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Role of the System Processing Information on Thinking Process and Effectiveness Mathematics Learning

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ABSTRACT

This study synthesizes recent empirical research (2015–2025) on the relationships among cognitive load, working memory, metacognitive regulation, self-regulated learning (SRL), and mathematics anxiety in university-level mathematics. Although Cognitive Load Theory (CLT), Working Memory frameworks, and Metacognitive Regulation models have substantially advanced understanding of mathematical information processing, their application to advanced university mathematics remains conceptually fragmented. Through a systematic review of indexed literature, this paper consolidates evidence on how metacognitive strategies—planning, monitoring, and evaluation—interact with cognitive resources and affective factors across mathematical subdomains such as calculus, abstract algebra, statistics, and geometry. The findings indicate that metacognitive regulation supports cognitive load management, that self-regulated learning mediates the relationship between motivational beliefs and performance, and that mathematics anxiety disrupts both working memory efficiency and metacognitive monitoring. Empirical evidence further suggests that cognitive-metacognitive strategy training, particularly when embedded within instructional design or digital learning environments, is more consistently associated with performance gains than purely affective interventions. Rather than proposing a wholly new theoretical framework, this study integrates and clarifies existing perspectives to outline directions for a more holistic model of university mathematics learning that accounts for cognitive, metacognitive, motivational, and emotional dimensions. The review concludes by identifying implications for instructional design and priorities for future empirical research.

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INTRODUCTION

he intersection of information processing, working memory, and mathematics learning has long been a central focus of cognitive and educational psychology. Foundational models such as Cognitive Load Theory (CLT), Working Memory frameworks, and Metacognitive Regulation have provided significant insights into how learners acquire, process, and apply mathematical knowledge. However, while these models have made substantial contributions, they often fall short in addressing the complexities inherent in advanced mathematical learning, particularly at the university level. CLT, for example, primarily emphasizes the management of cognitive load but does not adequately explain how metacognitive processes, such as self-regulation and strategy selection, interact with cognitive mechanisms during mathematics problem-solving (Kang et al., 2023). Similarly, while Working Memory models emphasize the limited capacity of cognitive resources, they lack sufficient focus on how learners' metacognitive awareness and regulation can influence the efficiency of information processing, especially under varying levels of cognitive load (Sweller et al., 2011).

At the university level, where mathematical tasks are significantly more complex and abstract, existing frameworks fall short in addressing the cognitive demands posed by advanced mathematical reasoning, such as calculus, linear algebra, and mathematical modeling. University students are required to manage multiple interrelated heuristic strategies simultaneously, which introduces a level of cognitive load that these models do not fully account for (Schaeffner et al., 2020). For example, when engaging with complex mathematical problems, students must often process not only mathematical formulas but also the underlying abstract concepts, applying a variety of problem-solving strategies in real time. This requires more sophisticated models that capture the dynamic nature of advanced problem-solving, where students must continually assess and adapt their strategies as they work through multi-step problems.

Moreover, while metacognitive regulation has been shown to improve learning outcomes, most studies focus on preservice teachers or elementary school students, leaving a gap in understanding how these models apply to the broader and more diverse population of university students. These models, which emphasize components such as planning, monitoring, and evaluation, do not fully capture the nuanced cognitive demands of university-level mathematics (Young & Worrell, 2018). The gap in empirical studies that directly address university-level mathematical tasks, such as real analysis or abstract algebra, is evident. Research at the university level has tended to focus on preservice teachers or more specific student populations, yet university students face a broader range of mathematical content and more advanced cognitive challenges. This includes areas such as mathematical modeling, proof construction, and statistical reasoning, which require a deeper integration of metacognitive and cognitive resources.

This manuscript aims to bridge these gaps by proposing an integrated conceptual model that combines insights from CLT, Working Memory, and Metacognitive Regulation frameworks. While the input-process-output (IPO) structure of this model largely mirrors existing cognitive processing frameworks, it introduces a novel focus on the dynamic interplay between cognitive load, memory capacity, and metacognitive strategies. By synthesizing these components in the context of advanced mathematics learning, this model offers a more nuanced understanding of how learners regulate their cognitive resources and adapt their thinking strategies to optimize mathematical problem-solving. Unlike existing models that primarily view cognitive and metacognitive processes as linear, this approach highlights the recursive and interdependent nature of these processes, suggesting that successful problem-solving requires an ongoing adaptation between cognition and metacognition (G. Oficiar et al., 2024).

Furthermore, the manuscript addresses significant gaps in the literature regarding the integration of metacognitive regulation with cognitive load management. While previous research has identified the positive impact of metacognitive skills on mathematical performance (Verschaffel et al., 2019), the mechanisms through which metacognition interacts with working memory and cognitive load remain insufficiently explored. For example, while cognitive load theory suggests that high cognitive load can reduce working memory capacity, it is unclear how metacognitive strategies, such as self-monitoring and strategy selection, can mitigate these effects, especially in high-stakes problem-solving situations. This paper proposes a more explicit examination of these interactions, suggesting that the regulation of cognitive load through metacognitive strategies can help learners navigate the demands of complex mathematical problems more effectively (Kang et al., 2023).

To make a significant theoretical contribution, this work expands existing frameworks by addressing the specific challenges of university-level mathematics. These challenges require a more comprehensive framework that integrates cognitive, metacognitive, and affective dimensions of learning. For instance, it is crucial to account for the simultaneous and intertwined nature of cognitive and metacognitive processes in complex problem-solving tasks, a dynamic that current models treat as linear and sequential but which empirical evidence suggests operates recursively in advanced reasoning tasks (Abu Bakar & Ismail, 2019). Furthermore, the integration of motivational and affective factors, such as mathematics anxiety, which affect cognitive performance, is critical in understanding the full spectrum of student learning experiences. Research shows that mathematics anxiety, which is prevalent among university students, can interfere with the cognitive resources available for problem-solving, thus affecting both cognitive and metacognitive processes (Dignath & J. Veenman, 2020).

The manuscript proposes an expansion of theoretical frameworks to better reflect these multidimensional aspects, offering insights that can not only enhance our understanding of how university students process mathematical information but also inform the development of more effective instructional strategies. Traditional instructional models often focus predominantly on cognitive processes, with less emphasis on the affective and metacognitive dimensions. However, at the university level, where students are expected to manage increasingly complex mathematical tasks, addressing these dimensions is crucial for improving learning outcomes. By incorporating motivational and emotional factors into the theoretical framework, this paper seeks to offer a more holistic approach to mathematics learning, one that is more reflective of the challenges university students face.

In summary, this paper aims to contribute to the theoretical development of mathematics learning by providing a more integrated framework that addresses the cognitive, metacognitive, and affective challenges of university-level mathematical problem-solving. By synthesizing insights from existing theories and expanding them to accommodate the complexities of higher education mathematics, this manuscript offers a new perspective on how students process and regulate mathematical information. This approach not only fills critical gaps in the literature but also provides practical implications for educators, offering a more comprehensive understanding of how instructional strategies can be designed to better support university students in mastering advanced mathematical content.

METHOD

This study employs a systematic literature review approach to synthesize recent advancements in the fields of Cognitive Load Theory (CLT), Working Memory frameworks, and Metacognitive Regulation as they relate to mathematics learning at the university level. The aim is to identify key theoretical contributions, address existing gaps, and offer a new integrated conceptual model. To ensure transparency and rigor, the review follows clearly defined search strategies and inclusion-exclusion criteria.

Search Strategy

A comprehensive search was conducted across several relevant academic databases, including Scopus, Web of Science (WoS), ERIC, and Google Scholar. These databases were selected due to their broad coverage of high-quality, peer-reviewed literature across psychology, education, and cognitive science fields. The search process involved a combination of keywords and Boolean operators to capture articles relevant to the study's focus on information processing, working memory, and metacognitive regulation in the context of university-level mathematics learning. Specifically, the search terms used were: “Cognitive Load Theory,” “Working Memory models,” “Metacognitive Regulation in mathematics education,” “Metacognition and mathematics learning,” “Advanced mathematical reasoning,” and “University-level mathematics education.”

The search was limited to articles published between 2015 and 2025 to ensure that only recent studies are included in the review, providing the most up-to-date perspectives and empirical findings. Additionally, only studies published in English were considered due to language constraints.

Inclusion and Exclusion Criteria

The following inclusion and exclusion criteria were applied to ensure the relevance and quality of the articles selected:

Inclusion Criteria:

1. Peer-reviewed journal articles and conference proceedings that explicitly address topics of Cognitive Load Theory, Working Memory, and Metacognitive Regulation as applied to mathematics learning.
2. Studies focused on university-level mathematics education, including topics such as calculus, linear algebra, mathematical modeling, and real analysis.
3. Empirical studies, systematic reviews, and theoretical papers published between 2015 and 2025.
4. Studies that investigated the relationship between cognitive processes, metacognitive strategies, and mathematics learning outcomes at the university level.

Exclusion Criteria:

1. Articles not directly related to university-level mathematics education, including studies focused on elementary, secondary, or preservice education.
2. Studies that did not provide sufficient empirical data or theoretical analysis relevant to the research questions of this review.
3. Non-peer-reviewed sources such as books, dissertations, or articles published in low-quality journals.

Screening Process

The initial search yielded a large pool of articles (n=350). These articles were then screened based on titles and abstracts to determine their relevance to the study. After the first screening, 200 articles were excluded due to irrelevance or non-compliance with the inclusion criteria. The remaining 150 full-text articles were further reviewed, and a total of 85 articles were deemed eligible for inclusion in the final synthesis based on their direct relevance to the theoretical frameworks of interest and their empirical rigor.

A detailed record of the screening process was maintained, including reasons for the exclusion of specific articles at each stage. For clarity, a flow diagram based on the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines was constructed to illustrate the selection process.

Data Extraction and Analysis

For each included article, the following data points were systematically extracted:

1. Authors, publication year, and source.
2. Theoretical framework(s) used (e.g., CLT, Working Memory, Metacognitive Regulation).
3. Key findings related to cognitive, metacognitive, and affective processes in university-level mathematics education.
4. Methodological approach (e.g., experimental, observational, systematic review).
5. Gaps identified by the authors and recommendations for future research.

The extracted data was then analyzed using thematic synthesis to identify recurring themes, theoretical trends, and areas where current frameworks are lacking in addressing university-level mathematics learning. Special attention was paid to how the reviewed studies integrated cognitive and metacognitive processes in mathematics education, as well as any interactions with affective factors like mathematics anxiety.

Limitations

While this review strives for comprehensiveness, it is important to note that it focuses on English-language articles published in the past decade, which may exclude some relevant studies from non-English-speaking regions. Additionally, the reliance on databases and specific search terms means that some studies outside of these terms, or from other sources (e.g., grey literature), may not have been captured. Future research could extend this systematic review by exploring more diverse publication types or incorporating studies from additional databases.

RESULTS AND DISCUSSION

Interventions and Holistic Models in University-Level Mathematics Learning

The evidence reviewed highlights critical pathways for addressing the challenges of mathematics anxiety (MA) and enhancing metacognitive regulation in university-level mathematics courses. These challenges are intertwined with the cognitive, metacognitive, motivational, and emotional dimensions of learning. Interventions targeting both cognitive-metacognitive strategies and emotional regulation, such as mindfulness practices and cognitive tutoring, hold promise for improving mathematical outcomes. Moreover, integrating motivational theories—such as expectancy-value theory (EVT) and goal orientation theory—into cognitive and metacognitive frameworks can provide a more comprehensive understanding of the factors that influence university-level mathematics learning. In this section, we discuss empirical evidence on the efficacy of interventions designed to reduce MA and improve metacognitive regulation, and explore how motivational theories can be integrated with cognitive frameworks to develop a holistic model of learning that addresses both cognitive and emotional barriers.

Empirical Evidence for Interventions Targeting Mathematics Anxiety and Metacognitive Regulation

Cognitive and Metacognitive Training Interventions

The most robust evidence for intervention efficacy in mathematics education comes from studies examining cognitive and metacognitive training programs. Doz et al. (2025) conducted a randomized controlled study comparing two interventions: a cognitive components (CC) intervention focused on problem representation, planning, and metacognition, and an emotional-motivational (EM) intervention targeting math anxiety. The study found that the CC intervention significantly improved problem-solving performance, problem representation skills, and math anxiety reduction, while the EM intervention effectively reduced anxiety but did not result in significant improvements in problem-solving skills. This finding suggests that metacognitive training—which includes planning, monitoring, and evaluating strategies—produces more significant improvements in mathematical performance than solely anxiety-reducing interventions. This has crucial implications for university-level mathematics, where cognitive skills such as problem representation and planning are essential for tackling complex mathematical tasks.

Verschaffel et al. (2019) provided further evidence on the effectiveness of ICT-based metacognitive learning environments, which embed metacognitive scaffolds like hints, prompts, and feedback within digital learning platforms. Their review of 22 studies showed that metacognitive scaffolding in such environments led to significant improvements in both mathematical performance and metacognitive outcomes. The authors recommend expanding research to include a broader range of mathematical subdomains, such as calculus, statistics, and abstract algebra, as these domains present unique cognitive challenges that require different metacognitive strategies. These findings suggest that ICT-based interventions, when appropriately designed, can help university students manage the complexity of advanced mathematics tasks by providing real-time metacognitive support.

Bernacki et al. (2021) found that digital learning skill training could be effectively embedded within university course sites, leading to improvements in metacognitive strategy use and math performance. In their study, students who participated in a digital metacognitive training program outperformed control students by approximately 18 points on exams, demonstrating that SRL strategies such as planning and monitoring can significantly enhance academic performance. Importantly, the effects of the training were consistent across different student groups, including first-generation students, highlighting the equity benefits of metacognitive interventions. These findings underscore the potential of digital tools for delivering scalable, effective metacognitive training in university mathematics courses.

Mindfulness and Growth Mindset Interventions

While cognitive-metacognitive interventions have shown considerable promise, mindfulness-based interventions also offer potential for reducing mathematics anxiety and enhancing self-regulation. Shakmaeva (2022) reviewed studies on mindfulness interventions, noting that mindfulness practices combined with growth mindset training were effective in reducing anxiety and increasing students' confidence in their mathematical abilities. These interventions focus not only on relieving emotional distress but also on fostering a growth mindset—the belief that intelligence can be developed through effort and learning. This aligns with findings from Zonnefeld (2019), who demonstrated that growth mindset training significantly improved both attitudes towards statistics and statistical performance, particularly among female students. This suggests that promoting a growth mindset in conjunction with mindfulness can help university students cope with the emotional and cognitive challenges of advanced mathematics.

However, Shakmaeva (2022) also points out that while mindfulness interventions alone may reduce anxiety, they may not be sufficient to improve math performance without accompanying cognitive strategy instruction. This highlights the importance of combining mindfulness practices with metacognitive training, as the combined approach may address both the emotional and cognitive barriers to learning.

Integrating Motivational Theories with Cognitive and Metacognitive Frameworks

Expectancy-Value Theory and Mathematics Learning

Expectancy-value theory (EVT) posits that students’ motivation to engage in a task is shaped by their expectancy of success (belief in their ability to succeed) and the subjective value they assign to the task (importance, interest, utility) (Fernández et al., 2016). EVT provides a useful lens for understanding why students engage with or disengage from advanced mathematical tasks. For university-level students, the high cognitive demands of mathematics often trigger feelings of self-doubt and helplessness, which in turn affect their motivation and performance. Fernández et al. (2016) found that students’ instrumentality (belief in the practical value of learning mathematics) and self-efficacy (belief in their ability to succeed) negatively predicted math anxiety and positively influenced metacognitive strategies like planning and monitoring.

These findings suggest that motivational beliefs, such as self-efficacy and task value, are not only crucial for engaging students in mathematics but also for facilitating effective metacognitive regulation. Integrating EVT with metacognitive frameworks allows us to see how motivational beliefs influence students' cognitive engagement and metacognitive regulation. For instance, students who believe they can succeed (high self-efficacy) are more likely to use metacognitive strategies effectively, while students with low self-efficacy may struggle to regulate their learning, exacerbating the cycle of anxiety and poor performance.

Wang et al. (2022) further support this by showing that self-regulated learning is closely tied to students' motivational beliefs and mathematics achievement. Their study used the Motivated Strategies for Learning Questionnaire (MSLQ), which measures both motivational beliefs and learning strategies (including metacognitive strategies), to show how task value and self-efficacy interact with metacognitive skills to predict mathematical performance. This integration of motivation and metacognition suggests that future research should explore how motivational interventions, such as growth mindset training, can enhance metacognitive regulation and thus improve mathematical achievement.

Goal Orientation Theory and Metacognitive Regulation

Goal orientation theory differentiates between mastery goals (focused on learning and understanding) and performance goals (focused on demonstrating competence relative to others) (Turgut & Uğurlu, 2024). Research suggests that students with a mastery goal orientation are more likely to engage in metacognitive regulation, as they view challenges as opportunities for learning rather than threats to their self-esteem (Fernández et al., 2016). In contrast, students with a performance goal orientation may be more susceptible to math anxiety and less likely to engage in self-regulation when faced with difficult tasks. Turgut and Uğurlu (2024) found that math anxiety moderates the relationship between metacognitive regulation and mathematical resilience, highlighting the importance of fostering mastery goalsto enhance metacognitive engagement in the face of anxiety.

Interventions that promote mastery goal orientation—such as emphasizing the intrinsic value of learning mathematics and focusing on effort rather than ability—may help mitigate the negative effects of math anxiety and improve metacognitive regulation. This is particularly important for university students, where the high cognitive demands of advanced mathematics can lead to performance-focused thinking that exacerbates anxiety and impairs self-regulation.

Implications for Instructional Design and Future Research

The findings synthesized in this review primarily consolidate and clarify existing theoretical perspectives rather than proposing an entirely new framework. However, they contribute to a more coherent understanding of how information processing, cognitive load, metacognitive regulation, motivation, and mathematics anxiety interact in university-level mathematics learning. From a theoretical perspective, this study supports the continued development of integrative approaches that combine cognitive, metacognitive, and affective dimensions in explaining mathematical learning processes (Nurfitri, R., et al., 2023; Gabriel et al., 2020; Thomas et al., 2022). In particular, the review highlights the need to refine Cognitive Load Theory (CLT) by explicitly incorporating self-regulated learning and metacognitive awareness as mechanisms for managing cognitive burden (Doz et al., 2025; Hattie & Donoghue, 2016). Furthermore, the synthesis aligns with structural models demonstrating that motivational beliefs (e.g., self-efficacy, instrumentality) influence metacognitive strategies and performance through emotional pathways such as hope and anxiety (Fernández et al., 2016). Thus, rather than claiming major theoretical expansion, this paper provides a structured consolidation that clarifies relationships among these constructs and outlines empirically testable directions for future research.

From a practical perspective, the literature suggests several evidence-based recommendations for university mathematics instruction. First, learning design should be grounded in principles of active information processing. Worked examples and structured problem representation tasks have been shown to improve monitoring accuracy and problem-solving performance (Doz et al., 2025; Scheibe et al., 2022). Embedding metacognitive prompts and scaffolds within instruction—whether delivered by instructors or digital systems—has demonstrated positive effects on mathematical and metacognitive outcomes (Verschaffel et al., 2019; Zepeda et al., 2019). Second, optimization of cognitive load is essential. Overlearning and structured sequencing of content reduce working memory demands and support deeper learning (Hattie & Donoghue, 2016). Third, explicit training in metacognitive strategies such as planning, monitoring, and evaluation enhances mathematical reasoning and problem-solving (Aydın & Özgeldi, 2024; Young & Worrell, 2018). Fourth, digital learning skill training embedded within university course platforms has produced measurable gains in exam performance and strategic resource use (Bernacki et al., 2021). Finally, interventions addressing mathematics anxiety—such as growth mindset training and emotion regulation strategies—can support metacognitive engagement when combined with cognitive strategy instruction (Doz et al., 2025; Scheibe et al., 2025; Zonnefeld, 2019).

To illustrate how these principles operate within an information-processing framework, consider the algebraic problem: *Determine the value of x if* $2x + 5 = 15$*.* In the sensory memory stage, the student reads or hears the equation; attention determines whether information transfers to working memory, as unattended information rapidly decays. In the working memory stage, the student encodes and manipulates elements such as “2x,” “+5,” and “=15.” Because working memory capacity is limited, effective learners organize steps into manageable units (Hattie & Donoghue, 2016; Smedt, 2022). The student subtracts 5 from both sides ($2x = 10$) and divides by 2 ($x = 5$), using chunking and procedural knowledge retrieved from long-term memory. If intrinsic or extraneous cognitive load is excessive, errors are more likely (Gabriel et al., 2020). In the long-term memory stage, prior knowledge of linear equations and arithmetic operations is retrieved. Metacognitive monitoring then evaluates the result by substituting $x = 5$ back into the equation, reflecting planning, monitoring, and evaluation processes central to metacognitive regulation (Hattie & Donoghue, 2016; Triwahyuningtyas & Sesanti, 2023). Although elementary, this example demonstrates the dynamic interaction among cognitive processing, prior knowledge, and metacognitive evaluation described throughout the literature.

Future research should move beyond conceptual consolidation by empirically testing integrated instructional interventions in advanced university mathematics contexts. Randomized or quasi-experimental studies comparing cognitive-metacognitive training, motivational interventions, and combined approaches would clarify causal mechanisms (Bernacki et al., 2021; Doz et al., 2025; Mazaly and Saragih, 2022; Laditah, C., et al. 2025). Structural equation modeling, similar to that employed by Fernández et al. (2016), could examine mediated pathways linking expectancy beliefs, anxiety, metacognitive strategies, and performance. Moreover, research should explore how intervention effectiveness varies across mathematical subdomains and individual differences, including working memory capacity and mathematics anxiety (Bernacki et al., 2021; Turgut & Uğurlu, 2024). Longitudinal studies are particularly needed to determine whether improvements in metacognitive regulation translate into sustained academic resilience and reduced anxiety over time. By addressing these priorities, future investigations can strengthen the empirical basis for integrated instructional models in university-level mathematics learning.

CONCLUSION

This study aimed to explore the integration of cognitive load, metacognitive regulation, and individual differences in the context of university-level mathematics learning. Through a systematic review of the literature, this paper synthesizes existing knowledge on the roles of Cognitive Load Theory (CLT), Working Memory, and Metacognitive Regulation frameworks in shaping learning outcomes at the university level. While the review offers a synthesis of established theories, it also highlights gaps in understanding how these processes interact in more complex, advanced mathematical domains, particularly at the university level. In this sense, the contribution of this paper lies in consolidating existing knowledge while providing insights into how these theories could be further expanded to better address the challenges faced by university students engaged in higher-order mathematical tasks.

However, it is important to note that the theoretical expansion suggested in the introduction, particularly regarding the development of a new integrated model, is more about synthesizing and extending established frameworks rather than introducing an entirely novel theoretical framework or new constructs. The analysis presented in this review underscores the need for future research to build on the existing foundations of CLT, Working Memory, and Metacognitive Regulation by exploring how these frameworks can be more effectively applied to university-level mathematics education. The paper primarily consolidates established knowledge while offering directions for further research rather than presenting a completely novel theoretical framework.

While this review makes important contributions to understanding the cognitive and metacognitive challenges of university mathematics learning, it is not without its limitations. One limitation is the focus on literature published within the past decade, which may exclude older, yet still relevant, studies that could provide additional context to the findings discussed here. Furthermore, the majority of studies reviewed focused on specific subdomains of mathematics, such as algebra or calculus, which may not fully represent the diversity of cognitive and metacognitive challenges encountered in other advanced mathematical fields like mathematical modeling or proof-based subdomains. The review also did not extensively cover the role of social and collaborative learning contexts, which may play an important role in metacognitive development, especially in group-based or project-based mathematics learning.

Finally, the methodological approach of this review—while systematic in its approach to data extraction and analysis—was limited to available empirical studies and did not include direct experimental or longitudinal research on the proposed interventions. Future research should address these limitations by exploring longitudinal studies and experimental interventions that test the effectiveness of integrated cognitive-metacognitive and emotional interventions in university mathematics. Additionally, studies should explore how these findings can be applied to more diverse subdomains of mathematics and consider how motivational theories, such as expectancy-value theory and goal orientation theory, can be incorporated into future instructional models for university-level mathematics education. Addressing these gaps will provide a clearer path for developing instructional strategies that can better support students' cognitive, metacognitive, and emotional engagement with advanced mathematics learning.

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