International Journal of Advanced and Applied Sciences, 12(4) 2025, Pages: 164-172

Contents lists available at Science-Gate

International Journal of Advanced and Applied Sciences

Journal homepage: http://www.science-gate.com/IJAAS.html

The impact of visual and multimodal representations in mathematics on cognitive load and problem-solving skills

Marthinus Yohanes Ruamba, Yohanes Leonardus Sukestiyarno *, Rochmad Rochmad, Tri Sri Noor Asih

Faculty of Mathematics and Natural Science, Semarang State University, Semarang, Indonesia

ARTICLE INFO

Article history:
Received 30 November 2024
Received in revised form
6 April 2025
Accepted 25 April 2025

Keywords:
Cognitive load reduction
Multimodal learning
Mathematics education
Visual representations
Problem-solving skills

ABSTRACT

This study investigates how visual and multi-modal representations can reduce cognitive load and enhance problem-solving skills in mathematics. Through a systematic literature review following the PRISMA methodology, we analyzed studies (2014–2023) on the effects of visual, symbolic, and interactive representations in supporting mathematical understanding. Findings reveal that digital tools and multi-modal approaches significantly improve students' grasp of abstract concepts while increasing engagement and motivation. The study emphasizes adapting instructional design to learners' cognitive needs across educational levels, advocating for interactive strategies to strengthen critical thinking and retention. Future research should explore long-term impacts and extend to diverse cultural and educational contexts.

1. Introduction

Mathematical representations have long played a pivotal role in fostering students' understanding of abstract concepts. These representations—whether visual, symbolic, or verbal—help bridge the gap between theoretical constructs and practical applications. Visual representations, in particular, enable students to process complex information more intuitively, while multimodal approaches combine different formats to encourage critical thinking and deeper analysis (Ainsworth, 2014). Advances in technology have further amplified the potential of these methods. Tools such as interactive graphs and simulations now allow learners to explore mathematical concepts dynamically, reducing cognitive load and enhancing motivation (Fischer et al., 2013; Sweller, 2020).

Recent studies emphasize the benefits of multimodal representations in improving problem-solving skills and memory retention. Cognitive Load Theory (Sweller, 1988) and Dual Coding Theory (Paivio, 1990) serve as foundational frameworks, illustrating how combining visual and verbal elements engages multiple cognitive channels to facilitate understanding. For example, graphs and diagrams have been shown to clarify relationships between variables, simplifying problem-solving processes (Schnotz and Kürschner, 2007).

Despite these advances, significant gaps remain in applying these strategies to technologically constrained environments, particularly in developing countries. While research in developed nations has extensively explored Cognitive Load and Dual Coding theories, their practical application in resource-limited settings is still underrepresented. This study addresses this gap by proposing a multimodal instructional model tailored for pre-service teacher training programs, accounting for both infrastructure limitations and diverse educational contexts. Through a systematic literature review, this article synthesizes global insights and offers actionable recommendations for inclusive instructional design.

Research also highlights the role of multimodal approaches in optimizing mental concept construction and problem-solving skills. For instance, Sweller (1988) demonstrated that visual aids effectively reduce intrinsic cognitive load in complex mathematical tasks. Similarly, Paas et al. (2003) revealed that multimodal strategies enhance problem-solving capabilities by alleviating extrinsic cognitive load, particularly for visually oriented learners. Recent findings by Liu et al. (2024) underscored the importance of inter-modal connectivity in fostering conceptual understanding, further validating the efficacy of these approaches. The implications of this research extend beyond

* Corresponding Author.
Email Address: sukestiyarno@mail.unnes.ac.id (Y. L. Sukestiyarno)
https://doi.org/10.21833/ijaas.2025.04.018
Corresponding author's ORCID profile:
https://orcid.org/0000-0003-2377-5872

academic settings. Multimodal representations not only simplify abstract concepts but also cultivate critical thinking and analytical skills essential for professional success (Debrenti, 2024). By integrating visual, verbal, and symbolic elements, these strategies align with the demands of modern workplaces, where problem-solving and adaptability are paramount (Moreno and Mayer, 2007).

Although prior studies highlight the benefits of multimodal instruction, most focus on general applications of cognitive theories without delving into specific instructional designs or skills optimization. This study contributes to bridging that gap, offering targeted solutions for enhancing mathematics education in diverse and resource-constrained settings. Based on the problems above, the research questions that need to be answered through research are:

1. How can visual and multi-modal representations reduce the cognitive load of prospective teachers in understanding the mathematical concepts they will teach?
2. How does the use of multi-modal representations influence preservice teachers' mathematical problem-solving skills in the context of teaching preparation?
3. Can the integration of digital devices using multi-modal representations enhance student-teacher motivation and engagement in mathematics learning?

Based on the above research questions, this study aims to examine the impact of visual and multi-modal representations on cognitive load and problem-solving skills in mathematics education, focusing on current trends and research gaps that can still be explored. This study uses a systematic literature review to evaluate the effects of visual and multi-modal representations in mathematics education on cognitive load and problem-solving skills. This process follows a systematic approach (Xiao and Watson, 2019) and uses PRISMA-P, NVivo for qualitative analysis, and Excel for data management. The reviewed articles were retrieved from Scopus, Web of Science, and ERIC between 2014-2023, thus covering the latest developments in the field. These databases were selected due to their coverage of relevant and high-quality literature, with Scopus and Web of Science widely known for their interdisciplinary coverage, while ERIC has a specific focus on education (Mongeon and Paul-Hus, 2016). Through this approach, this study successfully reflects the current understanding of how visual and multi-modal representations can optimize mathematical understanding by reducing cognitive load and improving students' problem-solving skills (Ceulemans et al., 2015).

2. Materials and methods

2.1. Study design and overview

This study used a Systematic Literature Review (SLR) approach to screen, identify, and analyze literature on the impact of visual and multimodal representations in mathematics learning, specifically focusing on cognitive load and problem-solving skills. The SLR approach follows a structured procedure to ensure transparency and replicability in the literature analysis, thereby increasing the validity of the study results.

2.2. Systematic review framework

This SLR follows the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework, which includes the stages of article identification, screening, eligibility, and inclusion. The PRISMA flowchart illustrates the article selection process, from initial search to final analysis, thus increasing clarity and reliability in presenting the selection process. Fig. 1 shows the process of selecting scientific publications for a systematic review.

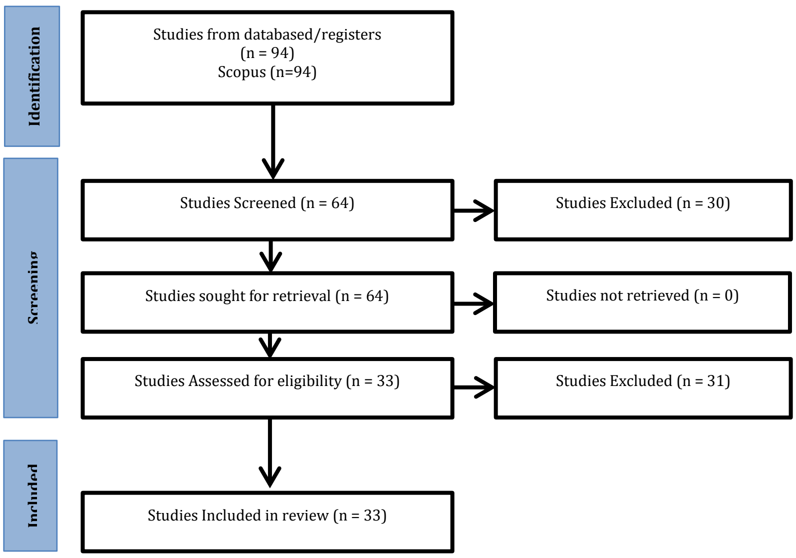

Fig. 1: Illustration of data collection with PRISMA diagram

2.3. Quality assessment

To ensure the validity and reliability of the selected studies, a quality assessment was conducted using the CASP (Critical Appraisal Skills Program) checklist. The assessment evaluated key aspects such as methodological rigor, clarity of data analysis, and relevance to the research questions. Studies that did not meet the minimum quality threshold were excluded.

The results of the quality assessment are summarized in Table 1. Each article was rated on three criteria (methodological rigor, data analysis, and relevance), with an overall score calculated to determine inclusion.

2.4. Keyword identification and search strategy

Keywords such as "visual representation," "symbolic representation," "multimodal mathematics," and "cognitive load in mathematics" were used in the search in leading databases such as Scopus, Web of Science, and IEEE Xplore. Boolean operators (AND, OR) were used to broaden or narrow the search results, ensuring comprehensive yet relevant literature coverage.

2.5. Inclusion and exclusion criteria

Inclusion criteria targeted peer-reviewed articles from 2014 to 2024 that examined visual and multimodal representations in mathematics education. Articles that lacked a clear methodology or failed to measure cognitive impact or problem-solving skills were excluded to maintain the quality and relevance of the review results (Liberati et al., 2009).

2.6. Data extraction and synthesis

Data extraction involved a standardized form that recorded the methodology, sample, results, and key findings of each study. Thematic analysis was conducted to identify key patterns related to the impact of visual and multimodal representations on students' cognitive load and problem-solving skills (Thomas and Harden, 2008).

Table 1: Quality assessment summary

Reference	Methodological rigor	Data analysis	Relevance	Overall score
Naseem et al. (2023)	High	Comprehensive	High	4.7/5
Kaur et al. (2024)	Medium	Good	Moderate	3.9/5
Asmara et al. (2024)	High	Strong	High	4.5/5
Wang et al. (2013)	Medium	Moderate	Moderate	3.7/5
Maries And Singh (2023)	High	Robust	High	4.5/5
Sirock et al. (2023)	Medium	Advanced	Medium	3.5/5
Hahn and Klein (2023)	High	Comprehensive	High	4.7/5
Ayabe et al. (2022)	Medium	Satisfactory	High	4.0/5
Saha et al. (2022)	High	Rigorous	High	4.8/5
Yan et al. (2020)	High	Comprehensive	Highly relevant	5/4
Xian and Tian (2019)	Medium	Robust	Moderately relevant	4/5
Ngu (2019)	High	Detailed	Highly relevant	5/5
Choi et al. (2019)	High	Moderate	Relevant	4.5/5
van Lieshout and Xenidou-Dervou (2018)	Medium	Adequate	Moderately relevant	4/5
Sheridan et al. (2017)	Well	Advanced	High relevance	4/5
Attout et al. (2017)	Moderate	Strong	Relevant	3/5
Hardman et al. (2017)	High rigor	Advanced	Strong	3/5
Richland et al. (2016)	Strong	Advanced	Highly	4/5
Maboudi et al. (2015)	Moderate	Advanced	Relevant	3/5
Bennett and Stark (2016)	High	Advanced	Highly	4.5/5
Luzón and Letón (2015)	Medium	Advanced	Relevant	3.5/5
McCrink and Galamba (2015)	High	Advanced	Relevant	4.5/5
Reisslein et al. (2014)	Medium	Advanced	Relevant	4/5
Palmisano et al. (2014)	High	Advanced	Directly relevant	4./5
Waisman et al. (2014)	Rigorous	Strong	Highly relevant	4.5/5

3. Results and discussion

3.1. Research article trends

The trend of publication of research articles on this topic in leading international journals from 2014 to 2024 shows significant variation, with a fluctuating pattern reflecting the dynamics of academic research output. In 2014, two articles were published, with a slight increase to three in 2015. Despite a slight decrease, the number of articles remained stable at two in 2016, indicating a period of gradual but steady growth. In 2017, the number of articles increased significantly to four, marking a peak indicating increased interest or research activity in that year.

However, this trend did not continue into subsequent years. In 2018, the number of articles dropped to three, followed by a sharper decline to just one article in 2019. This low publication rate persisted into 2020. The period from 2018 to 2020 showed a significant decline, possibly due to a variety of external factors affecting research activity. 2021 marked a turning point, with the number of articles increasing sharply to six, the highest number in the decade. This indicates a significant increase in research production, which could be due to additional support, increased research focus, or other incentives that encourage publication. In the last two years, from 2022 to 2024, the number of publications is stable, with only minor fluctuations. After dropping to four articles in 2022, the number increases again to six in 2023 and remains stable through 2024. This indicates stability in the number of publications associated with research titles at the end of the period. Fig. 2 below shows the increasing trend in research articles from 2014 to 2024.

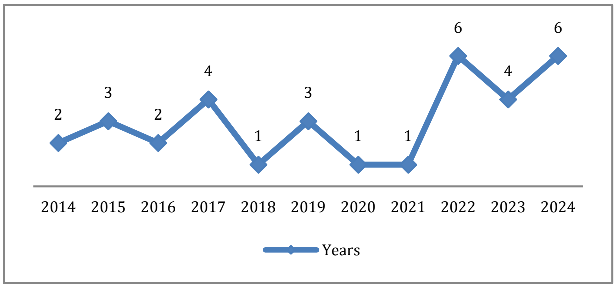

Fig. 2: Trend of increasing number of research articles 2014–2024

Visual and multimodal representations in mathematics have been shown to enhance students' cognitive processes and problem-solving abilities. This approach reduces cognitive load, provides multiple methods for understanding complex concepts, and encourages students to internalize abstract mathematical concepts (Sweller, 2010; Mayer and Moreno, 2003). Studies show that the combination of visual, symbolic, and interactive elements can build effective, deeper, and efficient learning.

3.2. How do visual and multimodal aids reduce cognitive load in pre-service teachers' math learning?

Research has shown that visual representations help students understand the structural relationships between mathematical concepts, thereby reducing cognitive load. In mathematical discussions, students often compare solutions and identify relational patterns between concepts. Research by Richland et al. (2017) found that parallel visual mapping and explicit visual cues can facilitate students in connecting abstract concepts more easily, without feeling cognitively overloaded. They stated, "Pedagogical practices such as providing explicit comparison cues and spatially arranging visuals can help students notice the desired relationships between solutions while minimizing the burden on their cognitive resources (Richland et al., 2017).

Discussions involving comparisons of different solutions are effective in developing students' conceptual understanding, especially with the support of multi-modal representations. Waisman et al. (2014) highlighted that when students compare graphical and symbolic representations in solving mathematical problems, their relational reasoning skills are strengthened. With the help of appropriate visualization, students can understand the relationships between mathematical variables without being burdened by excessive cognitive load. The authors explained, "Higher brain activity was found in students who excelled in mathematics who were not identified as gifted in general, indicating increased cognitive load in this group of students (Kuznetsova et al., 2024).

Coloring variables in learning materials can reduce cognitive load, especially in learning involving complex diagrams or representations. Reisslein et al. (2014) tested the effects of using color on symbols in circuit diagrams and found that students who learned with color coding were more likely to recognize variables, experienced higher engagement, and had lower cognitive load. The study stated that "the color group achieved higher post-test scores, rated the instructions higher and felt they were helpful, and rated cognitive load lower than the black letter group (Liu et al., 2021). Multi-modal representations in the form of animations also showed significant impacts in improving the understanding of basic mathematical concepts. In a study by Luzón and Letón (2015), the animation effect was applied to mathematical text in a video podcast, which helped students focus their attention on important information.

The results of the study showed that "the inclusion of appropriate animation effects in the material can facilitate cognitive processes that focus on selecting information, building representation models, and understanding, thereby improving students' learning abilities (Luzón, and Letón, 2015). In complex mathematics learning, multi-state models have been shown to be effective in simplifying the cognitive processes required to understand complex concepts. Palmisano et al. (2014) developed a multi-state-based model that allows for the simplification of mathematical representations in biochemical systems, making it easier for students to understand without being burdened by the complexity of the usually complicated models. The authors stated, that the use of multi-state reactions reduces the number of reactions required to represent many biochemical network models, which reduces the cognitive load for a particular model, making it easier for modelers to build more complex models" (Palmisano et al., 2014).

3.3. How do multimodal representations affect pre-service teachers' math problem-solving in teaching preparation?

A study by van Lieshout and Xenidou-Dervou (2018) showed that combining images with auditory information reduced cognitive load and increased accuracy in solving basic arithmetic problems, such as subtraction. The results of this study support cognitive load theory, especially for students who are underachieving in mathematics, by showing that multimodal combinations are more effective than single visualizations in improving problem-solving skills (van Lieshout and Xenidou-Dervou, 2018). Sheridan et al. (2017) investigated how mental mapping using a "mental number line" helped college students simplify numerical processing tasks.

This study emphasizes that problem-solving skills are enhanced by combining numerical processing with sensory-motor control. This study suggests that solving mathematical problems involving visual representations can be more effective when combined with physical activity, such as the use of a stylus in number line exercises (Sheridan et al., 2017). Richland et al. (2017) examined the role of mathematical discussion in comparing alternative solutions to problems. They found that the use of parallel visual representations and relational reasoning can strengthen problem-solving skills, especially in understanding common mathematical algorithms.

By providing appropriate visual cues, students can more easily notice the relationships between different solutions without feeling cognitively overwhelmed, thus supporting the development of effective problem-solving skills (Richland et al., 2017). Reisslein et al. (2014) proved that the use of mathematical variable coloring in circuit diagrams can improve students' understanding of analyzing electrical circuits. Mathematical variable coloring helps students recognize patterns and understand relationships between variables more quickly, which supports their problem-solving skills in circuit analysis situations.

These results suggest that visualization with coloring can be an effective tool in problem-solving-based learning (Reisslein et al., 2014). Luzón and Letón (2015) showed that animation in visual representations can facilitate cognitive processes, thereby helping students build internal representational models that support problem-solving. In their study, the use of animation in texts explaining basic probability concepts was shown to improve mathematical problem-solving skills. This suggests that a multimodal approach involving animation can deepen students' understanding of complex concepts in mathematics (Luzón and Letón, 2015).

3.4. Can multimodal digital tools boost pre-service teachers' motivation and engagement in learning math?

Tso et al. (2022) examined how dynamic visualization through body simulation affects students' motivation and understanding of algebraic manipulations. This study found that visualization through body simulation or instructional animation improves students' perceptions of the learning process and increases engagement with algebraic content. The results of this study indicate that the use of body movement simulation during learning has a positive effect on student's motivation to be actively involved in the mathematics learning process. Kaur et al. (2024) discussed how multimodal medical image fusion (e.g. CT/MRI) can improve user focus and engagement in understanding complex visual content. Although this study was conducted in a medical context, the findings suggest that multimodal representations can also be applied to improve engagement in the context of mathematics learning, especially when understanding concepts that require clear and structured visual representations. Saha et al. (2022) explored how digital tools based on galvanic skin response (GSR) and photoplethysmography (PPG) can be used to monitor users' cognitive load in activities that require high cognitive engagement.

The results showed that digital devices that can monitor and adjust cognitive load can help increase user engagement by adjusting the appropriate level of stimulation. In the context of mathematics learning, the use of similar devices can increase student engagement by facilitating optimal levels of stimulation. Tso et al. (2022) also found that when high-achieving students used embodied simulations or instructional animations, they tended to show increased positive perceptions of initiative in learning. For students with lower abilities, instructional animations increased their perceptions of self-efficacy and learning strategies. These findings suggest that digital devices that incorporate multi-modal representations can increase motivation and engagement in mathematics learning, especially when the instructional methods are tailored to students' achievement levels.

3.5. Findings and implications

The use of visual and multimodal representations in mathematical problem-solving significantly reduces cognitive load while improving students' understanding and problem-solving skills. Visual representations, such as diagrams, simplify the understanding of mathematical space and logic, while the combination of visual text improves memory and academic performance in process-based learning (Maries and Singh, 2023). In line with the findings of Moreno and Mayer (2007), this approach stimulates diverse sensory engagement, which supports stronger and more efficient conceptual construction.

This study shows that visual and multimodal representations have a positive impact on understanding mathematical concepts, reducing cognitive load, and improving problem-solving skills. However, the effectiveness of these strategies may vary depending on the level of education and the characteristics of different age groups. Adjustment in teaching approaches based on the level of education is important to optimize student learning outcomes. At the elementary level, approaches involving concrete manipulatives and simple visuals are more effective. Children at this age tend to respond well to learning materials that use concrete visual representations, such as pictures or colors, to facilitate understanding of abstract mathematical concepts. For example, visual blocks or other manipulatives that students can physically handle help convey basic concepts of numbers and mathematical operations through direct experience.

In contrast, at the secondary education level, students begin to have more developed cognitive capacities so that they can handle more abstract and symbolic visual representations. For example, complex graphs or diagrams can help students interpret the relationships between variables in mathematical equations or functions. Multimodal approaches that include interactive graphs, digital simulations, and animated videos are also very effective in stimulating students' interest and understanding of more complex concepts. At higher education levels, such as universities, the use of more dynamic and abstract multimodal representations can help students understand more complex mathematical concepts. Students can benefit from digital tools that allow for real-time simulation and manipulation of variables, such as mathematical software or computer-based applications. Visual representations in the form of animations and 3D models can facilitate their understanding of concepts such as calculus and statistics, which require higher abstract thinking. Thus, the adaptation of visual and multimodal representation approaches that are tailored to the cognitive characteristics and specific needs of each age group will increase the effectiveness of mathematics learning. Further research is recommended to explore the long-term impact of this approach on different age groups in the context of mathematics learning, to ensure that this technique can be optimized and applied widely.

These results strengthen the cognitive load theory which states that more comprehensive and structured representations can reduce the complexity of information, thereby enhancing the learning process. By distributing information across multiple sensory modalities, multimodal representations not only minimize extrinsic cognitive load but also optimize the information processing process, supporting a deeper understanding of mathematical concepts (Paivio, 1990). At the elementary level, multimodal representations such as images and colors have been shown to be more effective in facilitating a basic understanding of mathematical concepts. At the college level, more abstract representations, such as dynamic graphs and computer-based mathematical simulations, may be more appropriate to help students solve more complicated problems.

The findings of this study have direct implications for mathematics teaching practices, which can be improved by implementing a multimodal representation-based approach. The use of aids such as diagrams, graphs, and visual-text combinations can be implemented in the curriculum to help students understand difficult concepts while reducing their cognitive load. This approach not only facilitates conceptual understanding but also allows early detection of students' learning difficulties, providing them with alternatives to explore deeper solutions and concepts. The practical implications of these findings show the great potential of multimodal representations in enriching mathematics teaching methods at various levels of education. At the elementary level, teachers can use simple visual representations such as diagrams or concept maps to introduce basic mathematical concepts. For example, in learning arithmetic operations, colored bar or block diagrams can be used to help students understand addition or subtraction calculations, making it easier for them to relate abstract concepts to concrete objects.

The findings of this study are consistent with previous studies that underline the role of visual representations in reducing cognitive load and increasing learning efficiency (Sweller, 1988; Mayer and Moreno, 2003). However, recent literature suggests that multimodal representations are more effective than single visuals in supporting problem-solving skills. In particular, the use of multimodal representations is considered more effective in dealing with complex mathematical tasks, especially in learning environments that require deep understanding.

This study has two main contributions that distinguish it from previous literature. First, this article proposes a visual-based and multimodal instructional approach that can be implemented in pre-service teacher training in developing countries. This approach is relevant to improving the quality of mathematics learning in environments with limited access to technology. For example, teachers can utilize simple tools such as manual visual manipulatives or picture-based aids to overcome technological barriers.

Second, this study adapts existing theories, such as Cognitive Load Theory, to the specific context of education in developing countries. Thus, this article opens up space for further discussion on how this approach can be integrated into more inclusive curricula and teacher training programs. Furthermore, this study highlights the importance of instructional design that takes into account the cognitive needs and technological readiness levels of students at different levels of education.

These findings provide a basis for the development of a visual and multimodal curriculum that can be adapted to different levels of education in developing countries. Further research is needed to evaluate the effectiveness of this approach in a wider cross-cultural and educational context. Further research is recommended to investigate the long-term impact of using multimodal representations on students with different skill levels, including students with special needs. In addition, cross-cultural research would be useful to see whether this method produces equally effective results across different socio-cultural backgrounds. Research should also expand the scope of evaluation tools to assess the effectiveness of visual representations in supporting students' analytical skills and explore how digital technologies can be used in the development of problem-solving skills in mathematics classrooms.

While this study provides valuable insights into the impact of visual and multimodal representations on reducing cognitive load and improving problem-solving skills, it is important to acknowledge certain limitations. First, this study is based solely on a systematic literature review, which synthesizes findings from existing research but does not include empirical validation through direct experimentation or longitudinal data collection. As a result, the conclusions drawn are foundational and may require further empirical investigation to establish their applicability in real-world educational settings.

Future research should focus on conducting experimental studies and longitudinal analyses to validate the findings presented here. For instance, empirical studies could evaluate the effectiveness of multimodal instructional designs in different cultural and educational contexts, particularly in resource-constrained environments. Additionally, employing advanced tools such as eye-tracking or physiological sensors could provide deeper insights into how students interact with multimodal learning resources and how these interactions influence cognitive load and problem-solving skills.

Furthermore, while this study highlights the potential of visual and multimodal approaches for enhancing mathematics education, the generalizability of these findings across diverse student populations remains to be tested. Variations in educational systems, technological accessibility, and individual learning preferences may significantly influence the outcomes of multimodal instructional strategies.

3.6. Critical analysis of findings

The findings of this study indicate that multimodal representations significantly reduce cognitive load and enhance problem-solving skills, aligning with Cognitive Load Theory (Sweller, 2020). These results support the argument that engaging multiple sensory modalities during instruction can facilitate a deeper understanding and retention of abstract mathematical concepts. For instance, integrating visual and symbolic representations allows students to process information more efficiently by leveraging both working memory and long-term memory.

However, the findings also challenge traditional pedagogical approaches that prioritize single-modality instruction. The evidence suggests that multimodal strategies not only improve cognitive outcomes but also increase student motivation and engagement, particularly when digital tools are employed. This aligns with the work of Ainsworth (2014), who highlighted the importance of representational diversity in learning environments.

3.7. Implications for practice

Educators can apply these findings by incorporating multimodal tools, such as interactive simulations, color-coded diagrams, and digital applications, into their teaching strategies. These tools not only simplify complex concepts but also accommodate diverse learning preferences, making education more inclusive. Furthermore, integrating these tools in resource-constrained settings can bridge gaps in educational equity, providing students with accessible and effective learning experiences.

3.8. Policy recommendations

Policymakers should support the adoption of multimodal instructional practices by investing in teacher training programs and providing funding for educational technology. Additionally, curriculum developers should prioritize the inclusion of multimodal resources to ensure alignment with contemporary pedagogical research. Establishing guidelines for effective multimodal instruction can also standardize best practices across different educational contexts.

4. Conclusion

This study highlights the significant impact of visual and multimodal representations in mathematics education, demonstrating their effectiveness in reducing cognitive load and improving students' problem-solving skills. By providing a richer distribution of information, the multimodal approach optimizes students' understanding of complex mathematical concepts through diverse representations, including visual, verbal, and symbolic formats. This approach facilitates knowledge retention while encouraging higher motivation and deeper conceptual understanding. These findings are in line with cognitive load theory, which states that adjusting the presentation of information to students' cognitive capacities improves learning efficiency.

The systematic review methodology used in this study supports a structured and comprehensive analysis, which offers important insights for developing curricula that incorporate multimodal representations. The practical implications of this study advocate the implementation of a multimodal approach in the curriculum, including visual aids such as diagrams and graphs and the integration of digital devices. This approach also expands opportunities for implementation in inclusive learning contexts, allowing early detection of learning challenges and offering a variety of alternative solutions.

4.1. Recommendations for future research

Future studies should validate these findings through empirical research, particularly in diverse cultural and educational contexts. Longitudinal studies are needed to assess the long-term impacts of multimodal instruction on cognitive development and academic performance. Additionally, exploring the integration of emerging technologies, such as augmented reality and artificial intelligence, could further enhance the effectiveness of multimodal learning approaches.

Compliance with ethical standards

Conflict of interest

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

References

Ainsworth S (2014). The multiple representation principle in multimedia learning. In: Mayer RE (Ed.), The Cambridge handbook of multimedia learning: 464-486. Cambridge University Press, Cambridge, UK. https://doi.org/10.1017/CBO9781139547369.024

Asmara AS, Waluya SB, Suyitno H, Junaedi I, and Ardiyanti Y (2024). Developing patterns of students' mathematical literacy processes: Insights from cognitive load theory and design-based research. Infinity Journal, 13(1): 197-214. https://doi.org/10.22460/infinity.v13i1.p197-214

Attout L, Noel MP, Nassogne MC, and Rousselle L (2017). The role of short-term memory and visuo-spatial skills in numerical magnitude processing: Evidence from Turner syndrome. PLOS ONE, 12(2): e0171454. https://doi.org/10.1371/journal.pone.0171454 **PMid:28222116 PMCid:PMC5319680**

Ayabe H, Manalo E, and Vries ED (2022). Problem-appropriate diagram instruction for improving mathematical word problem solving. Frontiers in Psychology, 13: 992625. https://doi.org/10.3389/fpsyg.2022.992625 **PMid:36262435 PMCid:PMC9574201**

Bennett IJ and Stark CE (2016). Mnemonic discrimination relates to perforant path integrity: An ultra-high resolution diffusion tensor imaging study. Neurobiology of Learning and Memory, 129: 107-112. https://doi.org/10.1016/j.nlm.2015.06.014 **PMid:26149893 PMCid:PMC4699874**

Ceulemans K, Molderez I, and Van Liedekerke L (2015). Sustainability reporting in higher education: A comprehensive review of the recent literature and paths for further research. Journal of Cleaner Production, 106: 127-143. https://doi.org/10.1016/j.jclepro.2014.09.052

Choi JW, Cha KS, and Kim KH (2019). Covert intention to answer to self-referential questions is represented in alpha-band local and interregional neural synchronies. Computational Intelligence and Neuroscience, 2019(1): 7084186. https://doi.org/10.1155/2019/7084186 **PMid:30723496 PMCid:PMC6339759**

Debrenti E (2024). Game-based learning experiences in primary mathematics education. Frontiers in Education, 9: 1331312. https://doi.org/10.3389/feduc.2024.1331312

Fischer F, Kollar I, Stegmann K, and Wecker C (2013). Toward a script theory of guidance in computer-supported collaborative learning. Educational Psychologist, 48(1): 56-66. https://doi.org/10.1080/00461520.2012.748005 **PMid:23378679 PMCid:PMC3557614**

Hahn L and Klein P (2023). The impact of multiple representations on students' understanding of vector field concepts: Implementation of simulations and sketching activities into lecture-based recitations in undergraduate physics. Frontiers in Psychology, 13: 1012787. https://doi.org/10.3389/fpsyg.2022.1012787 **PMid:36687809 PMCid:PMC9849893**

Hardman KO, Vergauwe E, and Ricker TJ (2017). Categorical working memory representations are used in delayed estimation of continuous colors. Journal of Experimental Psychology: Human Perception and Performance, 43(1): 30-54. https://doi.org/10.1037/xhp0000290 **PMid:27797548 PMCid:PMC5179301**

Kaur H, Vig R, Kumar N, Sharma A, Dogra A, and Goyal B (2024). Multimodal medical image fusion utilizing two-scale image decomposition via saliency detection. Current Medical Imaging, 20(1): e15734056260083. https://doi.org/10.2174/0115734056269626231201042100 **PMid:38284702**

Kuznetsova E, Liashenko A, Zhozhikashvili N, and Arsalidou M (2024). Giftedness identification and cognitive, physiological and psychological characteristics of gifted children: A systematic review. Frontiers in Psychology, 15: 1411981. https://doi.org/10.3389/fpsyg.2024.1411981 **PMid:39635703 PMCid:PMC11615676**

Liberati A, Altman DG, Tetzlaff J, Mulrow C, Gøtzsche PC, Ioannidis JPA, Clarke M, Devereaux PJ, Kleijnen J, and Moher D (2009). The PRISMA statement for reporting systematic reviews and meta-analyses of studies that evaluate health care interventions: Explanation and elaboration. BMJ, 339: b2700. https://doi.org/10.1136/bmj.b2700 **PMid:19622552 PMCid:PMC2714672**

Liu S, Feng J, Yang Z, Luo Y, Wan Q, Shen X, and Sun J (2024). COMET: "Cone of experience" enhanced large multimodal model for mathematical problem generation. Science China Information Sciences, 67: 220108. https://doi.org/10.1007/s11432-024-4242-0

Liu Y, Ma W, Guo X, Lin X, Wu C, and Zhu T (2021). Impacts of color coding on programming learning in multimedia learning: Moving toward a multimodal methodology. Frontiers in Psychology, 12: 773328. https://doi.org/10.3389/fpsyg.2021.773328 **PMid:34925175 PMCid:PMC8677832**

Luzón JM and Letón E (2015). Use of animated text to improve the learning of basic mathematics. Computers and Education, 88: 119-128. https://doi.org/10.1016/j.compedu.2015.04.016

Maboudi H, Shimazaki H, Amari SI, and Soltanian-Zadeh H (2016). Representation of higher-order statistical structures in natural scenes via spatial phase distributions. Vision Research, 120: 61-73. https://doi.org/10.1016/j.visres.2015.06.009 **PMid:26278166**

Maries A and Singh C (2023). Helping students become proficient problem solvers part II: An example from waves. Education Sciences, 13(2): 138. https://doi.org/10.3390/educsci13020138

Mayer RE and Moreno R (2003). Nine ways to reduce cognitive load in multimedia learning. Educational Psychologist, 38(1): 43-52. https://doi.org/10.1207/S15326985EP3801_6

McCrink K and Galamba J (2015). The impact of symbolic and non-symbolic quantity on spatial learning. PLOS ONE, 10(3): e0119395. https://doi.org/10.1371/journal.pone.0119395 **PMid:25748826 PMCid:PMC4351879**

Mongeon P and Paul-Hus A (2016). The journal coverage of Web of Science and Scopus: A comparative analysis. Scientometrics, 106: 213-228. https://doi.org/10.1007/s11192-015-1765-5

Moreno R and Mayer RE (2007). Interactive multimodal learning environments: Special issue on interactive learning environments: Contemporary issues and trends. Educational Psychology Review, 19: 309-326. https://doi.org/10.1007/s10648-007-9047-2

Naseem U, Khushi M, Dunn AG, and Kim J (2023). K-PathVQA: Knowledge-aware multimodal representation for pathology visual question answering. IEEE Journal of Biomedical and Health Informatics, 28(4): 1886-1895. https://doi.org/10.1109/JBHI.2023.3294249 **PMid:37432797**

Ngu BH (2019). Solution representations of percentage change problems: The pre-service primary teachers' mathematical thinking and reasoning. International Journal of Mathematical Education in Science and Technology, 50(2): 260-276. https://doi.org/10.1080/0020739X.2018.1494860

Paas F, Renkl A, and Sweller J (2003). Cognitive load theory and instructional design: Recent developments. Educational Psychologist, 38(1): 1-4. https://doi.org/10.1207/S15326985EP3801_1

Paivio A (1990). Mental representations: A dual coding approach. Oxford University Press, Oxford, UK. https://doi.org/10.1093/acprof:oso/9780195066661.001.0001

Palmisano A, Hoops S, Watson LT, Jones TC Jr, Tyson JJ, and Shaffer CA (2014). Multistate model builder (MSMB): A flexible editor for compact biochemical models. BMC Systems Biology, 8: 42. https://doi.org/10.1186/1752-0509-8-42 **PMid:24708852 PMCid:PMC4234935**

Reisslein J, Johnson AM, and Reisslein M (2014). Color coding of circuit quantities in introductory circuit analysis instruction. IEEE Transactions on Education, 58(1): 7-14. https://doi.org/10.1109/TE.2014.2312674

Richland LE, Begolli KN, Simms N, Frausel RR, and Lyons EA (2017). Supporting mathematical discussions: The roles of comparison and cognitive load. Educational Psychology Review, 29: 41-53. https://doi.org/10.1007/s10648-016-9382-2

Richland LE, Begolli KN, Simms N, Frausel RR, and Lyons EA (2017). Supporting mathematical discussions: The roles of comparison and cognitive load. Educational Psychology Review, 29: 41-53. https://doi.org/10.1007/s10648-016-9382-2

Saha S, Jindal K, Shakti D, Tewary S, and Sardana V (2022). Chirplet transform-based machine-learning approach towards classification of cognitive state change using galvanic skin response and photoplethysmography signals. Expert Systems, 39(6): e12958. https://doi.org/10.1111/exsy.12958

Schnotz W and Kürschner C (2007). A reconsideration of cognitive load theory. Educational Psychology Review, 19: 469-508. https://doi.org/10.1007/s10648-007-9053-4

Sheridan R, van Rooijen M, Giles O, Mushtaq F, Steenbergen B, Mon-Williams M, and Waterman A (2017). Counting on the mental number line to make a move: Sensorimotor ('pen') control and numerical processing. Experimental Brain Research, 235: 3141-3152. https://doi.org/10.1007/s00221-017-5019-z **PMid:28752328 PMCid:PMC5603638**

Sirock J, Vogel M, and Seufert T (2023). Analyzing and supporting mental representations and strategies in solving Bayesian problems. Frontiers in Psychology, 14: 1085470. https://doi.org/10.3389/fpsyg.2023.1085470 **PMid:37397310 PMCid:PMC10311000**

Sweller J (1988). Cognitive load during problem solving: Effects on learning. Cognitive Science, 12(2): 257-285. https://doi.org/10.1016/0364-0213(88)90023-7

Sweller J (2010). Cognitive load theory: Recent theoretical advances. In: Plass JL, Moreno R, and Brünken R (Eds.), Cognitive load theory: 29–47. Cambridge University Press, Cambridge, UK. https://doi.org/10.1017/CBO9780511844744.004

Sweller J (2020). Cognitive load theory and educational technology. Educational Technology Research and Development, 68: 1-16. https://doi.org/10.1007/s11423-019-09701-3

Thomas J and Harden A (2008). Methods for the thematic synthesis of qualitative research in systematic reviews. BMC Medical Research Methodology, 8: 45. https://doi.org/10.1186/1471-2288-8-45 **PMid:18616818 PMCid:PMC2478656**

Tso TY, Feng-Lin L, and Lei KH (2022). Effects of embodied dynamic visualization on middle-school students' learning of algebraic manipulation. Journal of Research in Education Sciences, 67(4): 285-318. https://doi.org/10.6209/JORIES.202212_67(4).0009

van Lieshout EC and Xenidou-Dervou I (2018). Pictorial representations of simple arithmetic problems are not always helpful: A cognitive load perspective. Educational Studies in Mathematics, 98: 39-55. https://doi.org/10.1007/s10649-017-9802-3

Waisman I, Leikin M, Shaul S, and Leikin R (2014). Brain activity associated with translation between graphical and symbolic representations of functions in generally gifted and excelling in mathematics adolescents. International Journal of Science and Mathematics Education, 12: 669-696. https://doi.org/10.1007/s10763-014-9513-5

Wang J, Peng J, Feng X, He G, Wu J, and Yan K (2013). Image fusion with nonsubsampled contourlet transform and sparse representation. Journal of Electronic Imaging, 22(4): 043019. https://doi.org/10.1117/1.JEI.22.4.043019

Xian Y and Tian Y (2019). Self-guiding multimodal LSTM—When we do not have a perfect training dataset for image captioning. IEEE Transactions on Image Processing, 28(11): 5241-5252. https://doi.org/10.1109/TIP.2019.2917229 **PMid:31135361**

Xiao Y and Watson M (2019). Guidance on conducting a systematic literature review. Journal of Planning Education and Research, 39(1): 93-112. https://doi.org/10.1177/0739456X17723971

Yan M, Lv Z, Sun W, and Bi N (2020). An improved common spatial pattern combined with channel-selection strategy for electroencephalography-based emotion recognition. Medical Engineering and Physics, 83: 130-141. https://doi.org/10.1016/j.medengphy.2020.05.006 **PMid:32475767**