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Metacognitive Training and Mathematical Cognition: The Effects on Self-Efficacy and Academic Performance

Alexios Kouzalis [a*]

[a] *RUDN University, RUSSIA*

[*]*Corresponding author:* Alexios Kouzalis. *E-mail address:* alexiskouzalis@gmail.com

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abstract

Background: Metacognition, defined as the awareness and regulation of one's cognitive processes, plays a crucial role in learning and problem solving. In mathematics education, metacognitive training is essential for improving learners' ability to manage thinking processes and enhance performance. However, previous studies often examine metacognition separately from mathematical cognition, self-efficacy, and academic performance, indicating a lack of integrative understanding.
Aims: This narrative literature review aims to examine the relationships among metacognition, mathematical cognition, self-efficacy, and academic performance. It also explores how metacognitive training contributes to self-regulated learning and investigates the neurocognitive mechanisms underlying mathematical cognition.
Methods: A structured literature search was conducted across major academic databases, including Scopus, Web of Science, and Google Scholar, using relevant keywords. A total of 48 peer-reviewed studies were selected, with approximately 50% published within the last five years to ensure recency.
Results: The thematic synthesis identified five major themes: (1) metacognitive training and self-efficacy, (2) metacognition and self-regulation, (3) mathematical performance, (4) mathematical operations and task complexity, and (5) neural correlates of mathematical cognition. The findings show that metacognitive training enhances planning, monitoring, and evaluation processes, improves mathematical accuracy and efficiency, and strengthens self-efficacy as a mediating factor.
Conclusion: Metacognition functions as a central mechanism linking cognitive, affective, and behavioral aspects of learning. Integrating structured metacognitive training into educational practices is essential to improve mathematical performance and promote sustainable learning outcomes.

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1. Introduction

Metacognition has increasingly been recognized as a fundamental component of higher-order thinking and a key determinant of learning effectiveness across disciplines. It is defined as the ability to understand one's own knowledge, perceptions, and assumptions (Keestra, 2024), to reflect on one's knowledge and its sources (Meyer et al., 2024), and to use awareness of one's learning processes to monitor and regulate cognition (Braad, 2024). Metacognition involves stepping back from one's thinking to evaluate it, requiring continuous monitoring of actions, assessment of strategy effectiveness, and adaptive adjustments for future tasks. This "contemplating thinking" process represents a second-order reflection that enables individuals to evaluate their cognitive performance and flexibly modify their behavior based on feedback from the environment (Di Edwardo, 2020; Zacharopoulos et al., 2022).

In educational contexts, metacognition plays a transformative role by enabling learners to actively regulate their cognitive processes, thereby enhancing learning effectiveness and academic achievement (Srivastava, 2024; Dennis & Somerville, 2023). Students with well-developed metacognitive awareness are better able to plan, monitor, and evaluate their learning strategies, leading to improved problem-solving skills and deeper conceptual understanding. In mathematics education, metacognition is particularly critical, as it supports the decomposition of complex problems, strategic decision-making, and error correction (Rajadurai & Ganapathy, 2023). Moreover, metacognitive skills contribute to increased self-efficacy, as learners gain confidence in their ability to manage academic challenges through self-regulation (Guntur & Purnomo, 2024). At the instructional level, the integration of metacognitive strategies promotes a shift from teacher-centered to learner-centered approaches, fostering independent learning and adaptability across domains.

The relationship between metacognition and cognition has long been established, with metacognition considered essential for higher-order learning processes (Meyer et al., 2024). It consists of two core components: metacognitive knowledge (declarative, procedural, and conditional) and metacognitive regulation (planning, monitoring, and evaluation), both of which contribute significantly to learning effectiveness (Keestra, 2024). Empirical studies further indicate that metacognitive abilities developed in controlled settings can transfer to real-world educational contexts (Fleur et al., 2025). Through metacognition, students are able to evaluate their understanding, develop learning strategies, and enhance problem-solving skills. When faced with complex tasks, metacognitive learners can break problems into sub-tasks, evaluate alternative solutions, and make informed decisions (Srivastava, 2024). However, not all students possess equal levels of metacognitive ability, making metacognitive training a crucial strategy for improving academic performance (Braad, 2024).

Mathematics, as a foundational discipline for many fields, requires strong cognitive and analytical skills (Buianova et al., 2025). In this context, metacognitive strategies play a vital role in managing the cognitive demands of mathematical learning, particularly in complex problem-solving situations. There is also a strong connection between computational thinking and metacognition, as both involve planning, monitoring, and evaluating problem-solving processes (Ocak et al., 2025). This relationship becomes especially important for learners experiencing mathematical difficulties, such as dyscalculia, a learning disorder that affects an individual's ability to understand numbers and perform arithmetic operations.

As illustrated in Figure 1, dyscalculia emphasizes the necessity of targeted metacognitive support to help students develop effective learning strategies in mathematics.

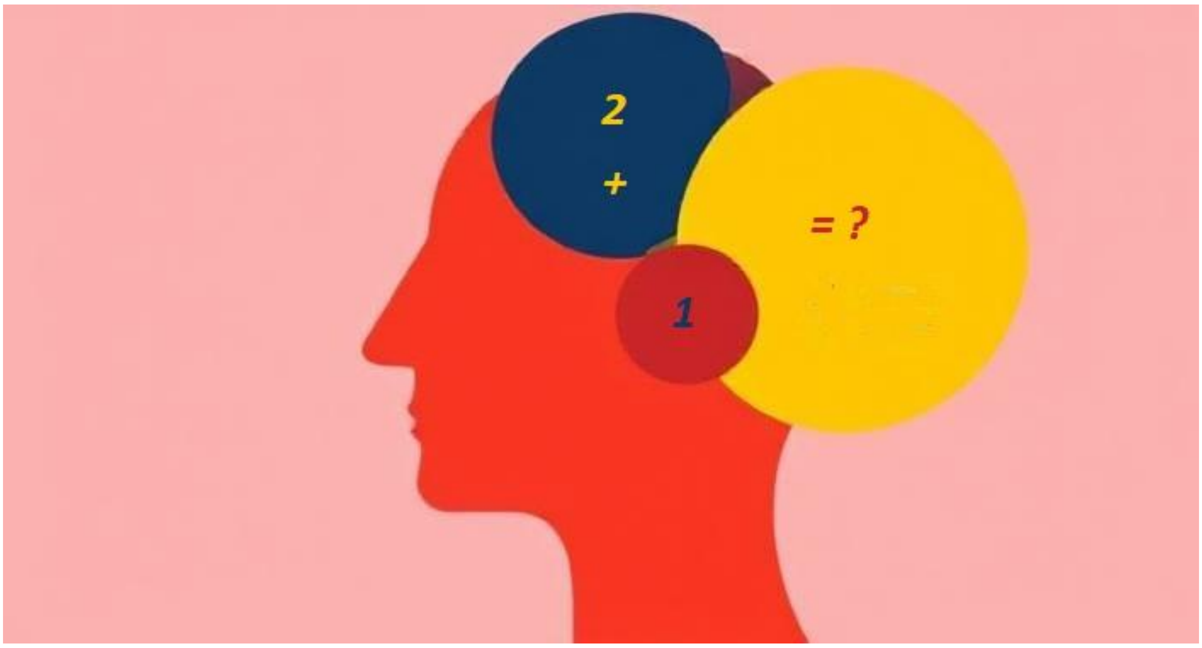

Figure 1. Dyscalculia is a learning disorder that can cause difficulties with arithmetic, number sense, and understanding mathematical concepts.

Metacognition and mathematical cognition are closely interconnected, as they jointly support effective mathematical learning and problem-solving. Mathematical cognition involves mental processes such as numerical understanding, pattern recognition, and logical reasoning, whereas metacognition functions as a regulatory system that oversees these processes. For example, when solving an equation, a student not only applies mathematical rules but also evaluates each step and verifies the correctness of the solution. This interaction enhances accuracy, conceptual understanding, and knowledge transfer to new contexts. Research in cognitive psychology and mathematics education consistently shows that students who employ metacognitive strategies demonstrate higher academic performance and greater lenjing autonomy.

From a theoretical perspective, the foundations of mathematical cognition can be traced back to early philosophical thought. Scholars such as Aristotle contributed to the development of logic and categorization, which underpin modern mathematical reasoning. Similarly, the Pythagoreans introduced the idea that "everything is number," emphasizing the fundamental role of numerical relationships in understanding the universe (Herrmann, 2022). Contemporary research further conceptualizes mathematical cognition as an interdisciplinary field encompassing cognitive, social, and biological dimensions (Soylu, 2022). Advances in neuroimaging techniques, particularly functional magnetic resonance imaging (FMRI), have revealed that mathematical cognition and metacognition are associated with specific brain regions, including the prefrontal cortex, parietal lobules, and insular cortex (Matejko & Ansari, 2018). These findings provide deeper insights into the neural mechanisms underlying mathematical processing and cognitive regulation.

Despite the substantial body of research, several critical gaps remain. First, metacognition and mathematical cognition are often studied as separate constructs, resulting in a lack of integrative frameworks linking metacognitive training to specific indicators of mathematical performance. Second, the effects of metacognitive training on mathematical cognition in non-clinical populations remain underexplored, particularly in relation to self-efficacy and self-regulation (Aydın & Özgeldi, 2024). Third, although neurophysiological studies have identified relevant brain regions, there is limited integration of these findings into educational practices. Finally, most studies rely on self-report measures, which may not adequately capture the dynamic and context-specific nature of metacognition in mathematical problem-solving (Toikka et al., 2024).

In response to these gaps, this study offers a novel integrative perspective that connects metacognitive training with mathematical cognition across cognitive, educational, and neurophysiological dimensions. Unlike previous studies that focus on isolated aspects, this study incorporates self-efficacy and self-regulation as mediating mechanisms and bridges cognitive neuroscience with educational practice. Therefore, the aim of this study is to examine the relationships among metacognition, mathematical cognition, and academic performance through a narrative literature review. Specifically, this study aims to: (1) analyze the role of metacognitive training in improving mathematical performance, (2) explore its influence on self-efficacy and self-regulation, and (3) synthesize neurocognitive evidence related to mathematical cognition. By integrating these dimensions, this study seeks to propose a comprehensive conceptual framework for enhancing mathematics learning outcomes.

1.1 Conceptualization of metacognition

Metacognition is widely recognized as a central construct in contemporary learning theory, referring to individuals' awareness and regulation of their own cognitive processes. The concept was first introduced by Flavell (1979), who defined it as "thinking about cognition." Subsequent studies have conceptualized metacognition as comprising two interrelated components: *knowledge of cognition* and *regulation of cognition*. Knowledge of cognition includes learners' understanding of their cognitive abilities, strategies, and task requirements, while regulation of cognition involves planning, monitoring, and evaluating cognitive activities (Verschaffel et al., 2019; Öztürk, 2020).

Metacognition plays a crucial role in fostering self-regulated learning, enabling learners to take control of their learning processes. Students with higher levels of metacognitive awareness tend to employ more effective learning strategies, demonstrate better problem-solving skills, and engage in reflective thinking (Rasheed & Zafar, 2023). Therefore, metacognition is not only a cognitive construct but also a foundational element for developing independent and lifelong learners.

1.2 Mathematical cognition in learning

Mathematical cognition refers to the mental processes involved in understanding, processing, and solving mathematical problems. These processes include conceptual understanding, reasoning, representation, and problem solving. Research suggests that successful mathematical cognition requires not only domain knowledge but also the ability to regulate cognitive processes effectively through metacognitive strategies (Verschaffel et al., 2019).

In mathematics education, students frequently encounter complex and non-routine problems that demand higher-order thinking skills. In such contexts, metacognition supports learners in organizing information, selecting appropriate strategies, and evaluating the accuracy of their solutions. Thus, mathematical cognition and metacognition are closely interconnected and mutually reinforcing in enhancing students' learning outcomes.

1.3 Metacognitive training in education

Metacognitive training refers to instructional approaches designed to enhance students' metacognitive awareness and regulation through explicit teaching and structured activities. Common strategies include think-aloud protocols, self-questioning, reflective journaling, and guided feedback. Empirical evidence demonstrates that metacognitive training significantly improves learning outcomes across various disciplines. For instance, Mutambuki et al. (2020) found that integrating metacognitive instruction with active learning resulted in significantly higher performance in cognitively demanding chemistry tasks compared to active learning alone. Similarly, studies in mathematics education indicate that metacognitive training enhances students' problem-solving abilities and higher-order thinking skills (Maor et al., 2023; Rasheed & Zafar, 2023).

However, the effectiveness of metacognitive training depends largely on instructional design. Research highlights the importance of explicit instruction, teacher modeling, and scaffolding to ensure that students can internalize and apply metacognitive strategies effectively (Denke et al., 2020; Öztürk, 2020).

1.4 Self-efficacy in mathematics learning

Self-efficacy, defined as individuals' beliefs in their ability to perform specific tasks (Bandura, 1997), is a critical affective factor influencing learning outcomes. In mathematics education, self-efficacy affects students' motivation, persistence, and choice of learning strategies. Students with high self-efficacy are more likely to engage in challenging tasks, persist in problem solving, and apply metacognitive strategies effectively. Conversely, students with low self-efficacy tend to avoid difficult tasks and exhibit lower levels of cognitive engagement (Kim & Alghamdi, 2023). Furthermore, research suggests a reciprocal relationship between metacognition and self-efficacy. Metacognitive training can enhance self-efficacy by providing students with successful learning experiences, while higher self-efficacy encourages the use of metacognitive strategies (Rasheed & Zafar, 2023).

1.5 Effects of metacognitive training on mathematical cognition, self-efficacy, and academic performance

A growing body of research indicates that metacognitive training has significant effects on mathematical cognition, self-efficacy, and academic performance. In mathematics learning, metacognitive interventions have been shown to improve conceptual understanding, problem-solving skills, and overall academic achievement (Verschaffel et al., 2019; Mutambuki et al., 2020). In addition, metacognitive training contributes to the development of self-efficacy. As students gain better control over their learning processes, they become more confident in their abilities, which in turn enhances their academic performance (Kim & Alghamdi, 2023). This suggests that metacognition acts as a mediating mechanism linking cognitive processes and affective outcomes. Despite these positive findings, some studies report inconsistent results, indicating that the effectiveness of metacognitive training may vary depending on contextual factors such as instructional quality, student characteristics, and learning environments. Therefore, it is essential to examine these relationships within specific educational context.

2. Methods

2.1 Research design

This study employed a narrative literature review design to synthesize and critically analyze existing research on metacognition, mathematical cognition, and their relationships with self-efficacy and academic performance. A narrative review approach was selected because it allows for a comprehensive and interpretative synthesis of findings across diverse study designs, including empirical, theoretical, and review studies.

A structured and transparent procedure was adopted throughout the review process to ensure the credibility and rigor of the findings. This approach enables readers to evaluate the reliability, relevance, and validity of the included studies, while also providing an integrative understanding of the current state of knowledge in the field.

2.2 Research procedure

The review process followed several systematic stages, beginning with the identification of relevant literature through a comprehensive database search. The search was conducted across multiple academic databases, including Scopus, Web of Science, PubMed, and Google Scholar.

To ensure a thorough search, combinations of keywords and Boolean operators were applied, such as:

- “metacognition” AND “mathematical cognition”
- “metacognitive training” AND “self-efficacy”
- “metacognition” AND “academic performance”
- “mathematical cognition” AND “brain” OR “neuroimaging”
- “self-regulation” AND “learning strategies”

In addition to database searching, a backward snowballing technique was used by reviewing the reference lists of selected articles to identify additional relevant studies that may not have appeared in the initial search results.

2.3 Participants

As this study is based on a literature review, it does not involve direct human participants. Instead, the units of analysis consist of published scholarly articles related to metacognition, mathematical cognition, self-efficacy, and academic performance.

The inclusion criteria for selecting studies were as follows:

1. Articles published in peer-reviewed journals
2. Written in English
3. Directly related to the research variables (metacognition, metacognitive training, mathematical cognition, self-efficacy, or self-regulation)
4. Including empirical studies, theoretical papers, or review articles

Priority was given to recent publications last five years to capture the most up-to-date developments, although seminal works were also included to strengthen the theoretical foundation.

Studies were excluded if they:

- Were not peer-reviewed
- Were duplicates
- Lacked relevance to the research focus
- Did not provide sufficient methodological detail

Through this selection process, a total of 48 studies were included in the final review, with 24 studies published within the last five years, ensuring both comprehensiveness and recency.

2.4 Data collection

Data collection was conducted systematically by extracting relevant information from each selected study. The extracted data included:

- Research objectives
- Study design and methodology
- Sample characteristics (if applicable)
- Key findings
- Contributions to understanding metacognition and mathematical cognition

Special attention was given to findings related to:

- Self-efficacy
- Self-regulation
- Academic performance
- Mathematical cognition processes
- Neurocognitive or brain-based evidence (where applicable)

All data were organized using a structured review matrix to facilitate comparison and synthesis across studies.

2.5 Data analysis

The collected data were analyzed using a thematic analysis approach, allowing for the identification of recurring patterns, relationships, and conceptual connections across studies. The analysis process involved:

1. Data familiarization through repeated reading of selected studies
2. Coding key themes related to metacognition and learning outcomes
3. Categorizing findings into major thematic areas
4. Synthesizing relationships among variables

The findings were organized into several major themes, including:

- Metacognitive training and self-efficacy
- Metacognition and self-regulated learning
- Mathematical cognition and academic performance
- Problem solving and task complexity
- Neural and cognitive mechanisms underlying mathematical cognition

To enhance the credibility of the review, priority was given to studies published in reputable journals and those demonstrating strong methodological rigor. However, as a narrative literature review, this study does not employ formal systematic review protocols or meta-analytic techniques. Therefore, potential limitations include selection bias and variability in research designs, which may affect direct comparability across studies. Despite these limitations, the structured approach adopted in this study provides a comprehensive and integrative synthesis of the literature.

3. Results

This study synthesized findings from 48 selected studies examining the relationships among metacognitive training, mathematical cognition, self-efficacy, and academic performance. The thematic analysis revealed five major themes that consistently emerged across the literature.

3.1 Self-efficacy: the metacognitive training strategy

Metacognition is strongly associated with success in mathematics; however, factors such as age, domain, and culture significantly influence this relationship (Xie et al., 2024). Dysfunction in metacognition and social cognition often manifests as difficulties with planning, time management, attention, and emotional regulation due to impaired executive functions (Fraiwan et al., 2025). These challenges pose substantial barriers for university students, affecting both academic achievement and social well-being. Furthermore, metacognition plays a vital role in understanding and modeling human auditory perception and communication, especially within complex environments.

One study proposed a 'meta-listening' framework based on Bayesian perception models by exploring how neural encoding precision might influence auditory metacognition (Obleser, 2025). According to the sociocognitive approach, students' abilities are influenced by environmental factors, and metacognitive beliefs significantly shape learners' perceptions of self-efficacy throughout the learning process (Bouchkioua, 2021). Students who have strong beliefs in their learning capabilities tend to be more effective at employing metacognitive strategies to achieve their learning objectives than those lacking this confidence (Hayat & Shateri, 2019). A study examining the pathways through which self-efficacy influences problem-solving found that university students' self-efficacy significantly predicts their metacognition and critical thinking (Wang, 2024). A tutorial program was developed for first-year chemistry students enrolled in an introductory course to deliver direct instruction in metacognitive skills (Graham et al., 2019). Based on student surveys and grade records, the implementation of this program enhanced students' self-efficacy and academic performance, with notably greater effects observed among female students.

Metacognitive training typically involves structured and explicit instruction designed to help learners become aware of, monitor, and regulate their own thinking processes. These interventions often follow a sequence of procedures. First, instructors introduce metacognitive concepts such as planning, monitoring, and evaluation, often through direct instruction and modeling. For example, teachers may use "think-aloud" strategies to demonstrate how to approach a task, make decisions, and detect errors. Second, students engage in guided practice, where they apply specific strategies (e.g., goal setting, self-questioning, progress monitoring, and error analysis) with scaffolding and feedback. Third, learners gradually move to independent practice, applying these strategies autonomously across different academic tasks.

Reflection activities such as learning journals, checklists, or self-evaluation prompts are also commonly incorporated to reinforce awareness and regulation of learning processes. The influence of such training on self-efficacy can be explained through several causal mechanisms. First, metacognitive training enhances students’ sense of control over their learning by equipping them with concrete strategies to manage tasks effectively. This increased perceived control directly contributes to stronger self-efficacy beliefs. Second, repeated successful use of strategies leads to mastery experiences, which are the most powerful source of self-efficacy. As students observe their improvement (e.g., completing tasks more efficiently or achieving better outcomes), their confidence in their capabilities increases. Third, guided practice and teacher feedback provide social persuasion, reinforcing students’ beliefs that they can succeed. Fourth, metacognitive awareness reduces uncertainty and anxiety during task performance, allowing students to approach challenges with greater confidence. Finally, the ability to monitor and adjust one’s performance fosters adaptive attributions; students begin to attribute success to effort and strategy use rather than fixed ability, further strengthening self-efficacy. Through these interconnected processes, structured instruction, guided application, reflective practice, and repeated mastery metacognitive training create a clear pathway by which learners develop stronger beliefs in their academic capabilities. Training in metacognitive skills significantly bolstered students' academic self-efficacy, their ability to manage homework, family, and school responsibilities, and their academic engagement (Taghani & Razavi, 2022). Furthermore, training in metacognitive strategies is recommended to enhance process skills and self-efficacy among students with learning disabilities (Gomaa, 2016). Additionally, the employment of metacognitive strategies can augment not only students’ but also teachers' metacognitive awareness and self-efficacy (Yıldız & Akdağ, 2017).

3.2 Self-regulation: metacognitive training versus conventional training

Effective self-regulation, achieved through monitoring, plays a vital role in adults' everyday cognitive functioning. Studies using the metacognitive intervention approach have demonstrated greater learning effects than those employing traditional strategy-training methods (Hertzog & Dunlosky, 2011). Effective metacognitive training interventions promote the application and transfer of self-regulation strategies and skills to novel learning situations (Schuster et al., 2020). Due to their task-specific nature, cognitive and motivational strategies possess limited transferability; however, metacognitive strategies are applicable across numerous learning tasks (Schuster et al., 2020). Different cognitive learning strategies influence the depth of text content processing; nonetheless, research indicates that the metacognitive self-regulation component enhances students' performance, particularly when cognitive strategy training alone proves ineffective (Leopold & Leutner, 2015). In error management training, the emphasis is on intentionally making errors and learning from these experiences. Compared to conventional training methods that focus on error avoidance, error management training consistently yields superior performance (Keith & Frese, 2005). Variations in error management performance have been found to be affected by emotion control and metacognitive skills, highlighting the importance of integrating self-regulation into training processes (Keith & Frese, 2005). The impact of metacognitive training has also been examined under stressful conditions, notably during critical examinations, with results indicating that students who received training demonstrated a richer array of cognitive regulation skills than the control group (Mevarech & Amrany, 2008).

3.3 Mathematical performance (accuracy and reaction time)

A crucial part of almost all arithmetic performance is the ability to recall basic arithmetic facts, providing an opportunity to explore memory functions within a small, naturally occurring data set (McCloskey et al., 1991). It is widely believed that adult simple arithmetic performance involves automated solution retrieval from a network of stored facts in memory, however such an explanation of performance is incompatible with the solid observation that reaction time rises with problem size and difficulty since it always predicts a uniform reaction time for solution retrieval (Jackson & Coney, 2005). There has been extensive debate over whether there are correlations among response time, accuracy, individual differences (such as IQ and math skills), and various numerical tasks. Some studies in numeracy have used response time as a dependent variable, while others have focused on accuracy (Ratcliff , 2005). A study involving 120 participants examined arithmetic and control tasks to explore the role of processing speed (Shen & Wei, 2023). The results showed a significant correlation between the approximate number system and math proficiency, suggesting that processing speed may serve as a distinct mechanism underlying this relationship. Furthermore, an empirical study by Jackson & Coney (2005) found that both problem size and arithmetic fluency affected response times.

3.4 Mathematical operations

Students are prone to a natural-number bias when reasoning with numbers. Christou et al, (2020) investigated the natural number bias by asking students to assess the validity of algebraic equations involving multiplication and division. The numbers were either decimal or natural, small or big. It was found that the natural-number bias influences assessments by leading people to link each operation to a particular magnitude of outcome: division makes things smaller and multiplication makes them larger. It was also demonstrated that the effect was greater for small numbers, which may be because the multiplication table, taught in primary education, contains number combinations. This finding implies that, when feasible, students may rely on direct retrieval of facts from memory. One study investigated basic addition procedures, with true-false verification using single-digit questions (Ashcraft & Battaglia, 1978). It was discovered that promptly repeated stimuli facilitated response time. Another study (Miller et al., 1984) measured response times for adding, multiplying, and comparing stimuli after pairs of single-digit integers were presented and found a strong correlation between tie-addition and tie-multiplication response times for the same digits. Additionally, response times for both addition and multiplication increased more gradually with problem size than for non-tie problems. Concerning effect sizes for different mathematical operations, one study (Raddatz et al., 2017) found the following values. For calculation accuracy, addition yielded an effect size value of 8.83, subtraction 21.36, and multiplication 19.14. For calculation response time, addition yielded an effect size value of 0.93, subtraction 0.70, and multiplication 0.87.

3.5 *Mathematical* c*omplexity or difficulty*

Performance in higher education often hinges on students' ability to effectively apply their existing knowledge to complex tasks (Hakami, 2025). A recent study found that perceived competence and self-efficacy are distinct constructs, both mediating the relationship between learner traits (such as age and prior knowledge) and outcomes, including performance and perceived task difficulty during the post-test (Helm et al., 2026). These results underscore the need to differentiate between perceived competence and self-efficacy in education and highlight their distinct roles in mediating how learner characteristics influence outcomes. It is conceivable to conceptualize arithmetic problem-solving as a multi-phase process encompassing step-by-step task execution, strategy selection, and task encoding. Prior research utilizing functional magnetic resonance imaging (fMRI) indicates a frontal-parietal network involved in the performance of complex numerical tasks (Tschentscher & Hauk, 2016). In one investigation, as task complexity increased, measurable alterations in prefrontal and parietal cortical activity patterns were observed, along with the recruitment of additional brain regions, such as the caudate nucleus and midcerebellar cortex. More notably, the left insular/orbitofrontal cortex demonstrated the primary effect of stimulus presentation rate, whereas the left and right angular gyri exhibited the primary effect of arithmetic difficulty (Menon et al., 2000). In a subsequent FMRI study, twenty-five adult participants were divided into groups based on their respective mathematical proficiency. Participants were tasked with verifying the correctness of single-digit and multi-digit multiplication problems. The analysis revealed that, during the process of solving both types of arithmetic problems, individuals with greater mathematical proficiency exhibited heightened activity in the left angular gyrus (Grabner et al., 2009).

3.6 Several brain areas associated with mathematical cognition

According to a study conducted by Vandervert, conceptual creations arise from the collaborative interactions of working memory and cerebellar cognitive processes, thereby providing a neurophysiological explanation for the cognitive origins of mathematics (Vandervert, 2003). Vandervert proposed a theoretical framework aimed at understanding the fundamental source of mathematics and "number sense," as delineated by S. Dehaene (Vandervert, 2017). The modern characterization of mathematics as the "science of patterns,' along with the identification of cerebellar sequences (patterns) and the realization that the cerebellum automates numerical manipulation, constitute the foundational aspects of Vandervert's methodology. Findings from a recent study (Sherman et al., 2025) reveal significant dynamic interactions within the thalamus and, potentially, between thalamic nuclei and cortical networks that support cognitive control functions. The interactions within the thalamic network during mathematical cognition are underscored by the role of specific thalamic regions in rapid cognitive responses during mathematical tasks (Sherman et al., 2025). According to another study, individuals with higher automaticity in processing complex arithmetic formulas demonstrated greater structural integrity of the arcuate fasciculus and superior longitudinal fasciculus, whereas individuals with lower automaticity exhibited stronger cortico-thalamic connections (Jeon et al., 2019). An fMRI study investigated which brain regions showed greater activity in response to correctly versus incorrectly solved arithmetic problems (Ansari et al., 2011). The research involved twenty-four adult participants with diverse levels of mathematical proficiency, who solved problems involving all four basic arithmetic operations. Error commission, defined as selecting the incorrect solution among two options in an arithmetic problem, was associated with activation in the brain stem. Ponting

(2010) conducted functional magnetic resonance imaging (fMRI) while participants performed a task involving adding a double-digit and a single-digit number. The results indicated activation of the caudate nucleus, which corroborated previous research by demonstrating the expected activity pattern that distinguished between positive and negative feedback.

4. Discussion

The thematic synthesis of the reviewed literature demonstrates that metacognition plays a central role in enhancing mathematical cognition, self-efficacy, and academic performance. The main findings of this study indicate that metacognitive training consistently improves learners' ability to regulate their thinking processes, which subsequently leads to better academic outcomes. Flavell (1979) proposed the foundational concept of metacognition, defining it as the awareness and regulation of one's cognitive processes, which aligns with this finding. Furthermore, this result supports the self-regulated learning framework developed by Zimmerman (2010), which emphasizes that metacognitive processes such as planning, monitoring, and evaluation are essential components of effective learning.

More specifically, the relationship between metacognitive training and self-efficacy emerged as a significant finding. Students who engaged in structured metacognitive training demonstrated higher levels of confidence in their academic abilities. This can be explained through the concept of mastery experiences, which are considered the most influential source of self-efficacy (Bandura, 1997). The findings are consistent with Rasheed and Zafar (2023), who reported that metacognitive strategies significantly enhance sustainable learning skills and learners' confidence. Similarly, Mutambuki et al. (2020) found that the integration of metacognitive strategies within active learning environments leads to greater improvements in academic performance compared to traditional instructional methods.

However, not all findings were entirely consistent. Some studies reported that the relationship between metacognition and academic performance is influenced by contextual factors such as motivation, instructional quality, and learning environments (Kim & Alghamdi, 2023). This suggests that metacognition does not operate independently but interacts with other variables that shape learning outcomes. This interpretation is consistent with social cognitive theory, which posits that learning is the result of reciprocal interactions among personal, behavioral, and environmental factors (Bandura, 1997).

In addition, the relationship between metacognition and self-regulated learning was identified as a key theme. Learners with higher metacognitive awareness tend to demonstrate stronger self-regulatory skills, including goal setting, progress monitoring, and self-evaluation. These findings are supported by Schuster et al. (2020), who emphasized that metacognitive training enhances the transferability of self-regulation skills across different learning contexts. Moreover, metacognitive approaches have been shown to produce more durable and meaningful learning outcomes compared to conventional instructional strategies (Hertzog & Dunlosky, 2011). With regard to mathematical performance, the findings indicate that metacognition contributes to both accuracy and efficiency in problem-solving. Students with strong metacognitive skills are better able to select appropriate strategies, detect errors, and revise their solutions. This is consistent with the findings of Leopold and Leutner (2015), who demonstrated that metacognitive regulation significantly improves students' performance, particularly in complex learning tasks. Furthermore, Shen and Wei (2023) found that processing speed is associated with mathematical performance, suggesting an interaction between cognitive processing and metacognitive regulation.

Task complexity also emerged as an important factor influencing the effectiveness of metacognition. Complex mathematical tasks require higher-order thinking skills, making metacognitive processes increasingly essential. Neurocognitive research supports this finding, showing that complex mathematical tasks activate the frontal-parietal brain network associated with cognitive control (Tschentscher & Hauk, 2016). Similarly, Grabner et al. (2009) reported that individuals with higher mathematical proficiency exhibit greater activation in brain regions associated with numerical processing.

From a neurocognitive perspective, the findings suggest that metacognition has a strong biological foundation. Brain imaging studies have identified the involvement of prefrontal and parietal regions in metacognitive monitoring and control processes (Menon et al., 2000). This indicates that metacognitive training may influence not only behavioral performance but also underlying neural mechanisms associated with learning.

Despite these contributions, several limitations must be acknowledged. First, this study employed a narrative review method, which may introduce selection bias. Second, the variability in research designs across the reviewed studies limits the comparability of findings. Third, differences in metacognitive measurement instruments may affect the consistency and validity of the results (Öztürk, 2020). Therefore, future research should consider using systematic review or meta-analytic approaches to provide more robust evidence.

In terms of generalizability, the findings of this study are applicable to secondary and higher education contexts, particularly in mathematics and science learning. However, the effectiveness of metacognitive strategies depends on several factors, including instructional design, teacher expertise, and learner characteristics. Consequently, the implementation of metacognitive training should be adapted to specific educational contexts.

From an implication perspective, this study contributes both theoretically and practically. Theoretically, it reinforces the role of metacognition as a central mechanism linking cognitive and affective aspects of learning. Practically, the findings suggest that integrating metacognitive strategies into instructional practices can enhance academic performance, promote learner autonomy, and support the development of higher-order thinking skills. At the policy level, the results highlight the importance of incorporating metacognitive training into teacher professional development programs and integrating technology-supported learning environments to foster 21st-century skills.

5. Limitations and future research

This study has several limitations that should be considered when interpreting the findings. First, the conclusions are based on a thematic synthesis of existing literature, making them dependent on the scope, quality, and methodological diversity of the reviewed studies. Second, variations in educational contexts, participant characteristics, and metacognitive intervention designs may have influenced the consistency of the reported outcomes. Third, the review primarily focused on mathematics education, limiting the generalizability of the findings to other disciplinary contexts.

Future research should conduct longitudinal and experimental studies to examine the causal mechanisms linking metacognition, self-efficacy, self-regulated learning, and academic performance. Further investigations are also needed to explore the effectiveness of specific metacognitive strategies across different educational levels, cultural settings, and mathematical domains. Additionally, research integrating educational technology and neurocognitive approaches may provide deeper insights into how metacognitive training can be optimized to support sustainable learning and higher-order thinking development.

6. Conclusion

This study confirms that metacognition plays a central role in enhancing mathematical learning outcomes by strengthening the relationship between cognitive abilities, self-efficacy, and self-regulated learning. The findings indicate that metacognitive training improves students' capacity to plan, monitor, and evaluate their thinking processes, leading to better problem-solving performance, more effective strategy use, and greater learning autonomy. Self-efficacy emerged as an important mediating factor, as increased metacognitive awareness was associated with higher confidence and learning engagement. The review also highlights that the effectiveness of metacognition is influenced by instructional and learner-related factors, emphasizing the need for context-sensitive implementation. Therefore, integrating explicit metacognitive strategies into mathematics instruction is recommended to foster higher-order thinking, independent learning, and sustainable academic achievement.

Author Contributions

Alexios Kouzalis: Conceptualization, methodology, investigation, data curation, formal analysis, visualization, writing—original draft, writing—review and editing.

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