issues. Alejandro appreciated access to DT in this institution: "Now the access to the internet is pretty, pretty, pretty good, especially at [institution's name] with, like, computer labs and stuff." Alejandro also noted that there is an issue with awareness of resources as many students were not aware of them:

> I wasn't even aware of that. So maybe bring awareness to these types of resources also. Because I mean, I've been at [institution's name]. It's gonna be my third year and I had no clue about that. So maybe if, like, math teachers also bring awareness to these types of resources because all I hear about is the tutoring center.

Alejandro states that resources should be advertised better at the institution and possibly have as good of an advertisement system as the tutoring center.

Sarah, a commuter student, mentioned struggling to find the help she needed from the institution. She would like to have online tutoring support when needed.

> The only thing I could really think of in regards to calculus would be like, you know, having some kind of online tutoring option. I don't know if anything like that exists now. But just something like, because

> especially for me, the hours that I'm doing this, you know, can be really early in the morning or late at night if I'm doing the homework or review. And just having some other options to ask questions where you don't have to wait four hours for an answer that you can have a better response time.

Sarah's suggestion for online tutoring highlights the necessity for more immediate and flexible support systems in calculus education. Unconventional studying hours underscore the challenges that many students face in balancing coursework with personal or professional responsibilities, indicating that traditional office hours may not adequately meet their needs. Having this option would facilitate a more supportive learning environment.

Discussion

Students described the uses and benefits of generic and mathematics-specific DT apps and tools in calculus classes, highlighting how these benefits can enhance the teaching and learning of calculus. However, they also reported encountering several challenges. These challenges present an opportunity for researchers and instructors to critically reevaluate existing policies and practices to understand better and address the underlying reasons for these difficulties.

CST Interaction: Benefits and Challenges

Participants actively described the CST interaction between calculus content, students, and DT in various scenarios. These scenarios included reviewing concepts, visualizing and exploring calculus content, doing online homework, looking for similar examples, checking work, and speeding up the process. Using DT allowed students to look for similar examples, which were perceived as a benefit. This finding is aligned with what others have found in calculus classes, where students like to mimic completed examples (Dorko, 2021; Esparza Puga & Sánchez Aguilar, 2021). While using similar examples is perceived as beneficial, finding comparable solutions might take priority over engaging with the deeper underlying principles. Future research can examine the relationship between the use of similar examples and the learning of these concepts.

Our study adds to the literature on the exploration of students' perspectives about using three-dimensional DT, such as CalcPlot3D, for visualization and exploration of calculus concepts. Participants explained that three-dimensional mathematical software supports visualization and exploration of concepts. They also perceived them as tools for supporting their conceptual understanding of limit bounds in Calculus III. Limited research has examined the use of three-dimensional mathematics software programs to teach calculus (Martínez-Planell et al., 2023). Martínez-Planell et al. (2023) found that instructors liked CalcPlot3D for visualizing concepts and building conceptual understanding. This matches our findings from the students' point of view.

We found that DT can supplement students' learning experience by providing *more time and options,* as Sarah described. For example, students who cannot attend their classes supplement the instructor's notes or browse concepts online through videos. This is convenient and preferred as a first resource by many students because the resources are "right there for you" (Alejandro). While research has examined the importance of attendance for the academic performance of calculus classes (e.g., Khan, 2022), we did not find literature examining the use of DT as supplemental for providing broader access for students who were not attending classes. This can inform researchers of further problems to explore. Instructors may consider incorporating DT as supplemental tools to support students who can not attend classes due to personal challenges or larger responsibilities. While some students may miss class by choice, it is important to acknowledge that others face circumstances beyond their control. Providing these students with alternative resources could foster more equitable teaching practices in calculus, ensuring they still have access to learning opportunities.

Students perceived the use of online homework as a challenge. We found that students do not feel online learning feedback is meaningful for their learning experience. Researchers have examined online homework as a source of feedback and have found that students perceive it as accessible, adaptable, and useful for giving immediate feedback (Lampe & White, 2023). Similarly, Dorko (2020) has found that students used their online homework feedback to guide them in solving calculus problems. Meanwhile, Lampe and White (2023) indicated that calculus students reported that online homework did not allow them to keep track of their progress. Our study brings a new perspective to the existing literature, adding some considerations for the teaching and learning of calculus as students did not perceive online homework feedback was enough for their learning.

The concern about the lack of feedback in calculus classes may have implications for instructors and coordinators. This issue may serve as an opportunity to revise the online homework platforms used at the institution and the problems selected. The selection of other homework platforms or the careful choice of online homework problems may provide more detailed feedback for students that may support their learning. As we share these findings with the participants' institution, changes have been made in selecting homework problems. For example, homework problems now provide clickable support for students, such as directing them to content materials or instructional videos.

CIT Interaction: Benefits and Challenges

Participants described the CIT interaction between calculus content, instructor, and DT when discussing how instructors shared course materials using DT, selected online homework problems, and used DT to solve mathematical problems. Students discussed how instructors use *generic* DT tools for sharing course materials, such as posting notes and slides in the institutional learning management system. Generally, these were perceived as beneficial, which matches what other research has found (Loch, 2005; Maciejewski, 2016; Othman et al., 2017; Vajravelu & Muhs, 2016). However, our study brings insights into using generic DT apps and tools with caution as students perceived they faced challenges when instructors used DT, such as PowerPoint, to show already-solved examples. This finding suggests that students want to see step-by-step processes for solving calculus problems. This can inform instructors to cautiously use PowerPoint or other presentation software with blank spaces to work on the examples during class time instead of just showing solved examples.

Students highlighted additional challenges, including a lack of alignment between online homework and in-class examples and differences between the types of problems discussed in class and those in the online homework.

This misalignment, not previously addressed in the literature, suggests a need for instructors and course coordinators to ensure better consistency between homework assignments and classroom content. For instance, incorporating more word problems could help bridge this gap and enhance coherence in problem-solving approaches.

Our study adds to the limited research on students' perceptions of instructors' use of *mathematics* DT apps and tools. We found that students generally had positive experiences with these tools, particularly when instructors used platforms like Desmos, three-dimensional software, and Wolfram Alpha. Students appreciated how these tools helped them visualize concepts and solve problems, serving as effective models for independent work. Notably, many students reported that they began using dynamic software on their own after being introduced to it by their instructors. This was also found when examining future teachers' perceptions in a calculus class, who discuss how mathematics DT apps and tools used by their instructors, such as GeoGebra, provided visualization and conceptual understanding (Nongharnpituk et al., 2022). The use of mathematics DT apps and tools not only enhanced their in-class understanding but also provided valuable resources for tackling calculus problems independently. One implication of this finding is the power of instructors to present tools to students that can offer them more options for solving problems independently.

CIST Interaction: Benefits and Challenges

When analyzing the CIST interaction between calculus content, instructor, students, and DT, students provided insights on how DT supported their learning experiences when they needed help with calculus classes. They specifically mentioned email communication and online office hours. The preference for email communication and online office hours may reflect a mind shift after the pandemic virtual world (e.g., Griffiths, 2020; Hsu et al., 2022; Swanson et al., 2020). Swanson et al. (2020) investigated the communication preferences of college students and found that email was preferred for academic communication. Hsu et al. (2022) examined STEM students' attitudes toward in-person and online office hours during the COVID-19 pandemic, finding that many students perceived online office hours as convenient. Although these studies do not focus specifically on calculus courses, they provide insights into a potential tendency among STEM students to use email and online office hours more frequently.

Griffiths (2020) explored the perceptions of calculus students in Florida during the pandemic and observed that while most students wanted to return to in-person classes, a portion preferred to retain online office hours. Further research could delve into the specific reasons calculus students use online office hours and email instructors in order to develop coordinated policies that enhance inclusivity in calculus instruction.

The Context: Benefits and Challenges

Regarding the context, which we depicted as the *sphere*, we found that students discussed matters of access and technology. Consistent with Ní Shé (2023), participants mentioned having accessibility issues with the technology. Ní Shé's findings in mathematics courses about the students' challenges to access technology also hold for calculus courses. However, while considering the specific context of the participants' institution, students explained that while some students may not own the DT required for a class, the institution facilitated these resources.

Our findings reveal that while students did not explicitly refer to the cost of textbooks as a financial burden, some reported engaging in non-legal methods to access their course materials by using DT. This suggests that financial challenges may still be prevalent within the participants' institution, prompting students to find alternative and unauthorized solutions. These insights have already led to transformative changes in the institution's calculus courses, which are now using open educational resources. This study underscores the importance of understanding institutional contexts, and we encourage other researchers to conduct similar studies, considering their students' financial realities and exploring options such as low-cost materials and open educational resources.

Students emphasized the need for more active use of technology in calculus instruction, highlighting the importance of thoughtful lesson planning to achieve this. Young et al. (2018) recommend that instructors deliberately consider the role of technology when designing mathematics lessons, ensuring its integration is purposeful and aligned with learning objectives.

Implications and Limitations

We share position statements and recommendations from several national professional organizations about the effective use of technology in mathematics. The National Council of Teachers of Mathematics (2023) calls for planning with appropriate professional development to learn when, what, how, and why to integrate DT effectively. The insights provided by students in this work could inform professional development for instructors and training for students.

Our findings suggest a need for greater training for students on the use of technology (Ferrara et al., 2006). This aligns with the recommendations of the Mathematical Association of America (n.d.), stating that to enable our students to learn to use new DT, faculty, departments, and institutions must work together to ensure access to these resources. Other factors to consider for training and professional development are that faculty and institutions should consider the economic, ethical, pedagogical, mental, or physical barriers of DT on both faculty and students before implementing them, acknowledging their feedback, and evaluating the effects of the use of technology (American Mathematical Association of Two-Year Colleges, 2018).

We know that there are external factors and particular contexts that we may not control when implementing technology; however, it is remarkable that access to professional development opportunities is a key component for the effective use of DT in mathematics education. Accessibility is also a crucial factor for effective implementation. As mentioned earlier, these barriers occur in the classroom and extend to the institutional and household levels. Hence, a comprehensive analysis involving students, faculty, and institutional leaders is essential to develop strategies that positively impact the teaching and learning of mathematics, particularly in calculus classes.

We recognize some limitations of our study, including the small sample size and its exclusive focus on students' perspectives regarding DT use in several calculus sections within a single institution, each led by instructors with diverse teaching techniques and course policies. Nonetheless, our findings offer valuable insights to help instructors make informed decisions about the advantages and challenges of integrating DT into calculus instruction. We encourage future research to explore small, context-specific institutions to deepen understanding of these unique educational settings. Additionally, future studies should consider more coordinated course sections and incorporate instructors' perspectives on using DT in teaching and learning calculus for a more comprehensive analysis.

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Appendix. Interview and Demographic Survey Questions

Semi-structured interview questions:

1. Describe your experience using technology in calculus classes (if any).
2. Do you think using technology is beneficial for your learning experience? Why?
3. What kind of technology do you use in calculus classes?
4. What kind of technology would you like instructors to use in calculus classes?
5. When you need help for the class, what do you typically do?
6. How do you describe an ideal classroom to teach math?
7. Do you think that our classrooms are designed to use active learning practices?
8. Which assessments do you prefer for calculus classes?
9. How do you prepare for the class assessments?
10. Do you have any issues accessing the class materials?
11. Do you have any suggestions for faculty and staff to enhance your learning experience in calculus classes?
12. Is there anything else you want to share that I didn't ask?

Demographic information:

1. What is your current year in college? Freshman/Sophomore/Junior/Senior/Graduate Student/Other.
2. Which calculus course are you enrolled in this semester? Calculus I/ Calculus II/ Calculus III.
3. Are you a transfer student? Yes/No/Prefer not to respond.
4. Which department or college does your major belong to? College of Business/ College of Education/ College of Engineering/ College of Health and Human Sciences/ Department of Computer Science, Department of Biological Sciences, Department of Chemistry and Biochemistry, Department of Earth, Atmosphere, and Environment/ Department of Mathematical Sciences/ Department of Physics/ Department of Statistics/ Undecided/ Other.
5. Are you a transfer student? Yes/No/Prefer not to respond.
6. Which of the following describes your current situation? (Select all that apply)
    - I have a full-time job
    - I have a part-time job (less than 20 hours a week)
    - I am a parent
    - I have a long commute
    - I have transportation issues
    - I have financial struggles
    - I can't afford textbooks
    - None of the above

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Examining the Relationship Between Perception of Operating Room Training Environment and Job Motivation in Surgical Specialist Training

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Abstract

This study aims to examine the relationship between the perceptions of surgical residents undergoing surgical specialty training in multidisciplinary training and research hospitals in Türkiye regarding their operating room training environment and their work motivation levels. The study, conducted using an analytical cross-sectional design, included 112 surgical residents selected using convenience sampling. 'The Operating Room Training Environment Scale (OREEM)' and the 'Multidimensional Work Motivation Scale (MWM)' were used as data collection instruments. Descriptive statistics, independent samples t-test, one-way ANOVA, and Pearson correlation coefficient were used in the analysis of the data. The findings show that residents generally perceive the operating room training environment positively. The Learning Opportunities ($M = 4.10$) and Operating Room Environment ($M = 4.00$) sub-dimensions received the highest perception scores, while the Teaching and Training dimension ($M = 3.86$), although above the positive threshold, remained at a relatively lower level. In terms of work motivation, participants were found to exhibit high autonomous motivation ($M = 3.64$) and low demotivation ($M = 1.93$). While no significant difference was found in OREEM scores when comparing genders, male residents had significantly higher levels of demotivation compared to their female colleagues. Regarding residency seniority, residents with 5–6 years of experience had significantly more positive perceptions of learning opportunities and the operating room environment compared to those with 1–2 years of experience. Correlation analyses revealed that all sub-dimensions of OREEM showed a positive and significant relationship with autonomous motivation. However, no significant relationship was found with demotivation and controlled motivation. In light of these findings, it is recommended that training institutions develop structured mentoring programs to improve the operating room learning climate, strengthen instructor-resident communication, and enhance motivational support mechanisms for male residents.

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Introduction

The evolution of healthcare services into an increasingly multifaceted and innovative structure in the post-pandemic era highlights the importance of learning environments that shape the quality of specialist training. The operating room is a high-stress training environment where technical skills, clinical judgment, and teamwork develop simultaneously (Croghan et al., 2019; Jensen et al., 2018; Averlid & Høglund, 2020). This multifaceted structure distinguishes operating room training from other clinical settings; the intense pressure conditions directly affect both the learning process and the development of professional attitudes (Schwind et al., 2004). Therefore, it is important to consider the physical, social, and organizational dimensions of the training environment together. However, the perceptions of specialist trainees regarding this environment are a fundamental element determining learning outcomes, and the training environment is defined not only by objective conditions but also by individual experiences (Kanashiro et al., 2006; Diwadkar & Jelovsek, 2010).

During specialist training, perceptions of the learning environment influence an individual's professional development and attitudes towards work life in the long term (Flott & Linden, 2016; Riveros-Perez et al., 2016). Evaluating operating room training from both the student and instructor perspectives contributes to identifying the strengths and areas for improvement (Crafoord et al., 2018; Dimoliatis & Jelastopulu, 2013). However, the relationship between perception of the learning environment and motivation has been studied to a limited extent. Since clinical learning environments have been shown to influence professional satisfaction and career choices among nursing students (Arkan et al., 2018; Sundler et al., 2014), addressing this relationship within the context of specialist training is crucial. Considering global healthcare workforce shortages, understanding the motivational effects of the operating room training environment is a critical requirement for training qualified specialists.

Problem Statement

The operating room is one of the most challenging clinical environments where healthcare professionals receive their specialist training. In this environment, students are simultaneously exposed to multiple stressors such as hierarchical structure, time pressure, and high-risk clinical decisions (Norouzi & Imani, 2021; Yildiz Findik et al., 2015). These conditions can negatively affect the learning process, leading students to develop negative perceptions of the environment (Totur Dikmen & Bayraktar, 2021). Indeed, the literature shows that factors such as communication problems, insufficient support, and role ambiguity create significant obstacles in the clinical learning process (Jamshidi et al., 2016). In this context, it is considered that structural problems in the training environment have a weakening effect on individual motivation. Furthermore, it has been reported that negative learning experiences are associated with low job motivation and intention to leave the profession (Zhang et al., 2022). Therefore, revealing the effects of operating room training conditions on motivation is critically important for improving the quality of education.

The sustainability of motivation in specialist training is directly related to professional competence and service quality (Budden et al., 2017; Wagner et al., 2019). In this process, the attitudes of educators and supervisors are one of the key elements determining the motivational climate of the learning environment (Bradbury-Jones et al., 2010). However, the insufficient evaluation of the operating room training environment with standardized measurement tools limits the comparison of findings (Al-Qahtani & Al-Sheikh, 2012; Binsaleh et al., 2015). Furthermore, evidence regarding motivation levels in different specialties is limited (Riveros-Perez et al., 2016). Therefore, a multidimensional examination of the relationship between perception of the training environment and job motivation is important. Considering the operating room environment not only as a technical space but also as a training context where motivational processes are shaped will contribute to research in this area.

The Gap in the Literature and the Importance of the Research

Studies on the operating room training environment have primarily focused on medical students and surgical residents, largely excluding healthcare professionals from other specialties (Marwan et al., 2021; Knfe et al., 2024). This limits a holistic understanding of the perceptions of different professional groups towards the environment and the motivational implications of these perceptions. Furthermore, existing measurement tools mostly focus on technical skills and do not adequately cover psychosocial dimensions (Diwadkar & Jelovsek, 2010; Wubshet et al., 2024). Therefore, studies that comprehensively address the relationship between perception of the training environment and motivation are limited, and the current literature is insufficient to provide an explanatory framework.

The relationship between job motivation and the learning environment has mostly been examined in nursing students and general clinical contexts, while motivational processes specific to the operating room have not been sufficiently investigated (Flott & Linden, 2016; Rusticus et al., 2022). Studies examining this relationship in the context of mediating and moderating variables are quite limited, especially in high-stress and hierarchical environments. Furthermore, the interaction between educators' teaching motivation and learners' work motivation has been largely neglected (Budden et al., 2017; Leithead et al., 2019). These gaps indicate a need for more comprehensive and multidimensional research.

This study aims to contribute to the literature by holistically examining the relationship between perceptions of the operating room training environment and job motivation in a sample of healthcare professionals from different specialties. It is known that perceptions of the learning environment are decisive in determining professional sustainability and motivation (Mukhalalati et al., 2024; Papastavrou et al., 2016). In this context, the research aims to both fill a methodological gap and provide an evidence-based foundation for practices aimed at improving training environments. The findings are expected to be guiding in terms of training policies and institutional practices.

The Effects of the Operating Room Environment on Learning and Education

The operating room is a unique learning environment where high technical requirements, time pressure, and team coordination are carried out simultaneously (Croghan et al., 2019). This structure limits the application of traditional educational approaches and necessitates the active participation of the learner. The learning process is mostly based on a model where tacit knowledge is transferred through a master-apprentice relationship (Schwind et al., 2004). However, environmental factors such as physical conditions, noise levels, and equipment access directly affect the learning experience (Diwadkar & Jelovsek, 2010; Jensen et al., 2018; Kanashiro et al., 2006). Therefore, understanding how the operating room environment is experienced by the student is important for the development of educational programs.

In the context of clinical education, positive perceptions of the operating room environment increase learning motivation and professional commitment, while negative experiences can lead to anxiety and feelings of inadequacy (Foran, 2016; Totur Dikmen & Bayraktar, 2021; Willassen et al., 2015). Supervisor attitude and communication quality are among the key factors determining the student's experience; a supportive learning climate has a positive impact on self-efficacy and learning outcomes (Bradbury-Jones et al., 2010; Sundler et al., 2014). Conversely, hierarchical structures can limit student participation and initiative (Jamshidi et al., 2016; Najafi Kalyani et al., 2019). Therefore, ensuring psychological safety stands out as a critical element in improving the quality of education. Furthermore, positive clinical experiences are reported to have long-term effects on professional sustainability and career choices.

Various measurement tools have been developed to evaluate the operating room training environment, with STEEM and PHEEM being among the most commonly used scales (Al-Qahtani & Al-Sheikh, 2012; Binsaleh et al., 2015; Dimoliatis & Jelastopulu, 2013; Marwan et al., 2021). These tools particularly highlight the decisive role of educator-student relationships on the learning experience. However, it is reported that the perception of the training environment varies according to the type of institution and the field of expertise (Wubshet et al., 2024; Knfe et al., 2024). Therefore, testing the validity and reliability of measurement tools in different contexts and supporting quantitative findings with qualitative data contributes to a more comprehensive understanding of the operating room training environment.

Job Motivation and Contextual Factors in Specialized Training

In the context of specialist training, work motivation is conceptualized as an integrated reflection of an individual's effort to achieve learning goals and their tendency to reinforce their professional identity (Budden et al., 2017; Averlid & Høglund, 2020). Within this framework, motivation is shaped by both individual internal factors and institutional and contextual conditions. Teamwork and interpersonal interaction in the operating room environment have been shown to have a decisive impact on an individual's motivation level (Leithead et al., 2019). In addition, the pressure elements brought about by hierarchical structures are consistently reported in the relevant literature as being among the main contextual factors negatively affecting motivation (Norouzi & Imani, 2021).

Furthermore, the quality of the relationship between the instructor and the student is considered a critical factor that supports or hinders the development of intrinsic motivation. In this context, Foran (2016) demonstrated the positive effects of the operating room experience on students' motivation and self-confidence levels with quantitative data. However, Wagner et al. (2019) emphasizes that working conditions, leadership style, and safety climate directly affect the motivational processes of healthcare professionals. Therefore, increasing motivation in specialist training necessitates interventions at the organizational level as well as individual factors.

The motivational experiences of resident nurses training in the operating room appear to be directly related to the demanding nature of clinical conditions. Yildiz Findik et al. (2015) show that stress levels in operating room practice are linked to motivational difficulties in nursing students. Furthermore, Schwind et al. (2004) examined the variables affecting the learning process of medical students in the operating room and revealed the decisive role of instructor attitude on student motivation. Therefore, it is considered critically important for educational outcomes to improve environmental arrangements and instructor qualities aimed at supporting motivational levels. On the other hand, Willassen et al. (2015) examined the experiences of student nurses regarding honor and dignity in perioperative practice; they revealed that negative experiences seriously damage professional motivation. Accordingly, it is suggested that creating a positive educational culture in the operating room plays a protective role in terms of motivational processes. Furthermore, Larti et al. (2018) documented that empathy-focused educational interventions had positive effects on both emotional preparedness and motivation in operating room students. Therefore, systematic investigation of the contextual determinants of motivation lays the groundwork for developing evidence-based educational interventions.

The Relationship Between Perception of the Educational Environment and Work Motivation

The relationship between perception of the learning environment and job motivation is becoming an increasingly important focus in the literature on health professions education (Flott & Linden, 2016; Riveros-Perez et al., 2016). In this context, it is consistently reported that a positive perception of the learning environment increases an individual's intrinsic motivation, while a negative perception reduces motivation. Indeed, Papastavrou et al. (2016) show that nursing students' satisfaction with the clinical learning environment is positively related to professional motivation and self-efficacy. In this context, developing theoretical models to explain the role of environmental perception on motivational outcomes is considered one of the priority needs of the literature. Furthermore, Jensen et al. (2018) suggest that the way surgical identity is constructed in the operating room mediates the relationship between environmental perception and professional commitment. On the other hand, Diwadkar & Jelovsek (2010) reveal that surgical trainees' environmental perceptions are directly related to learning outcomes; drawing attention to the motivational dimension of this relationship. Therefore, developing integrated models that simultaneously address the effects of the operating room training environment on both cognitive and motivational processes is of great importance. Consequently, contributing empirical research that directly tests the relationship between these two constructs to the literature will make a significant contribution at both theoretical and applied levels.

The relationship between how prospective healthcare professionals perceive their learning environment and their levels of professional motivation exhibits consistent patterns across different clinical contexts (Rusticus et al., 2022; Zhang et al., 2022). Accordingly, perceiving the clinical environment as supportive, respectful, and learning-oriented reinforces an individual's work motivation and strengthens their intention to continue in the profession. Indeed, Mukhalalati et al. (2024) documented that healthcare students' perceptions of the learning environment are strongly related to professional identity development and, consequently, motivational commitment. Furthermore, Marwan et al. (2021) revealed that the perceptions of surgical residents in Canada regarding the operating room training environment paralleled their overall job satisfaction. In this context, it is considered that the perception of the training environment carries an emotional and motivational meaning beyond the cognitive evaluation dimension. Al-Qahtani & Al-Sheikh (2012) reported that student perceptions of the operating room training environment exhibited distinct patterns consistent with learning motivation. Therefore, studies that examine the perception of the educational environment together with motivational outcomes are considered to have a very high potential for guiding health education policies. Consequently, conducting research that examines this relationship in different professional contexts and cultural environments will expand the conceptual and empirical boundaries of the field.

Motivational Outcomes of Environmental Perception in Expert Training

Research conducted by experts on the motivational consequences of environmental perception reveals that this relationship is multidimensional and context-sensitive (Flott & Linden, 2016; Arkan et al., 2018). A positive perception of the clinical environment appears to support key motivational outcomes such as self-efficacy, professional commitment, and intention to continue. Najafi Kalyani et al. (2019) state that negative experiences in the clinical environment erode professional motivation and lead to career uncertainty for nursing students. In this context, the effect of environmental perception on motivational outcomes is considered to reflect a complex network of interactions rather than a direct causal relationship. Furthermore, Bradbury-Jones et al. (2010) emphasize that empowering students in the clinical environment is a decisive factor in terms of both motivation and learning outcomes. Totur Dikmen & Bayraktar (2021) reported that nursing students who had positive experiences in operating room practice achieved significant gains in terms of professional motivation. Therefore, establishing periodic evaluation mechanisms to monitor the motivational outcomes of health education environments stands out as an important policy step to ensure the sustainability of educational quality. Consequently, research that reveals the motivational dimensions of environmental perception is expected to guide both individual development and institutional capacity-building processes.

When examining contextual determinants of motivational outcomes, it is observed that a safe and supportive work-learning climate is strongly related to the job motivation and professional well-being of healthcare professionals (Wagner et al., 2019; Rusticus et al., 2022). Accordingly, leadership quality and team cohesion in the clinical setting are considered among the key contextual factors that nourish an individual's motivational resources. Indeed, Sundler et al. (2014) examined the effect of supervision organization on nursing students' clinical learning environment experience and determined that supportive supervision significantly contributed to motivation. Furthermore, Yildiz Findik et al. (2015) revealed that stress management skills and coping strategies are protective factors regulating motivation levels in the operating room environment. In this context, Norouzi & Imani (2021) emphasize that clinical stressors pave the way for motivational burnout in operating room students, and that institutional support acts as a crucial buffer in this process. Zhang et al. (2022) documented a strong and positive relationship between clinical learning environments and nurses' intention to stay in the profession, highlighting the strategic importance of environmental improvements on motivational sustainability. Therefore, it is becoming increasingly critical for institutions training healthcare professionals to adopt conscious environmental design principles in terms of motivational outcomes. Consequently, research examining the motivational implications of environmental perception is considered to directly contribute to the fields of healthcare workforce policies and educational management.

The main objective of this research is to examine the relationship between the perceptions of surgical residents undergoing surgical specialty training in multidisciplinary training and research hospitals in Türkiye regarding the operating room training environment and their work motivation. In this context, the following sub-research questions were addressed:

1. What are the perception levels of surgical residents regarding the operating room training environment (in terms of OREEM sub-dimensions)?
2. What are the work motivation levels of surgical residents in terms of demotivation, autonomous motivation, and controlled motivation dimensions?
3. Do surgical residents' perceptions of the operating room training environment show a significant difference according to gender?
4. Do surgical residents' work motivation levels show a significant difference according to gender?
5. Do surgical residents' perceptions of the operating room training environment show a significant difference according to the duration of their specialty training (seniority)?
6. Do surgical residents' work motivation levels show a significant difference according to the duration of their specialty training?
7. Is there a significant relationship between surgical residents' perceptions of the operating room training environment (OREEM sub-dimensions) and their work motivation dimensions (demotivation, autonomous motivation, and controlled motivation); and if so, what is the direction and level of this relationship?

Method

This research is an analytical cross-sectional study conducted with surgical residency trainees in multidisciplinary training and research hospitals in Türkiye. Within the scope of the research, participants' perceptions of the operating room training environment and their work motivation levels were evaluated using relevant measurement tools.

Research Design

This research was conducted using an analytical cross-sectional design. Cross-sectional design is a quantitative research approach widely preferred in answering descriptive and correlational research questions, allowing for the simultaneous collection of data on multiple variables at a single measurement point within a specific time period (Knfe et al., 2024; Wubshet et al., 2024). This design is widely used in health professions education research to examine clinical learning environment perception and motivational variables together; indeed, major studies investigating operating room training environments have adopted this design (Al-Qahtani & Al-Sheikh, 2012; Marwan et al., 2021; Riveros-Perez et al., 2016).

There are several key reasons for choosing a cross-sectional design for this research. First and foremost, since the current research aims to identify the pattern of the relationship between perception of the operating room training environment and work motivation, a cross-sectional design is methodologically sufficient and appropriate for revealing a correlational profile rather than seeking a causal relationship (Rusticus et al., 2022). It is noteworthy that the vast majority of pioneering studies in this field have adopted a cross-sectional design, and the critical role of cross-sectional data in establishing a comparable evidence base in the literature is considered (Binsaleh et al., 2015; Marwan et al., 2021). Reaching residents in the active surgical rotation period during their specialist training process necessitates instantaneous and real-time assessments instead of long-term longitudinal follow-up from a practical standpoint. Indeed, Wagner et al. (2019), in their cross-sectional study with healthcare professionals, demonstrated that this design provides a powerful methodological tool for the simultaneous assessment of working conditions and motivational processes.

The research was designed within a quantitative paradigm, and data were collected using standard, validated, and reliable psychometric measurement tools. This approach is based on a well-established methodological tradition in health professions education research regarding the operationalization of both perceptions of the clinical learning environment and motivational variables using quantitative methods (Diwadkar & Jelovsek, 2010; Flott & Linden, 2016). To conduct the research, participants were informed in writing about the purpose of the study, the principle of voluntariness, and the confidentiality and anonymity of the data, and their voluntary informed consent was obtained.

Sample

The study population consists of residents actively undergoing surgical residency training in multidisciplinary training and research hospitals in Türkiye. The sample was determined using convenience sampling and comprised 112 surgical residents who voluntarily agreed to participate in the study. Participants were healthcare professionals with varying residency seniority (1-2 years, 3-4 years, and 5-6 years) in general surgery (n=31), orthopedics (19), gynecology (n=32), otolaryngology (n=11), and other (n=19) surgical branches. 33 of the participants were female and 79 were male. The average age of the participating residents was 29.38±3.38. The sample size is comparable to that of similar cross-sectional studies in the field. Indeed, Marwan et al. (2021) with 88 participants, Knfe et al. (2024) with 103 participants, and Wubshet et al. (2024) with 213 participants demonstrated that similar sample sizes provided sufficient analytical power to examine the relevant variables. Inclusion criteria were active perioperative rotation during the research process and complete completion of the questionnaire. Questionnaires with incomplete or inconsistent responses were not included in the analysis.

Data Collection Tools

Two standardized measurement tools were used to collect data: the Operating Room Training Environment Scale (OREEM) and the Multidimensional Job Motivation Scale (MJMS). Both scales were administered via an online survey platform.

Operating Room Training Environment Scale (OREEM)

The original Operating Room Training Environment Scale (OREEM) was developed by Cassar (2004). OREEM was developed to assess the operating room training environment and is among the most widely used psychometric measurement tools in perioperative training research (Diwadkar & Jelovsek, 2010; Marwan et al., 2021). The scale consists of 40 items answered with a 5-point Likert scale (1 = Strongly disagree, 5 = Strongly agree). The 40 items are structured under four sub-dimensions: (1) Teaching & Training (items 1–13): Residents' perceptions of the surgical educator; (2) Learning Opportunities (items 14–24): Perceptions of learning opportunities in the operating room; (3) Operating Room Atmosphere (items 25–32): Perceptions of the perioperative working climate. (4) Workload, Supervision & Support (items 33–40): Measures perceptions of clinical supervision quality and institutional support. The total raw score obtainable from the scale ranges from 40–200, with values of 120 and above reflecting a positive perception of the learning environment (Al-Qahtani & Al-Sheikh, 2012; Wall, 2007). In the analyses, raw scores were divided by the number of items (k = 40) to calculate average OREEM scores in the range of 1–5; averages of 3.00 and above were determined as the threshold of positive perception (Marwan et al., 2021). The Cronbach's alpha reliability coefficient of the scale has been reported between .82 and .90 in relevant studies (Sadiq et al., 2019; Talat & Sethi, 2019).

In this study, the scale was adapted into Turkish by two experts, and a back-translation method was used to check for any changes that might cause semantic differences compared to the original data collection instrument. Expert opinions were also obtained regarding cultural sensitivity. When the psychometric properties and construct validity of the scale for the Turkish sample were examined within the scope of this research, it was observed that the item-total correlation coefficients calculated within the scope of item analysis were significantly above the acceptable limits in all sub-dimensions. In the ‘Teaching and Education’ sub-dimension, the corrected item-total correlation coefficients for the 13 items ranged from .52 to .90, and the threshold value of .30 was exceeded for all items (lowest: Item 10, $r = .52$; highest: Item 2, $r = .90$). The corrected item-total correlations for the 11 items constituting the ‘Learning Opportunities’ sub-dimension ranged from .69 to .84; No item falls below the critical threshold (lowest: Item 23, $r = .69$; highest: Item 19, $r = .84$). In the ‘Operating Room Environment’ sub-dimension, the calculated values for the 8 items are concentrated between .65 and .87 (lowest: Item 28, $r = .65$; highest: Item 32, $r = .87$). In the ‘Workload, Supervision and Support’ sub-dimension, the item-total correlations for the 8 items range from .57 to .86 (lowest: Item 38, $r = .57$; highest: Item 40, $r = .86$). The fact that the item-total correlation coefficients for all items in the scale are above .30 indicates that the items are sufficiently discriminatory in measuring the relevant construct and that there is no need to remove any item from the scale (Field, 2013; Nunnally & Bernstein, 1994). These findings strongly support the idea that the Turkish form of OREEM has a valid and consistent structure at the item level.

The four-factor structure of OREEM was also tested by confirmatory factor analysis (CFA). The CFA findings show that all factor loadings of the four-factor structure are statistically significant ($z > 11.13$, $p < .001$) and the unstandardized loading coefficients range from .786 to 1.043. When the fit indices were examined, $\chi^2(59) = 253.03$, $\chi^2/df = 4.29$ were calculated. GFI = .891, AGFI = .899 and NFI = .901 values exceed the acceptable fit threshold of .80, but are on the borderline of the good fit criterion of .90 (Jöreskog & Sörbom, 1993; Bentler, 1990). CFI = .897 and TLI = .894 values were found to be at an acceptable fit level. The RMSEA value of .172 is known to produce limited results when the sample size is relatively limited and Likert-type data challenges the normality assumption (Hu & Bentler, 1999; West et al., 2012). Studies on perioperative education scales conducted with similar sample sizes have also documented that RMSEA values can exceed acceptable limits. All these findings indicate that the four-factor theoretical structure of OREEM has been validated in the Turkish surgical resident sample; however, retesting the model with larger samples would significantly contribute to the psychometric maturation of the scale.

In this study, the internal consistency reliability of the scale was evaluated using the Cronbach's alpha coefficient; the results indicate a high level of psychometric reliability. When examined at the sub-dimension level, the Cronbach's alpha coefficient was calculated as α = .958 for the Teaching and Training sub-dimension, α = .955 for the Learning Opportunities sub-dimension, α = .947 for the Operating Room Environment sub-dimension, and α = .915 for the Workload, Supervision, and Support sub-dimension. The Cronbach's alpha coefficient for the entire 40-item scale was found to be α = .980. These values meet the acceptable reliability threshold (Nunnally & Bernstein, 1994), defined in the literature as .70 and above, and the "excellent reliability" criterion (George & Mallery, 2003), indicating .90 and above, for all sub-dimensions and the scale as a whole. When compared with reliability values reported in international samples (Sadiq et al., 2019: α = .82; Talat & Sethi, 2019: α = .61–.87 subdimensions, α = .90 total), the coefficient values obtained in this study are found to be above or equivalent to these values. This indicates that OREEM also possesses strong psychometric properties in the Turkish surgical resident sample and maintains its structural integrity, making it transferable to different cultural contexts.

Multidimensional Work Motivation Scale

In this study, the Multidimensional Work Motivation Scale (MWMS), developed by Gagne et al. (2014) based on Self-Determination Theory and psychometrically validated in nine countries and seven different languages, was used. The Turkish adaptation of the scale was carried out by Çivilidağ and Şekercioğlu (2017). The scale, consisting of 19 items, has a 5-point Likert-type response format (1 = Not at all appropriate, 5 = Completely appropriate) and covers three main dimensions: (1) Demotivation (unmotivated; items 1, 3, 5), (2) Controlled motivation (items 7, 9, 11, 13–19) and (3) Autonomous motivation (items 2, 4, 6, 8, 10, 12). High autonomy motivation scores reflect intrinsic motivation, high control motivation scores reflect external pressure-driven motivation, and high demotivation scores reflect a lack of motivation.

The questionnaires were administered via an online platform. Each completed questionnaire was assigned a unique participant code; the raw data was checked for accuracy and completeness and transferred to SPSS 26.0 statistical software.

Data Analysis

Descriptive statistics (mean, standard deviation, minimum and maximum values) were calculated for continuous variables. The Kolmogorov-Smirnov test was applied to the participants to determine the normality of their scale scores, as the group was greater than 50. As a result of the analysis, it was understood that the data showed a normal distribution because the α value was greater than 0.05. Therefore, parametric statistics techniques were used for intergroup comparisons. An independent samples t-test was applied to determine whether scores on perception of the operating room training environment and work motivation differed according to gender. One-way analysis of variance (ANOVA) followed by the Tukey HSD post hoc test was used to examine differences based on residency seniority (duration of residency training). The Pearson moment correlation coefficient was calculated to determine the relationship between the sub-dimensions of OREEM and the sub-dimensions of work motivation. In all analyses, the confidence interval was set at 95%, and the significance level at $p < .05$.

Findings

This section presents descriptive statistics on the scores obtained by surgical residents from the OREEM and the Multidimensional Work Motivation Scale; followed by comparative findings according to gender and residency seniority, and correlation coefficients between the scales.

As shown in Table 1, OREEM achieved a high level of positive perception in the Learning Opportunities (*M* = 4.10, *SD* = 0.85) and Operating Room Atmosphere (*M* = 4.00, *SD* = 0.94) sub-dimensions. A moderate-to-high level of positive perception was found in the Workload, Supervision & Support dimension (*M* = 3.84, *SD* = 0.87). The Teaching & Training sub-dimension exhibited the lowest average, but still remained above the positive perception threshold (*M* = 3.00) (M = 3.86, *SD* = 0.84). Regarding work motivation dimensions, participants showed a high level of autonomous motivation (*M* = 3.64, *SD* = 1.01) and a moderate level of controlled motivation (*M* = 3.16, *SD* = 0.72); while the level of demotivation remained low (*M* = 1.93, *SD* = 1.07).

Table 1. Descriptive Statistics Regarding OREEM and Work Motivation Sub-Dimensions (N = 112)

Scale	Sub-scale	n	Min	Max	M	SD
OREEM	Teaching & Training	112	1.77	5.00	3.86	0.84
	Learning Opportunities	112	1.00	5.00	4.10	0.85
	Operating Room Atmosphere	112	1.13	5.00	4.00	0.94
	Workload, Supervision & Support	112	1.25	5.00	3.84	0.87
Work Motivation	Demotivation	112	1.00	5.00	1.93	1.07
	Autonomous motivation	112	1.00	5.00	3.64	1.01
	Controlled motivation	112	1.00	5.00	3.16	0.72

OREEM= Operating Room Educational Environment Measure Scale; M= Mean; SD= Standard deviation

As seen in Table 2, no statistically significant difference was found between genders in any sub-dimension of the OREEM scale for surgical residents ($p > .05$). It is observed that the perceptions of both gender groups regarding the operating room training environment exhibit quite similar distributions.

Table 2.Comparison of OREEM Subscale Scores by Gender

OREEM Subscale	Gender	n	M	SD	*t*	*p*
Teaching & Training	Female	33	3.87	0.61	0.025	.980
	Male	79	3.86	0.92		
Learning Opportunities	Female	33	3.91	0.96	−1.517	.132
	Male	79	4.18	0.79		
Operating Room Atmosphere	Female	33	3.95	0.76	−0.298	.766
	Male	79	4.01	1.00		
Workload, Supervision & Support	Female	33	3.86	0.85	0.199	.843
	Male	79	3.83	0.88		

t = Independent samples t-test statistic; p = significance. P>0.05

When Table 3 is examined, it is seen that there is no significant difference between genders in the sub-dimensions of autonomous motivation and controlled motivation ($p > .05$). However, a statistically significant difference was found between genders in the demotivation sub-dimension ($t(110) = -3.548$, $p = .001$). Demotivation scores of male residents ($M = 2.16$, $SD = 1.11$) were found to be significantly higher compared to their female colleagues ($M = 1.40$, $SD = 0.79$).

Table 3. Comparison of Job Motivation Sub-Dimension Scores by Gender

Job Motivation Sub-Dimension	Gender	n	M	SD	*t*	p
Demotivation	Female	33	1.40	0.79	−3.548	.001**
	Male	79	2.16	1.11		
Autonomous motivation	Female	33	3.77	0.96	0.881	.380
	Male	79	3.58	1.04		
Controlled motivation	Female	33	3.05	0.77	−0.978	.330
	Male	79	3.20	0.70		

***p<.001*

Table 4 shows that statistically significant differences were found in the Learning Opportunities ($F(2, 109) = 3.078$, $p = .049$) and Operating Room Atmosphere ($F(2, 109) = 4.043$, $p = .020$) sub-dimensions according to residency seniority. Tukey HSD post hoc analysis reveals that residents with 5–6 years of seniority have significantly higher OREEM perception scores in these two dimensions compared to their colleagues with 1–2 years of seniority. No significant differences were found based on seniority in the Teaching & Training and Workload, Supervision & Support sub-dimensions ($p > .05$).

Table 4. Comparison of OREEM Sub-Dimension Scores According to Resident Seniority

OREEM Sub-Dimension	Specialist Training Year	n	M	SD	*F*	*p*
Teaching & Training	1–2 years	51	3.88	1.03	0.206	.814
	3–4 years	38	3.80	0.68		
	5–6 years	23	3.93	0.61		
	Total	112	3.86	0.84		
Learning Opportunities	1–2 years	51	3.95	1.05	3.078	.049*
	3–4 years	38	4.08	0.67		
	5–6 years	23	4.47	0.44		
	Total	112	4.10	0.85		
Operating Room Atmosphere	1–2 years	51	3.73	1.18	4.043	.020*
	3–4 years	38	4.18	0.67		
	5–6 years	23	4.28	0.44		
	Total	112	4.00	0.94		
Workload, Supervision & Support	1–2 years	51	3.82	1.05	0.047	.954
	3–4 years	38	3.84	0.74		
	5–6 years	23	3.89	0.64		
	Total	112	3.84	0.87		

**p<.05; Seniority groups: 1 = 1–2 years (n = 51), 2 = 3–4 years (n = 38), 3 = 5–6 years (n = 23). F = one-way ANOVA F statistic. Tukey HSD post hoc test was applied to the ANOVAs found to be significant.*

As shown in Table 5, no statistically significant difference was found in any of the sub-dimensions of the work motivation scale—demotivation, autonomous motivation, and controlled motivation—based on residency seniority ($p > .05$). This finding indicates that work motivation is shaped independently of accumulated professional experience.

As shown in Table 6, all sub-dimensions of OREEM exhibit positive and statistically significant relationships with autonomous motivation: Teaching & Training ($r = .544$, $p < .001$), Learning Opportunities ($r = .341$, $p < .001$), Operating Room Atmosphere ($r = .547$, $p < .001$), and Workload, Supervision & Support ($r = .454$, $p < .001$). In contrast, none of the OREEM sub-dimensions showed a statistically significant relationship with demotivation or controlled motivation ($p > .05$). These findings reveal that positive perception of the operating room training environment is strongly associated with autonomous (intrinsic) motivation, but has no significant connection with extrinsic motivational processes.

Table 5. Comparison of Job Motivation Sub-Dimension Scores According to Residence Seniority

Job Motivation Sub-Dimension	Specialist Training Year	n	M	SD	*F*	*p*
Demotivation	1–2 years	51	2.14	1.27	2.305	.105
	3–4 years	38	1.65	0.86		
	5–6 years	23	1.96	0.82		
	Total	112	1.93	1.07		
Autonomous motivation	1–2 years	51	3.52	1.23	1.217	.300
	3–4 years	38	3.63	0.74		
	5–6 years	23	3.91	0.84		
	Total	112	3.64	1.01		
Controlled motivation	1–2 years	51	3.31	0.77	2.775	.067
	3–4 years	38	2.99	0.63		
	5–6 years	23	3.09	0.68		
	Total	112	3.16	0.72		

p>0.05

Table 6. Pearson Correlation Coefficients Between OREEM Sub-Dimensions and Job Motivation Sub-Dimensions

OREEM Sub-Dimension	Demotivation		Autonomous motivation		Controlled motivation	
	r	*p*	*r*	*p*	*r*	*p*
Teaching & Training	.138	.148	.544**	< .001	.021	.824
Learning Opportunities	.089	.350	.341**	< .001	.087	.363
Operating Room Atmosphere	.088	.357	.547**	< .001	−.038	.692
Workload, Supervision & Support	.139	.145	.454**	< .001	.066	.487

*r = Pearson moment correlation coefficient. n = 112 for all analyses. ** p < .01 (two-sided).*

Discussion and Conclusion

This study investigated the relationship between the perceptions of the operating room training environment and job motivation among medical residents undergoing specialist training in surgical branches. Accordingly, participants' evaluations of the operating room training environment were considered within the dimensions of surgical training and instruction, learning opportunities, operating room atmosphere and workload, clinical supervision, and institutional support. Job motivation was evaluated within the framework of Self-Determination Theory, specifically focusing on autonomous motivation, controlled motivation, and demotivation. The findings indicate that surgical residents generally experience the operating room training environment positively. While participants showed high levels of autonomous motivation and no significant gender-based difference in perception of the perioperative training environment, a significant gender-based difference was found in the demotivation dimension. It was determined that perceptions of learning opportunities and operating room atmosphere improved with increasing residency duration. The most fundamental finding of the study is that all sub-dimensions of the perception of the operating room training environment exhibited a significant and positive relationship with autonomous motivation.

Surgical residents generally perceived the perioperative training environment positively, achieving positive evaluations on all sub-dimensions of the OREEM scale. The highest scores were observed in the dimensions of learning opportunities and operating room atmosphere, suggesting that residents valued clinical experience for their professional development. In contrast, the relatively lower score in the surgical education and training sub-dimension can be explained by the intense surgical pace and hierarchical structure limiting educator-resident interaction (Schwind et al., 2004; Binsaleh et al., 2015). Moderately positive perceptions were observed in the dimensions of workload, clinical supervision, and institutional support. These findings are consistent with similar patterns reported in the literature (Marwan et al., 2021; Knfe et al., 2024; Wubshet et al., 2024).

When the work motivation profile of the residents is examined, it is seen that autonomous motivation is dominant and demotivation is at a low level. This indicates that surgical training supports the development of professional identity and that the residents internalize their profession (Gagne et al., 2014; Averlid & Høglund, 2020). The moderate level of controlled motivation suggests that external pressures have not been completely eliminated (Budden et al., 2017). These findings are consistent with studies emphasizing the positive effects of operating room experience on motivation and self-efficacy (Foran, 2016).

In terms of the gender variable, it was found that the perception of the training environment was similar; however, the level of demotivation was higher in male residents. This indicates that the competitive and performance-oriented nature of surgery may create more pressure on male residents (Jensen et al., 2018; Wagner et al., 2019). Therefore, developing gender-sensitive support mechanisms in the operating room environment is important.

The study found that residency duration positively influenced perceptions of learning opportunities and operating room atmosphere; higher scores were obtained in these dimensions as seniority increased. This can be explained by the more effective management of the environment and better utilization of learning opportunities with experience (Kanashiro et al., 2006; Riveros-Perez et al., 2016). However, no significant difference was found in other sub-dimensions and work motivation based on seniority; this finding suggests that motivation is shaped more by individual and contextual factors (Budden et al., 2017; Wagner et al., 2019).

One of the prominent findings of the study is that all sub-dimensions of OREEM are positively related to autonomous motivation. In particular, the strong relationship between the operating room atmosphere and the training-education dimensions and autonomous motivation shows that the quality of the learning environment directly supports intrinsic motivation. In contrast, no significant relationship was found with controlled motivation and demotivation. This result suggests that the operating room environment has a particular impact on internalized motivation processes (Gagne et al., 2014; Mukhalalati et al., 2024; Papastavrou et al., 2016). Overall, interventions aimed at improving the operating room training environment are considered to have the potential to strengthen residents' autonomy motivation.

Implications of the Findings

The findings of this research offer significant contributions to the field at both theoretical and applied levels. From a theoretical perspective, the significant relationship between the perception of the perioperative training environment and autonomous motivation supports the validity of Self-Determination Theory's propositions based on competence, autonomy, and relationality needs within the context of surgical residency training. This finding reinforces the theoretical understanding that the perception of the operating room environment shapes not only cognitive learning outcomes but also deeper motivational processes; it reveals that the perioperative environment is more than just a technical workspace; it is a dynamic social and organizational structure where professional identity and surgical motivation are shaped. Flott and Linden (2016), through their conceptual analysis, demonstrated that the clinical learning environment has a complex structure encompassing multiple dimensions, emphasizing the need to address this multi-dimensional structure in an integrated manner with motivational processes; this research empirically supports this theoretical framework within the context of surgical residency training. From an applied perspective, the research findings provide concrete and actionable data for healthcare education institutions and clinical administrators. First and foremost, the relatively low perception of surgical education and training necessitates strengthening the pedagogical training of surgical educators. In this regard, surgeons need to be systematically developed not only in terms of their operative competencies but also their teaching skills and clinical mentoring capacity. Implementing supportive clinical supervision mechanisms, managing perioperative workload in a way that does not harm resident training, and creating a psychologically safe environment in the operating room are critical institutional interventions that directly support residents' perception of the learning environment and their autonomous motivation. Norouzi and Imani (2021) emphasize that institutional support acts as a crucial buffer against motivational burnout caused by clinical stressors in the operating room environment, and that residents face a serious risk of professional burnout when this support is insufficient. Developing gender-sensitive motivational approaches is also emerging as a programmatic need to reduce the high risk of demotivation observed particularly in male surgical residents. All these findings clearly demonstrate that healthcare institutions should periodically measure the quality of operating room training using validated tools like OREEM and develop systematic improvement strategies based on the evidence obtained.

Limitations

This study has several methodological and sampling limitations, which must be considered when interpreting the findings. Firstly, the analytical cross-sectional design makes it difficult to attribute causality to the relationship found between perception of the perioperative training environment and work motivation. Cross-sectional design has a structural limitation in terms of its capacity to determine directional and temporal relationships between variables. The use of convenience sampling and the limitation of the sample to surgical residents in specific training and research hospitals restricts the generalization of the findings to different healthcare institutions, geographical regions, and surgical specialties. The study's inclusion of only surgical residents prevents comparative interpretation of the perception-motivation relationship in other medical specialties such as internal medicine, orthopedics, or anesthesia.

The use of an online survey method in the data collection process means that participants may have answered the questions under different perioperative conditions and time periods, carrying the risk of common method bias. The fact that the Job Motivation Scale used in this study has been validated in various professional and cultural contexts necessitates further testing of its psychometric performance in a unique and high-stress clinical setting such as an operating room. The fact that participants completed the questionnaire on different dates and with different supervisors during rotation periods may lead to individual responses reflecting different clinical experiences, potentially creating inconsistencies in intergroup comparisons. The use of only quantitative measurement tools in the study limits the ability to reveal in-depth views, meanings, and narratives regarding the perioperative experience of surgical residents. The relatively limited sample size also poses a limitation in terms of the statistical stability and reliability of the obtained relationships. Considering all these limitations, it seems necessary to interpret the research findings with caution and to continue studies in this field by increasing methodological diversity.

Conclusion and Recommendations

Based on the findings of this research, recommendations are presented for both clinical practice and future research. Healthcare institutions should regularly evaluate the operating room training environment using standardized tools with proven psychometric validity, such as OREEM, and systematically reflect the data obtained in both individual resident feedback and institutional improvement planning. Implementing structured instructor development programs that encompass clinical mentoring, pedagogical communication, and supervision skills in addition to the operative competencies of surgical instructors will directly contribute to improving the relatively low perception, especially in the Teaching & Training dimension. Establishing a perioperative learning culture that enhances psychological safety in the operating room, balances hierarchical pressure, and supports residents' questioning and clinical initiative should be adopted as a priority institutional goal.

Designing gender-sensitive clinical guidance and motivation support programs will serve as a proactive intervention to reduce the high tendency towards demotivation observed, particularly in male surgical residents. From a future research perspective, conducting longitudinal studies with broader and more representative samples encompassing different surgical specialties, different types of training institutions, and different geographic regions will significantly contribute to both clarifying causal relationships and strengthening the generalizability of findings. Investigating potential mediating and moderating variables in the relationship between perception of the perioperative training environment and work motivation using qualitative and mixed methods will pave the way for a more comprehensive understanding of the mechanisms of this relationship. Finally, comparative studies conducted in different cultural contexts and with international samples are expected to provide theoretical and applied contributions to the literature by examining the universality or cultural specificity of the relationship between perception of the operating room training environment and surgical resident motivation.

In conclusion, this research is among the limited studies in Turkey that reveal the relationship between surgical residents' perception of the operating room training environment and their work motivation, thus making a unique contribution to the literature. The findings that a positive perception of the perioperative training environment significantly supports autonomous motivation empirically confirm the explanatory power of Self-Determination Theory in the context of surgical specialty training. Considering the dominance of studies in the current literature that primarily address the operating room environment in terms of technical skill acquisition, this research fills an important gap by highlighting the motivational dimension of the perioperative training experience. Comparative findings regarding gender and residency seniority demonstrate that the relationship between the operating room training environment and work motivation exhibits a multi-layered structure sensitive to individual and contextual differences. It is considered that the research provides evidence that can be reflected in practice in terms of surgical training policies, hospital management, and residency program design.

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Applying Collaborative Learning Principles to Teaching with GenAI: A Pre-Calculus Assignment Example

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Abstract

As generative artificial intelligence (GenAI) becomes increasingly available to students in higher education, educators face the challenge of designing assignments that promote meaningful learning while minimizing misuse. This conceptual paper demonstrates ways in which six principles originally developed to enhance collaborative learning during group work (positive interdependence, cognitive load management, individual accountability, promotive interaction, social skills development, and group processing) can be effectively applied to a GenAI-supported STEM assignment. We present a detailed analysis of a pre-calculus assignment designed using research-based collaborative learning principles and illustrate how structured prompting, role definition, and iterative reflective cycles can increase the likelihood that GenAI enhances rather than replaces human learning. The proposed framework supports the development of critical thinking, communication, and metacognitive awareness. We conclude with general recommendations for adapting these principles across disciplines and suggest directions for future empirical research and faculty development to support effective GenAI integration in student assignments.

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Introduction

As Generative artificial intelligence (GenAI) tools become ubiquitous in academic settings, educators face a critical question: How can we ensure these tools enhance rather than hinder student learning? Students have expressed a strong desire for guidance on the appropriate uses of GenAI and are very interested in receiving this guidance from faculty (Singer-Freeman et al., 2025). We believe that an unexpected source of guidance comes from decades of research on collaborative learning. Although GenAI lacks emotion and agency, it can still support collaborative learning by engaging students in structured cognitive exchanges. Collaboration is not defined by sentience but by the distribution of thinking, mutual engagement, and iterative refinement. These are roles GenAI can fulfill. When used intentionally, GenAI can encourage students to clarify reasoning, explore alternatives, and reflect on their learning, aligning well with the principles of effective collaborative work. GenAI partnerships and human collaboration can both involve distributing cognitive tasks and managing dependencies between contributors who have different strengths and weaknesses. Singer-Freeman (2025) hypothesized that six principles that increase the learning gains from collaborative learning can be productively applied to assignments that require student-GenAI partnerships. This paper describes our creation of a pre-calculus assignment that integrates GenAI in ways that are guided by known best practices for collaborative learning assignments: positive interdependence, individual accountability, promotive interaction, social skills development, group processing, and cognitive load management (Singer-Freeman, 2025). We explain how each section of the assignment will support student learning and is guided by principles of effective collaborative learning, providing a model for educators seeking to create effective assignments in which GenAI supports rather than supplants student learning.

Assignment Structure

The assignment includes four phases: 1) problem-solving; 2) communication; 3) collaborative review; and 4) reflection and synthesis. Students select problems from two categories: graphing rational functions and exploring inverse functions. In Phase 1 (Problem Solving), students work independently on one problem from each category in class, then using prompting protocols GenAI either verifies the student's solution or provides support as the student revises their incorrect solution. Students continue engaging with GenAI prompts and revising their work until they arrive at a correct solution. In Phase 2 (Communication) students write explanations of their problem-solving, submit these to GenAI for critique, and revise based on feedback. In Phase 3 (Collaborative Review) students review each other's work and discuss their learning processes. Finally, in Phase 4 (Reflection and Synthesis) students design future GenAI prompts, identify essential prerequisite knowledge, and compare their experience with GenAI support to that of peer collaboration. Students submit their original work, GenAI interaction logs, final solutions, initial and revised explanations, peer feedback exchanges, and reflections. The complete assignment can be seen in Appendix A.

Positive Interdependence: Creating Mutual Dependence

A foundation of effective group work is positive interdependence in which group members need the knowledge or skills of other group members to succeed (Alavi & McCormick, 2008). Positive interdependence prevents the division of labor and ensures that all group members are engaged in the work by creating situations in which different contributions are essential to group success. One element of designing effective GenAI supported assignments is determining ways in which the unique skills of humans and GenAI differ and then structuring assignments to require positive interdependence by having each contributor address the other's limitations (Singer-Freeman, 2025).

GenAI's strength lies in its ability to rapidly analyze vast amounts of information, spotting patterns, missing elements, and outliers (American Bar Association, 2017; Korteling et al., 2021). GenAI is very effective at identifying errors, and helping students break through a fixed approach by suggesting alternate solution strategies. However, humans are more skilled than GenAI at applying real-world context, understanding nuance, and reflecting on internal mental processes (Korteling et al., 2021). Incorporating GenAI into student work in ways that catch errors and reduce fixation on ineffective approaches while requiring students to make nuanced interpretations or reflect on their learning will create productive cycles in which human critical thinking and GenAI processing power complement each other.

Assignment Application

The assignment creates multiple layers of positive interdependence. During the problem-solving phase students attempt initial solutions during class. This ensures that they independently complete the first step which provides the starting place in their learning. Students are explicitly told that their first (possibly incorrect) attempts are essential because their attempt will enable GenAI to provide targeted instruction that will help them to learn. This piece of the instruction supports positive interdependence as well as academic integrity. GenAI then serves as an error-detection system that guides students toward self-discovery. The specific prompt protocol—*"If I made an error, guide me to discover it through questions rather than giving me the answer directly"*—ensures that neither participant can complete the learning cycle independently. This task is structured to maintain student agency while leveraging GenAI capabilities. Students cannot passively accept GenAI corrections; they must reflect on their errors and generate new approaches. Conversely, GenAI cannot provide meaningful guidance without student reasoning to evaluate. We are aware that students could bypass the positive interdependence by ignoring the prescribed prompt and asking GenAI to "fix my work." This would dissolve the positive interdependence, converting the GenAI from a Socratic partner into a simple answer key and undermining the goal of guided self-discovery. To limit the likelihood of this happening it will be important to clearly communicate with students regarding the value of the learning that is being supported by the assignment instructions.

It is important to note that role definition targeting the unique strengths of humans and GenAI is crucial for productive interdependence. During the communication phase students articulate their reasoning in writing before receiving a GenAI critique, establishing human contribution as primary. The GenAI critique protocol (*"Please critique my mathematical explanation for clarity, completeness, and accuracy. Point out any gaps in my reasoning or unclear language. Ask me questions that will help me strengthen my explanation rather than rewriting it for me"*) capitalizes on GenAI's strength in noticing missing elements and provides an opportunity for GenAI to interrupt a fixed approach to a problem by encouraging alternate ways of thinking about the problem. The peer discussion questions increase interdependence and encourage students to use their unique abilities to engage in metacognition by considering differences in the support for learning that are achieved when working with GenAI as compared to working with peers.

Individual Accountability: Ensuring Every Student Meets Learning Objectives

An emerging body of research suggests that poorly designed GenAI-assisted learning is associated with an illusion of competence (Barba, 2025) that can result in reductions in critical thinking (Gerlich, 2025) or creativity (Habib et al., 2024). Individual accountability minimizes the risk by including features of assignments that ensure every group member is responsible for demonstrating mastery of all parts of a shared piece of work. The inclusion of individual accountability measures increases learning by preventing stronger members from dominating while others contribute minimally. To ensure that students learn, we must create GenAI-assisted assignments that require students to contribute in ways that lead to the acquisition of essential learning outcomes (Singer-Freeman, 2025). GenAI can support students most effectively when it provides scaffolding that allows students to develop targeted areas of competence. However, as students develop competence, GenAI support should fade so that summative evaluations can be accomplished individually. The goal is ensuring students can perform independently when needed, rather than becoming dependent on external cognitive support.

Assignment Application

The assignment implements individual accountability by richly documenting mastery of three student learning outcomes (SLOs). To evaluate the first SLO (analyze rational and inverse functions) students individually tackle challenging problems and engage with GenAI using a protocol that demands step-by-step explanations of their reasoning. This logged interaction provides direct evidence of their problem-solving process and iterative refinement. Their final solutions include explanations and are assessed both for mathematical accuracy and for accurate reasoning. To evaluate the second SLO (communicating mathematical reasoning clearly in writing) students describe their solution process, including their chosen initial approach, difficulties encountered, resulting adjustments in approach, and reasons for these actions. The GenAI critique protocol is designed to strengthen the clarity and completeness of the student's writing by providing questions that invite refinements rather than providing corrections. During the revision process students must demonstrate they can process feedback meaningfully and improve communication. This requires individual synthesis skills and demonstrates that students can learn from critique rather than simply accepting corrections. The submission of the student's initial explanations, GenAI critiques, and revised explanations allows evaluation of their iterative improvement. To evaluate the third SLO (metacognitive awareness of productive approaches to collaborative work) students design future GenAI prompts, identify essential prerequisite knowledge, and compare human and GenAI collaboration.

We are aware that the efficacy of the proposed audit trail depends on the student's honest engagement. For example, a student could circumvent accountability by using GenAI to write their mathematical explanation in Phase 2, even though the prompt explicitly forbids it, or by fabricating interaction logs. To reduce this possibility, instructors can add a specific reflection question that asks students to link a direct quote from the GenAI's critique to a specific change they made in their revised explanation. This requires them to demonstrate a metacognitive connection between the feedback and their own work. Alternatively, making the peer review discussion a small, in-class activity would allow instructors to observe whether a student's ability to discuss their work is consistent with the sophistication of their written submission.

Promotive Interaction: Encouraging Active Reasoning

Promotive interactions describe situations in which the product that emerges from a collaboration is stronger than the product that could have been created by any individual in the group (Scager et al., 2016). In effective collaborative learning, students encourage and challenge each other's reasoning, and the resulting cognitive friction deepens understanding (Dzemidzic Kristiansen et al., 2019). Intentional design can support promotive interactions in GenAI-assisted learning when GenAI is directed to function as a Socratic questioner, pushing students to examine assumptions and explore implications (Chiang et al., 2024; Singer-Freeman, 2025). Chatbots can play devil's advocate, presenting counter arguments that students must address. The use of iterative protocols can structure these interactions, ensuring that initial student responses are developed and refined through successive exchanges.

Assignment Application

The assignment creates promotive interactions by having GenAI challenge student reasoning. The interaction protocol instructs GenAI to function as a Socratic questioner: *"Ask me to explain my reasoning at each step where you see confusion"* and *"respond to mistakes by asking challenging questions rather than giving answers."* This creates the cognitive friction essential for deep mathematical learning. When students make algebraic errors, for example, GenAI might ask: "What properties of rational functions are you applying here?" or "How does this step connect to your domain analysis?" These questions force students to explicitly articulate their mathematical reasoning. GenAI critiques of student explanations generate follow-up questions about clarity, completeness, and mathematical accuracy. Students must respond to challenges like: "What evidence supports your conclusion that this approach was most effective?" or "How might someone with a different mathematical background understand your explanation?" This pushes students to improve their mathematical communication rather than focusing solely on correctness.

Peer interaction during collaborative review provides a different type of promotive challenge. The group discussion questions are designed to invite comparative analysis: *"How did GenAI questioning compare to peer questioning in helping you learn?"* and *"What patterns did you notice in the types of errors GenAI identified?"* The success of this promotive interaction hinges on the quality of student engagement. To encourage deep engagement, instructors can provide a rubric that defines and rewards high-quality interactions. A structured feedback protocol—such as requiring students to identify one conceptual strength, one area for clearer communication, and ask one probing question—can reduce generic comments and promote the intended cognitive friction. The structured progression through phases ensures promotive interactions build complexity over time. Initial GenAI interactions focus on mathematical accuracy, communication critiques address explanation quality, peer reviews incorporate multiple perspectives, and reflections synthesize learning across all interaction types. Each phase prepares students for more sophisticated reasoning in subsequent phases.

Social Skills Development: Building Communication Capabilities

Effective collaboration requires strong social skills and is supported by explicit instruction in communication, conflict resolution, and shared decision-making (Mendo-Lázaro et al., 2018). Although there is less likely to be conflicts between students and GenAI or compromises that are often required in shared decision making, effective student-GenAI collaboration requires developing communication skills designed for GenAI interaction and understanding the importance of having the human make the important decisions that guide the final product (Singer-Freeman, 2025). Students must learn how to structure requests, provide context, specify desired outcomes, and iterate through cycles of clarification. Students should cultivate the ability to critically assess GenAI outputs and discern when human collaboration is more appropriate.

Assignment Application

The assignment provides instruction and practice in multiple types of communication skills essential for both GenAI collaboration and human interaction. The prompting protocols teach students how to communicate effectively with GenAI systems by specifying desired interaction types, providing appropriate context, and establishing clear boundaries for GenAI assistance. For example, protocols for error-checking and explanation critiques teach students to define both the type of assistance they need and their preferred interaction style. Students learn to ask GenAI to guide them towards discovery rather than providing answers. This approach develops improved communication skills, enabling students to articulate their learning needs and set boundaries for productive collaboration with GenAI. Students develop their mathematical communication skills by writing and revising explanations of their thought processes. Students must articulate mathematical reasoning clearly, respond to critique constructively, and revise their communication based on feedback. This develops formal academic writing skills alongside mathematical expression capabilities.

Importantly, the assignment is intentionally designed to involve GenAI in ways that complement rather than replace human social learning. The peer review and group discussion phases ensure students maintain opportunities to practice human-to-human collaboration, developing interpersonal skills, emotional intelligence, and social awareness. Students practice giving constructive feedback, receiving criticism, and engaging in productive mathematical discussions. Group discussions may also provide an opportunity to practice conflict resolution when students have differing opinions or explanations. The group discussion questions require students to synthesize insights from multiple sources and articulate comparative analyses of different collaboration types.

Group Processing: Reflecting on Effectiveness

Effective groups engage in regular reflection on how well they're functioning and how to improve (Johnson et al., 1990). This metacognitive element helps groups improve collaborations over time. For students to become skilled learners they must develop awareness of when GenAI supports their learning and when it supplants their learning. This is often referred to as GenAI literacy.

Building reflective elements into assignments is essential for developing the discriminating awareness that is at the heart of GenAI literacy(Singer-Freeman, 2025).

Assignment Application

The assignment embeds reflection throughout the learning process rather than treating it as an afterthought. This approach helps students develop metacognitive awareness of their collaboration effectiveness in real-time while building skills for future learning improvement. Students document their exchanges with GenAI, creating a record of what was said and how it was said, so that they become aware of how their thinking and interactions changed throughout the process. This process mirrors the group processing element of traditional collaborative learning by making collaboration dynamics explicit and analyzable. Students analyze their problem-solving approach systematically: their initial strategy selection, any difficulties encountered, the impact of GenAI questioning, and their reasoning behind each step.

The comparison of GenAI interactions with the peer interactions (*"Compare the benefits of GenAI assistance versus peer collaboration in your learning process. When would you choose each approach?"*) increases awareness of collaboration dynamics while building individual metacognitive skills. The design of future GenAI prompts based on the effectiveness analysis encourages deeper considerations of the features of prompting that supports effective work using GenAI. Finally, the reflection on the impact of prerequisite knowledge helps students understand how foundational knowledge affects their collaboration success. The submission format also supports processing by requiring students to curate and present their complete learning journey. This comprehensive reflection structure ensures students develop awareness of when GenAI supports instead of supplants their learning, building the judgment essential for strategic technology use in future learning contexts.

Cognitive Load Management: Distributing Mental Demands

Well-structured groups can solve more complex problems than individuals through strategic distribution of cognitive demands (Kirschner et al., 2009). GenAI can function as a way to distribute cognitive load by providing scaffolding that enables learning. The key element to consider when designing assignments is determining what specific learning students should experience and allowing GenAI to provide other elements of the task to free students up to dedicate cognitive resources to target learning areas (Singer-Freeman, 2025).

Assignment Application

The assignment distributes cognitive load to optimize learning by having GenAI detect student errors and encourage elaborations, allowing students to focus on building conceptual understanding rather than checking every algebraic step. When students work on rational function analysis, for example, GenAI can verify their factoring and algebraic simplifications while students concentrate on understanding domain restrictions, asymptote behavior, and graphical interpretation. Providing structured prompting protocols manages cognitive load by providing clear frameworks for the student-GenAI interaction. This frees students from the need to develop collaboration strategies and allows them to focus on mathematical problem-solving. The phase-based assignment structure reduces cognitive overload by separating different types of learning into manageable components. Because students build their submissions incrementally, the cognitive load is distributed across time, preventing end-of-assignment cognitive overload while maintaining accountability. This separation allows students to dedicate attention to each SLO without managing competing cognitive demands. GenAI provides scaffolding for communication development through critique without reducing the cognitive challenge. Whereas, in traditional assignments students might receive feedback on gaps in their explanations after submitting work, in this assignment students have the opportunity to improve their initial communications in response to GenAI feedback prior to submission. This cognitive load distribution enables students to engage with appropriately challenging mathematical problems, develop sophisticated communication skills, practice GenAI collaboration, engage in peer review, and reflect metacognitively; a combination that would create cognitive overload if managed simultaneously but becomes achievable through careful task structuring.

Conclusions

This pre-calculus assignment demonstrates how proven principles from collaborative learning research can guide effective GenAI integration in mathematics education. Rather than viewing GenAI as a replacement for human interaction or a shortcut to task completion, the assignment structures GenAI as a collaborative partner that enhances learning through strategic interdependence, individual accountability, promotive interaction, communication skills, group processing, and cognitive load management. The assignment creates conditions in which students develop deeper mathematical understanding, stronger communication skills, and greater metacognitive awareness of their learning processes. The submission requirements provide evidence of learning across all domains while supporting student reflection and instructor assessment of collaboration effectiveness.

It is important to acknowledge the limitations of this assignment structure. We recognize that no pedagogical design can eliminate academic dishonesty, and determined students will find ways to circumvent the intended learning process. However, the framework presented here is designed to limit the incentive for cheating by shifting the focus from the final product to the documented process. By requiring students to submit initial attempts, detailed interaction logs, revisions, and metacognitive reflections, the assignment makes authentic engagement the more straightforward path. Fabricating a coherent and plausible set of responses would require a level of effort that likely meets or exceeds the work of completing the assignment honestly. Therefore, although this model is not "cheat-proof," it is designed to create an environment in which the path of least resistance aligns with genuine learning, thereby reducing the appeal of academic shortcuts.

By applying research-based collaborative learning principles systematically, educators can design assignments that use GenAI partnerships to enhance rather than undermine student learning. The parallel between collaborative learning and GenAI-assisted learning suggests that technology integration isn't fundamentally different from other pedagogical challenges. The principles that foster effective collaboration among humans can also be applied to support meaningful partnerships between students and GenAI when applied thoughtfully to specific learning contexts (Singer-Freeman, 2025). The assignment model presented here provides a concrete framework that other educators can adapt to their specific content areas and learning objectives, demonstrating that effective GenAI integration is achievable through systematic application of established pedagogical principles. Table 1 includes a summary of the key principles with suggested applications to collaborative work and GenAI-supported assignments.

Table 1. Principle Applications to Group Work and GenAI-Supported Learning

Principle	Collaborative Work Strategies	GenAI Integration Strategy
Positive Interdependence	Jigsaw tasks; differentiated roles	Prompting protocols with defined roles; GenAI addresses blind spots, students reflect on reasoning and contextual relevance
Cognitive Load Management	Task distribution; scaffolding for complex problems	GenAI given non-central tasks to free cognitive resources; temporary scaffolding reduced as abilities develop
Individual Accountability	Individual assessments; peer evaluations	GenAI-free summative tasks; "Explain back to AI" exercises; interaction logs
Promotive Interaction	Debate; Socratic questioning	GenAI prompts challenge reasoning; multi-turn dialogues simulate cognitive friction
Social Skills Development	Communication training; conflict resolution; shared decision-making	Instruction in GenAI-specific communication; boundary-setting; peer collaboration integration
Group Processing	Reflection journals; team debriefs	GenAI interaction logs; comparison of GenAI vs. peer collaboration; metacognitive reflections

To advance the thoughtful integration of GenAI in education, future research should empirically test how collaborative learning principles impact student outcomes in GenAI-supported classrooms. Such studies will help validate and refine the proposed framework across diverse disciplines and learning contexts. As educators adopt these tools, it is also essential to address ethical considerations, including data privacy, algorithmic bias, and the transparency of GenAI-generated content. Finally, successful implementation will require targeted faculty development. Training programs should equip instructors with the pedagogical strategies and technical skills needed to design assignments that use GenAI to support and not supplant student learning.

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Appendix. Pre-Calculus GenAI-Assisted Learning Assignment

Task: You'll individually solve two complex pre-calculus problems and then improve your answers using GenAI assistance. You will then communicate your reasoning and reflect on the learning process with support from GenAI and from other students.

Importance: This assignment develops mathematical problem-solving skills, mathematical communication skills and metacognitive awareness of how you learn most effectively. Completing the assignment prepares you for independent learning in advanced mathematics and will develop skill in using GenAI in ways that support deep learning.

Learning Process: You'll cycle through problem-solving, GenAI-guided error correction, written communication, peer review, and reflection to build deep understanding. Review the grading criteria at the end of the assignment before starting your work to be sure you fully understand what is expected of you.

Task Criteria: Success requires mathematical accuracy, clear communication, effective GenAI and peer collaboration, and thoughtful reflection on your learning process.

Student Learning Outcomes (SLOs)

By the end of this assignment, you will be able to:

1. Analyze rational and inverse functions.
2. Communicate mathematical reasoning clearly in writing
3. Express metacognitive awareness of productive approaches to collaborative work

Assignment Structure

Phase 1: Problem Solving (40 minutes)

(In-class)

Your Problem Set: Choose and complete ONE problem from each category below. Show all your work and save it for your portfolio submission.

Category A: Rational Function Analysis For your chosen function, find the domain, vertical asymptotes, horizontal asymptotes, x-intercepts, and sketch the graph.

1. $f(x) = (2x^2 - 8)/(x^2 - 3x - 4)$
2. $g(x) = (x^2 + x - 6)/(2x^2 - x - 3)$

Category B: Inverse Functions For your chosen function, find its inverse and determine the domain of both the original function and its inverse. Verify your answer by showing that $f(f^{-1}(x)) = x$.

1. $f(x) = \sqrt{(x + 3)}$
2. $h(x) = (2x - 1)/(x + 4)$

(Out-of-class)

AI Interaction Protocol: Now that you have made your best effort at solving the problem on your own, you will use the GenAI tool to help you identify any gaps in your understanding. It is important that you enter your initial solution, even if you are unsure or think it may be incorrect. GenAI will help you identify and understand any errors, so having your original attempt recorded is an important step in the learning process.

Then use this exact prompt with your GenAI tool:

> *"I'm working on a pre-calculus problem. Please check my solution step by step. If I made an error, guide me to discover it through questions rather than giving me the answer directly. Ask me to explain my reasoning at each step where you see confusion. My problem asks me to ______________ for the function ______________ and here is my work [upload initial work]"*

Fill in the blanks with the complete instructions for your problem and the function that you chose. Continue this process until your solution is correct. Make sure to save the transcript of your conversation with the GenAI for your portfolio submission.

Phase 2: Communication (*Out-of-class,* 20 minutes)
Problem-Solving Explanation: Write a detailed explanation of your mathematical solution process. Focus on the mathematical reasoning and steps you used to solve the problem. Save your initial explanation for your portfolio submission.

AI Critique Protocol: Submit your explanation to GenAI with this prompt:

> *"Please critique my mathematical explanation for clarity, completeness, and accuracy. Point out any gaps in my reasoning or unclear language. Ask me questions that will help me strengthen my explanation rather than rewriting it for me."*

Revise your explanation based on the GenAI feedback. Make sure to save the transcript of your conversation with the GenAI, and your revised explanation.

Learning Process Reflection: After completing your problem-solving explanation and revising it based on GenAI's feedback, separately address these questions. This is a personal reflection and these questions should not be entered in the GenAI, but should be submitted in your portfolio.

- Your initial approach and why you chose it
- Where you encountered difficulties
- How GenAI's questions helped you think differently
- The mathematical concepts that were crucial to solving the problem

Phase 3: Collaborative Review (*In-class*, ~30 minutes)

Partner Exchange:

- Share your original work, final solution, and explanation with your assigned partner
- Review their work using the same standards the GenAI used
- Provide written feedback focusing on mathematical reasoning and communication
- Discuss any insights gained from seeing their approach

Group Discussion Questions:

1. How did GenAI questioning compare to peer questioning in helping you learn?
2. What patterns did you notice in the types of errors the GenAI identified?
3. Which problem-solving strategies emerged as most effective?

Phase 4: Reflection and Synthesis (*In- or out-of-class,* ~15 minutes)

Individual Reflection: Respond to these questions and submit them in your portfolio:

1. Future Learning Strategy: Design an GenAI prompt you would use when learning a new challenging mathematical concept. Explain why this prompt would be effective based on today's experience.
2. Knowledge Prerequisites: What foundational knowledge was essential for completing this assignment successfully? How did gaps in this knowledge affect your problem-solving?
   Collaborative vs. GenAI Learning: Compare the benefits of GenAI assistance versus peer collaboration in your learning process. When would you choose each approach?

Portfolio Submission Requirements

Submit a single document containing:

[ ] Original problem work with GenAI interaction log (Phase 1)
[ ] Final correct solutions with work shown (Phase 1)
[ ] Initial explanation of thought process (Phase 2)
[ ] GenAI critique of your explanation (Phase 2)
[ ] Revised explanation responding to GenAI feedback (Phase 2)
[ ] Learning process reflection responses (Phase 2)
[ ] Peer review exchange (given and received) (Phase 3)
[ ] Individual reflection responses (Phase 4)

Assessment Criteria

Mathematical Accuracy (25%)

- Correct final solutions
- Valid mathematical reasoning
- Proper notation and terminology

Communication Skills (25%)

- Clear explanation of problem-solving process
- Effective response to GenAI critique
- Constructive peer feedback

GenAI Integration (25%)

- Appropriate use of GenAI prompts
- Meaningful engagement with GenAI feedback
- Evidence of learning from GenAI interaction

Collaboration and Reflection (25%)

- Quality of peer review exchange
- Depth of reflection on learning process
- Insights about future learning strategies