Volume 1 | Nomor 1 | Maret 2026

Integrating Cognitive Load Theory and Embodied Cognition to Enhance Mathematics Learning

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Abstract

This study analyzes the integration of psychological aspects in mathematics learning through Cognitive Load Theory (CLT) and embodied cognition as strategic efforts to reduce cognitive burden and improve students' learning performance. The research employs a narrative literature review approach by examining scientific sources relevant to instructional design, cognitive function, physical activity, and their implications in mathematics learning. The findings indicate that managing intrinsic, extraneous, and germane cognitive load contributes to more effective information processing and concept comprehension. Furthermore, sensorimotor engagement through physical activities, gestures, and object manipulation strengthens cognitive representation and supports understanding of abstract mathematical concepts. The integration of CLT and embodied cognition creates a complementary instructional framework: CLT structures information to prevent overload, while embodied cognition enhances schema construction through physical interaction. This review provides a theoretical foundation for developing mathematics learning designs that balance cognitive management with sensorimotor experiences, resulting in more meaningful, adaptive, and effective learning.

Keywords: *narrative literature review, cognitive load theory, embodied cognition, physical activity, mathematics learning.*

Introduction

Mathematics learning in schools often faces challenges related to the high cognitive load students experience when dealing with complex and abstract concepts. Excessive cognitive load can limit students' working memory capacity, making it difficult for them to process information and connect new concepts with prior knowledge. This condition reduces the effectiveness of instruction, lowers motivation, and affects academic performance. Cognitive Load Theory (CLT), as proposed by Sweller (2010; 2011), argues that instructional design must consider the limitations of working memory by managing three types of cognitive load: intrinsic, extraneous, and germane (Kirschner et al., 2018). The management of these components is essential in creating efficient and meaningful mathematics learning.

Alongside developments in cognitive science, recent research shows that physical activity and sensorimotor experience have a strong relationship with memory, focus, and executive function, all of which are crucial for mathematical problem-solving (Chang et al., 2012; Diamond & Ling, 2016; Schmidt et al., 2017). The embodied cognition perspective emphasizes that thinking is not solely a mental process but is shaped by the interaction between body, mind, and environment (Castro-Alonso et al., 2019). In the context of mathematics learning, physical engagement such as gestures, movement, and object manipulation, can strengthen mental representation and support the understanding of abstract concepts (Cook et al., 2008; Alibali & Nathan, 2012). The integration of CLT and embodied cognition provides a complementary approach: CLT guides the structuring of information to prevent cognitive overload, while embodied cognition offers sensorimotor reinforcement to deepen conceptual understanding. This synergy enables learning designs that are cognitively efficient, physically engaging, and aligned with students' natural learning processes.

Based on this background, this article aims to analyze the integration of psychological and physical activity aspects in mathematics learning through a *Narrative Literature Review* referring to studies related to cognitive load and embodied cognition. The results of this review are expected to provide a theoretical foundation for educators, researchers, and curriculum developers in designing mathematics instruction that reduces unnecessary cognitive load while enhancing comprehension and learning outcomes.

Method

This study employs a *Narrative Literature Review* approach to examine the integration of psychological aspects in mathematics learning through Cognitive Load Theory (CLT) and embodied cognition. This approach was selected because it allows for conceptual synthesis, thematic interpretation, and identification of theoretical relationships across existing literature. Unlike systematic reviews that rely on rigid procedural selection, the narrative review emphasizes analytical depth, thematic relevance, and critical interpretation of sources used in the discussion.

The literature analyzed in this study consists of journal articles, books, and empirical research reports focusing on cognitive load management, the relationship between physical activity and cognitive function, and the implementation of embodied cognition in mathematics education. Key references include foundational CLT works by Sweller (2010; 2011), Kirschner et al. (2018), and Paas et al. (2003), as well as embodied cognition studies by Alibali & Nathan (2012), Castro-Alonso et al. (2019; 2021), and

Cook et al. (2008). The selection of literature used a purposive sampling technique to ensure alignment with the research scope and the relevance of the theoretical contributions to the discussion.

Data analysis followed three stages. First, literature mapping, which involved categorizing studies into thematic clusters: (1) cognitive load in mathematics learning, (2) physical activity and executive function development, and (3) embodied cognition in instructional design. Second, conceptual and thematic synthesis, which identified patterns, theoretical intersections, and conceptual links across the reviewed literature. Third, interpretative analysis, which connected CLT and embodied cognition to explain how instructional design can reduce cognitive overload and support deeper conceptual understanding through sensorimotor engagement.

Through this narrative review approach, the study provides a comprehensive theoretical foundation for integrating cognitive and physical dimensions in the design of mathematics learning. This method supports the development of pedagogical strategies that align with cognitive principles while utilizing sensorimotor experiences to enhance learning outcomes.

Results and Discussion

3.1. Cognitive Load in Mathematics Learning

Mathematics learning presents a high level of complexity because students are required to process abstract and conceptual information simultaneously. This complexity increases when students are confronted with symbols, algorithms, procedural steps, and visual representations that must be understood at the same time. According to Cognitive Load Theory (CLT), these difficulties occur because the capacity of human working memory is limited; therefore, when the incoming information exceeds this capacity, the learning process becomes suboptimal (Sweller, 2010; 2011). In this context, student difficulties are not solely caused by low ability, but rather by cognitive load that is not properly managed during the learning process.

CLT explains that cognitive load consists of three components: intrinsic load, extraneous load, and germane load (Kirschner et al., 2018).
First, intrinsic load is related to the inherent difficulty of the mathematical content itself, such as limit, integral, or geometric transformation concepts, which contain interdependent units of information. In complex material, the number of information elements that students must process increases naturally, raising intrinsic load. Teachers need to simplify task structures, sequence concepts gradually, and group information elements so they do not exceed students' cognitive capacity.

Second, extraneous load arises from ineffective presentation of the material, such as unclear instructions, excessive explanations, or confusing visual displays. Extraneous load does not contribute to learning and instead interferes with information processing. This occurs when instructional materials are unfocused, contain distracting elements, or use learning media that are not well aligned with learning objectives (Mayer & Moreno, 2003).

Third, germane load refers to positive cognitive effort associated with building schemas, organizing information, and internalizing concepts into long-term memory (Paas et al., 2003). This type of load should be optimized through learning activities that promote knowledge construction such as problem-solving, conceptual reflection, and mathematical discussion.

In the context of mathematics learning, these three types of load interact and influence students' thinking processes. When extraneous load exceeds germane load, students are likely to experience cognitive overload, which inhibits conceptual understanding. Conversely, when intrinsic load is well managed and germane load is strengthened through appropriate instructional design, the internalization of mathematical concepts can occur more effectively. Therefore, teachers' responsibilities extend beyond providing information; they must also structure the flow of information so that it aligns with students' cognitive capacity.

Thus, effective mathematics learning requires strategic management of cognitive load. This regulation becomes an essential foundation before integrating further approaches, such as physical activity and embodied cognition, which not only support conceptual understanding but also enhance students' cognitive capacity to process mathematical information more adaptively.

3.2. Strategies for Managing Cognitive Load

Managing cognitive load is a crucial aspect of designing effective mathematics instruction. Cognitive Load Theory emphasizes that learning becomes optimal when extraneous load is minimized, intrinsic load is moderated, and germane load is maximized to support schema construction (Sweller, 2010; Kirschner et al., 2018). Therefore, instructional strategies must balance these components through structured, purposeful learning design aligned with students' cognitive capacity.

First, intrinsic load can be regulated by simplifying complex material through sequencing information and segmenting tasks. In mathematical topics with high element interactivity such as limits, algebraic manipulation, and geometric transformations, teachers can break down concepts into smaller units, present content from concrete to abstract, and provide representative examples before generalization. This helps students process information step by step without overloading working memory (Sweller, 2011).

Second, extraneous load can be reduced by using instructional designs that eliminate irrelevant cognitive demands. Clear directions, concise explanations, and visual representations that directly support the lesson objectives help avoid distraction. This aligns with multimedia design principles such as coherence, signaling, and modality proposed by Mayer & Moreno (2003), ensuring that attention is focused on essential information rather than unnecessary details.

Third, germane load can be increased by engaging students in cognitive activities that stimulate schema development, such as collaborative learning, reflective practice, and problem-solving tasks. The *collective working memory effect* in group learning allows students to share cognitive responsibility, reducing individual processing demands and creating space for deeper conceptual thinking (Kirschner et al., 2018). This shift supports long-term retention and conceptual understanding.

Through these strategies, mathematics learning becomes cognitively efficient and meaningful. Proper management of cognitive load is essential before incorporating physical activity and embodied cognition approaches so that learning experiences remain aligned with cognitive principles rather than becoming additional mental burden.

3.3. The Role of Physical Activity in Supporting Cognitive Function

Physical activity plays a significant role in supporting the cognitive processes required for mathematics learning. Research in neuroscience and educational psychology indicates that engaging in coordinated physical movement increases brain oxygenation, enhances neural activation, and improves executive functions such as working memory, attention control, and cognitive flexibility (Chang et al., 2012; Diamond & Ling, 2016). These executive functions are fundamental to students' ability to solve mathematical problems that demand sustained focus and reasoning.

Activities that involve complex motor coordination provide greater cognitive benefits than repetitive, low-engagement movements. For example, motor tasks requiring spatial awareness, direction changes, or decision-making stimulate the brain to regulate attention and memory simultaneously (Schmidt et al., 2017). Moreover, structured physical activity programs in school such as task-based movement, object manipulation, and kinesthetic learning routines have been shown to correlate positively with academic performance in mathematics (Castelli et al., 2007; Reed et al., 2010).

Thus, physical activity should not be viewed as a separate or optional component of classroom practice but as a cognitive tool that prepares students for learning. When aligned with instructional goals, physical engagement can reduce the cognitive burden of purely abstract instruction and create readiness for deeper conceptual processing.

3.4. Embodied Cognition in Mathematics Learning

Embodied cognition posits that thinking and learning are shaped not only by mental processes but also by bodily interaction with the environment. In mathematics learning, this means that students' gestures, body movements, and manipulation of physical objects play a direct role in conceptual formation (Castro-Alonso et al., 2019). Understanding moves beyond symbolic manipulation when supported by sensory–motor experience that creates concrete anchors for abstract reasoning.

Gestures have been shown to enhance long-term retention and strengthen schema internalization (Cook et al., 2008). Similarly, performing physical actions can compensate for limitations in visual working memory, allowing students to dedicate cognitive resources to reasoning rather than holding information mentally (Pouw et al., 2016). Practical examples include using hand movements to demonstrate algebraic transformation, walking along number lines to understand sequences, or manipulating geometric solids to visualize spatial relationships (Alibali & Nathan, 2012).

These embodied practices function as cognitive scaffolds. They help students transition from concrete experience to abstract representation, making mathematical concepts more intuitive and mentally accessible.

3.5. Integrating Cognitive Load Theory and Embodied Cognition

Integrating Cognitive Load Theory and embodied cognition creates a complementary pedagogical framework that optimizes mathematics learning. CLT ensures that instructional design does not overwhelm working memory, while embodied cognition strengthens understanding through sensory–motor engagement. Together, they reduce unnecessary mental effort, prevent overload, and enhance conceptual depth (Sweller, 2010; Castro-Alonso et al., 2019).

Physical engagement redistributes cognitive processing by shifting part of the mental load to bodily activity, thus freeing cognitive capacity for reasoning (Pouw et al., 2016). This alignment produces a learning environment that is simultaneously efficient and meaningful, students receive information in manageable cognitive units, while embodied interaction enriches schema formation. Through this integration, mathematics learning becomes adaptive to natural cognitive functioning rather than forcing students to process abstract ideas without support. This approach offers a direction for future classroom practices that merge cognitive design with physical engagement to achieve improved learning outcomes.

Conclusion

Mathematics learning requires effective cognitive regulation because students must process abstract concepts, symbolic representations, and procedural information simultaneously. Cognitive Load Theory (CLT) provides a foundational framework for managing these challenges by emphasizing the regulation of intrinsic, extraneous, and germane cognitive load. Through well-structured instructional design, cognitive overload can be reduced, allowing students to allocate working memory capacity more efficiently toward conceptual understanding and problem-solving.

Meanwhile, the embodied cognition perspective expands the instructional framework by recognizing the role of physical experience, gestures, and sensorimotor interaction in developing conceptual knowledge. Physical activity supports executive functions such as working memory, attention, and cognitive flexibility, which are essential for mathematical reasoning. When students engage in movement-based learning, manipulation of objects, or gesture-supported explanations, they build mental representations that strengthen long-term comprehension.

The integration of CLT and embodied cognition creates a complementary and holistic learning approach. CLT ensures that information is organized to support cognitive efficiency, while embodied cognition reinforces understanding through physical interaction and sensory engagement. Together, these approaches provide a theoretical and practical foundation for developing mathematics learning designs that are cognitively manageable and experientially meaningful. This integrated framework has the potential to improve learning outcomes, reduce cognitive strain, and create learning environments that align with students' natural cognitive processes.

Future research is recommended to explore practical classroom implementation through experimental or classroom action research designs, as well as the development of instruments that measure cognitive load and cognitive performance within movement-based mathematics learning. Such efforts will provide empirical reinforcement for the theoretical integration presented in this study.

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