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EXPLORING THE ROLE OF WORKING MEMORY AND COGNITIVE LOAD IN MATHEMATICS LEARNING : A SYSTEMATIC LITERATURE REVIEW

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Abstract

This study aims to explore the role of working memory and cognitive load in mathematics learning through a Systematic Literature Review (SLR) approach. This review was conducted to obtain a comprehensive understanding of how working memory capacity and cognitive load management influence mathematical thinking processes, conceptual understanding, and problem-solving performance. The SLR procedure refers to the PRISMA 2020 guidelines, which include the stages of identification, screening, eligibility, and inclusion. Article searches were conducted through the Scopus and Springer Nature Link databases, covering publications from 2015 to 2025. From the articles identified, six met the inclusion criteria and were analyzed thematically. The findings show that visuo-spatial working memory has a significant relationship with mathematical ability, particularly in the development of symbolic representation and problem-solving skills. Additionally, learning effectiveness is strongly influenced by instructional design that manages cognitive load, where strategies such as worked examples, scaffolding, and question-asking have been shown to reduce excessive cognitive load. This review highlights the importance of instructional approaches that consider students' working memory capacity and cognitive load regulation in order to achieve optimal mathematical understanding.

Keywords: Working Memory, Cognitive Load, Mathematics Learning

INTRODUCTION

Mathematics learning is a complex cognitive activity that requires students to process, store, and use information simultaneously when solving problems. This process demands structured thinking and effective information management within a limited mental capacity, which often leads students to experience difficulties when dealing with multi-step mathematical tasks (Allen et al., 2019). These difficulties become more apparent among students who encounter abstract and symbolic material, where the ability to maintain mental representations is crucial for successful learning (Macchitella et al., 2023). In relation to these challenges, students may also experience anxiety an affective response that arises when engaging in mathematical tasks, commonly characterized by feelings of fear, tension, or a tendency to avoid mathematics (He et al., 2025). Ideally, mathematics learning should foster meaningful conceptual understanding rather than mere procedural memorization. Under such ideal conditions, the learning process enables students to systematically process information, apply problem-solving strategies, and manage cognitive resources efficiently (Susanti et al., 2021). Moreover, effective learning should provide opportunities for students to reflect on their thinking processes so that they can articulate the reasoning behind the steps they take in solving problems (Menon, 2016). However, in reality, many students encounter barriers in solving mathematical problems due to limitations in working memory. Working memory capacity has a significant relationship with mathematical problem solving ability (Ji & Guo, 2023). Meanwhile, other studies have found that math anxiety can disrupt the functioning of working memory, thereby reducing students' performance on mathematical tasks (Finell et al., 2022). Working memory is a cognitive system that serves as a temporary storage space where information from perception, short-term memory, and long-term memory interacts and is processed before being used in thinking activities (Anjariyah et al., 2020). Research exploring the relationship between working-memory components and specific aspects of mathematics remains limited, as most studies focus on the general relationship between working memory and overall mathematical ability (Allen & Giofrè, 2021). These obstacles are often triggered by learning conditions that impose an excessively high cognitive load. Cognitive load also arises when the instructional strategies used by teachers lack variation (Nasution & Fadilah, 2024). When material is presented without proper organization and reduction of complexity, students' working-memory capacity becomes overloaded, resulting in suboptimal information processing (Richardo & Cahdriyana, 2021). Furthermore, the lack of learning strategies that support metacognitive monitoring makes it difficult for students to manage cognitive demands when solving mathematical problems (Alin Sholihah, 2022). The concept of cognitive load was introduced by Sweller to describe the conditions of storing and processing information in human memory when facing a task or complex situation (Lavy & Shriki, 2023). Materials with high element interactivity demand greater cognitive resources and thus generate higher cognitive load, and vice versa (Ngu et al., 2025).

To address these issues, instruction should be designed based on Cognitive Load Theory, which emphasizes the importance of managing information load through material segmentation, the use of visual representations, and the provision of scaffolding as needed (R. P. Kurniawati et al., 2018). In addition, working-memory training within mathematics instruction can improve students' information-processing capacity in problem-solving tasks (Sala & Gobet, 2020). Several previous studies have examined the relationship between working memory and mathematical ability. Ji and Guo (2023) demonstrated that working memory plays a crucial role in solving mathematical problems. Meanwhile, the study Visuo-Spatial Working Memory and Mathematical Skills in Children (2022) emphasized that the visuospatial component strongly contributes to understanding geometric representations and visual symbols. Additionally, Finell et al. (2022) found that anxiety can mediate the relationship between working memory and mathematical performance. These findings are supported by Eriksen et al. (2023), who showed a significant relationship between visuospatial working memory and mathematical competence among school-age children.

Nevertheless, these studies mainly focus on direct relationships between variables and there remains a lack of research synthesizing comprehensive insights into how working memory interacts with cognitive load within mathematics learning. Furthermore, no systematic review has mapped research findings based on instructional design perspectives, students' psychological conditions, and the cognitive demands of mathematical content. Therefore, this study aims to systematically explore the roles of working memory and cognitive load in mathematics learning through a Systematic Literature Review approach. This research is important for providing an in-depth understanding of the relationship between these two cognitive aspects and their implications for effective instructional design. The review is also expected to offer an empirical foundation for developing mathematics learning strategies that support optimal cognitive processing and enhance the quality of student learning outcomes.

LITERATURE REVIEW

Working memory is a crucial cognitive system that enables individuals to temporarily store and manipulate information during thinking processes. In the context of mathematics learning, the visuo-spatial component of working memory (VSWM) has received particular attention, as this capacity is closely related to processing visual representations and manipulating symbolic information commonly found in mathematical tasks (Allen et al., 2019). Research has shown that working memory capacity correlates positively with mathematics performance; however, this relationship is complex and depends on the specific WM component assessed and the type of assessment instrument used (Allen & Giofrè, 2021).

Neurocognitive studies further emphasize that limitations in VSWM represent a significant predictor of mathematical learning difficulties, especially for tasks requiring the maintenance of visual-spatial representations and multi-step manipulation (Menon, 2016). The role of each WM component also shifts with age and learning experience; VSWM tends to become increasingly dominant in mathematical skills involving spatial representation from late elementary school onward (Macchitella et al., 2023). Nonetheless, the literature indicates the need for more specific studies to map the contributions of each WM component to different mathematical subdomains (e.g., arithmetic, geometry, algebra) and to explore the moderating influences of age and educational background (Ji & Guo, 2023).

Sweller claims the concept of cognitive load refers to the burden placed on an individual's cognitive processing capacity when completing complex tasks (Lavy & Shriki, 2023). Cognitive load is typically categorized into three types: intrinsic (stemming from the inherent complexity of the material), extraneous (caused by suboptimal instructional design), and germane (related to schema construction). Instructional designs that fail to reduce extraneous load can overwhelm working memory and reduce the effectiveness of mathematics learning (Richardo & Cahdriyana, 2021).

Instructional interventions such as the use of worked examples have been shown to effectively reduce extraneous cognitive load, particularly for students with low prior knowledge. However, the expertise reversal effect suggests that such strategies become less effective or even counterproductive for high-knowledge students, who benefit more from independent problem-solving (Ngu et al., 2025). Other strategies such as gradual scaffolding, material segmentation, and questioning (self-questioning) have been reported to support information organization and concept internalization, although their effectiveness depends on the alignment between the complexity of the material and students' prior knowledge (N. Kurniawati, 2018).

METHOD

Type and Research Design

This study is a qualitative research employing a Systematic Literature Review (SLR) approach aimed at identifying, evaluating, and synthesizing previous research findings that discuss the role of working memory and cognitive load in mathematics learning. This approach is used to obtain a comprehensive overview of empirical patterns, research trends, and existing gaps in the field of mathematics education (Mengyao et al., 2025). SLR was selected because it enables the development of a valid, transparent, and replicable knowledge map, following the PRISMA guidelines commonly used in educational and psychological research. A Systematic Literature Review (SLR) can provide a synthesized understanding of the state of knowledge within a particular field (Page et al., 2021). The PRISMA approach also facilitates a more structured investigative process by identifying key components of non-quantitative research questions (Betty & Mohamad Nasri, 2023). PRISMA is further recognized as a set of guidelines for systematic reviews that emphasizes transparency and reproducibility (Fukaya et al., 2025). The data collection technique in this study involved article searches through online databases (Richardo & Cahdriyana, 2021). The databases used in this research were Scopus and Springer Nature Link.

Inclusion and Exclusion Criteria

Articles included in this review met the following inclusion criteria :

1. Empirical research articles or systematic reviews published in Scopus-indexed journals and Springer Nature Link.
2. Research focusing on the relationship between students' perceptions and learning interest in the context of mathematics learning.
3. Research populations involving elementary, secondary, vocational school students, university students, and learners with special needs.
4. Articles available in full-text and written in English.

Meanwhile, the exclusion criteria included :

1. Articles that only discuss mathematics learning outcomes without involving perception-related variables.
2. Non peer reviewed publications such as conference reports or editorials.
3. Articles that do not clearly present their research methods.

Article Selection Process

The article selection procedure in this study followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidelines. This SLR process refers to the PRISMA model, consisting of four main stages: identification, screening, eligibility, and inclusion (Mohamed et al., 2020). At the identification stage, the researchers expanded and adjusted the keywords to obtain more comprehensive and relevant articles from various databases. The screening stage was then conducted by reviewing initial search results to remove articles that did not meet basic criteria, such as inappropriate publication types or irrelevant topics. Next, at the eligibility stage, the remaining articles were examined more thoroughly by reading the titles, abstracts, methods, results, and discussions to ensure alignment with the research focus and objectives. The final stage, inclusion, involved selecting only those articles that fully met all criteria and demonstrated strong relevance to be used as primary sources for analysis in this review. This design ensures that the article search and selection process is carried out systematically and objectively. Each stage was documented in a flow diagram to illustrate the number of articles filtered at each step. The flowchart of the article selection process is presented as follows:

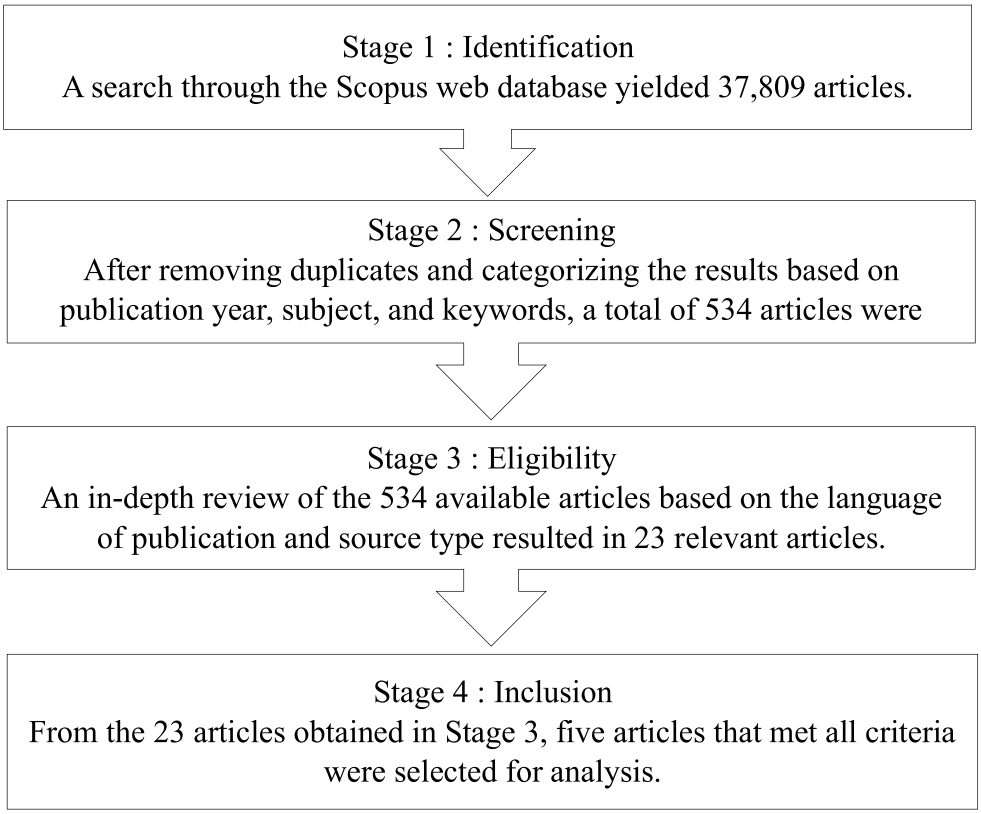

Image 1 : Flowchart of the article selection process

RESULTS AND DISCUSSION

The results of the article search process based on the inclusion criteria yielded studies that were appropriate and relevant to the focus of this research. This section presents a synthesis of findings from six articles that met the inclusion criteria in the Systematic Literature Review. The analysis process was conducted by examining the research objectives, methodology, samples, instruments used, and the main findings of each study. Emphasis is placed on how each study explains the role of working memory and cognitive load in mathematics learning, whether in the context of problem-solving ability, conceptual understanding, or instructional strategies used by teachers. To facilitate readability and comparison across studies, the review findings are summarized in an SLR table that outlines the key components of each analyzed study as follows :

No.	Author and Year	Research Title	Indexing	Method and Sample	Findings
1	Allen, Katie et. al (2019)	The Relationship between Visuospatial Working Memory and Mathematical Performance in School-Aged Children: a Systematic Review	Scopus and Springer Nature Link	Systematic Literature Review	Research on the relationship between visuospatial working memory (VSWM) and mathematics performance is still in its early developmental stage. The review results indicate a significant effect of using standardized mathematical assessment instruments, although no clear influence was found regarding the type of VSWM or the type of mathematical ability measured on the magnitude of the effect size. Overall, the obtained

					effect sizes are positive, indicating a positive relationship between VSWM and mathematics performance.
2	Macchitella, L et. Al (2023)	Visuo-Spatial Working Memory and Mathematical Skills in Children: A Network Analysis Study	Scopus	Network Analysis Approach	The purpose of this study was to investigate the relationship between various components of visuo-spatial working memory and several mathematical abilities in a sample of Italian children from third to fifth grade in elementary school. To analyze the relationships between the components of visuo-spatial working memory and different mathematical abilities, a Network Analysis (NA) approach was used. The results indicate that some, but not all, components of visuo-spatial working memory are related to certain specific mathematical abilities.
3	Menon, V (2016)	Working memory in children's math learning and its disruption in dyscalculia	Scopus	Theoretical Review	Working memory plays an important role in the development of mathematical abilities, both in the formation of number knowledge and in problem-solving skills. The role of each component changes according to task complexity and cognitive development, with visuo-spatial working memory becoming increasingly dominant with age. Limitations in this component have been shown to be a risk factor for mathematical learning difficulties, and therefore need to be considered in the design of instruction and interventions.
4	Ngu, Bing Hiong et. Al (2025)	Can Correct and Incorrect Worked Examples Supersede Worked Examples and Problem-Solving on Learning Linear Equations? An Examination from Cognitive Load and Motivation Perspectives	Scopus	Experimental research	The use of worked examples has been proven to reduce extraneous cognitive load and is more effective for students with low prior knowledge, whereas for students with high prior knowledge an expertise reversal effect occurs, in which independent problem solving becomes more efficient. Meanwhile, the incorrect worked examples approach (CICWEs) does not provide significant advantages in cognitive load or learning outcomes compared to

					other methods.
5	Ilana Lavy and Atara Shriki (2023)	On Reading Mathematical Texts, Question-Asking and Cognitive Load	Scopus	Quasi Experimental	This quasi-experimental study shows that engaging in question-posing activities while reading historical mathematics texts can significantly reduce cognitive load compared to instruction without such activities. In addition, the questioning strategy helps with the assimilation of new information, although its effectiveness depends on the alignment between students' prior knowledge and the complexity of the material being learned.

Table 1. Articles retrieved from searches in the Scopus and Springer Nature Link databases

The Role of Working Memory in Mathematics Learning

The review findings indicate that working memory (WM), particularly visuo-spatial working memory (VSWM), plays a significant role in mathematics learning. Allen et al. (2019) emphasize that VSWM has a positive relationship with mathematical performance, although research in this field continues to develop. This relationship does not depend on the type of mathematical ability assessed but rather on the use of standardized assessment instruments, suggesting that working memory capacity can influence the consistency of mathematics learning outcomes. Research by Macchitella et al. (2023) further strengthens this conclusion by highlighting that not all VSWM components contribute equally to mathematical ability, indicating that the connection between WM and mathematics is specific to the type of skills being developed. Similarly, Menon (2016) explains that the role of WM in mathematics develops progressively: at early stages, WM supports number concept understanding, whereas in later stages, it contributes to solving complex mathematical problems. Additionally, neuroimaging findings discussed by Menon show that weaknesses in VSWM are among the primary causes of mathematics learning difficulties, making working memory a critical cognitive factor that must be considered in instructional design. Collectively, these studies suggest that working memory not only affects students' ability to interpret mathematical symbols and representations but also shapes the development of thinking strategies, especially during the elementary to secondary school years.

The Role of Cognitive Load in Mathematics Learning

In addition to working memory capacity, cognitive load plays an essential role in determining the success of mathematics learning. Ngu et al. (2025) found that the use of worked examples can help reduce extraneous cognitive load and enhance learning performance, particularly for students with low prior knowledge. However, as students' prior knowledge increases, independent problem-solving strategies become more effective—a phenomenon known as the expertise reversal effect. These findings suggest that instructional strategies must be aligned with students' ability levels to prevent excessive working memory load. Meanwhile, the study by Lavy & Shriki (2023) reveals that self-questioning while reading mathematical texts significantly reduces cognitive load over time. This activity helps students organize information and improves concept internalization. However, the effectiveness of this strategy is limited by the gap between students' prior knowledge and the complexity of the material. If the gap is too large, the questions students generate may instead increase cognitive load. Both studies confirm that managing cognitive load through instructional design is essential in mathematical learning, where the primary goal is not merely to simplify material but to align cognitive demands with students' working memory capacities.

Synthesis of Research Findings

Taken together, the findings suggest that working memory and cognitive load are two interrelated cognitive mechanisms in mathematics learning. The limited capacity of working memory forms the foundational constraint on mathematical information processing, while instructional design determines the degree of cognitive load students must manage during learning.

Working memory functions as the basis for understanding and problem-solving, particularly in visual representation and symbolic manipulation. Meanwhile, appropriate instructional approaches can optimize WM usage by minimizing irrelevant cognitive load. Thus, effective mathematics learning should :

1. Provide clear visual representations.
2. Use worked examples adaptively.
3. Encourage metacognitive strategies such as questioning and self-reflection.

The integration of these two aspects helps students develop deeper mathematical understanding and reduces the risk of learning difficulties, especially for students with low working memory capacity.

CONCLUSION

Based on the analysis of the studies included in this review, it can be concluded that working memory and cognitive load play crucial and interconnected roles in the process of mathematics learning. Working memory particularly the visuo-spatial component serves as a fundamental basis for understanding number concepts, performing symbolic representations, and solving mathematical problems. Limited working memory capacity directly affects students' ability to process mathematical information, placing students with weaker WM at higher risk of experiencing difficulties in learning mathematics. Meanwhile, cognitive load determines how effectively information can be processed within working memory. Excessive cognitive load whether due to material complexity or inappropriate instructional design can hinder concept internalization. Instructional strategies such as worked examples, scaffolding, question-asking activities, and step-by-step structured instructions have been shown to reduce extraneous cognitive load and enhance information processing efficiency. However, the effectiveness of these strategies must be tailored to students' prior knowledge, as explained through the expertise reversal effect. Therefore, the success of mathematics learning depends not only on content delivery but also on aligning cognitive demands with students' working memory capacities. Teachers must implement instructional designs that support optimal working memory and cognitive load management. These findings highlight the importance of integrating cognitive psychology perspectives into mathematics teaching practices, including curriculum development, learning media design, and classroom instructional strategies.

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