JPPIPA 11(9) (2025)

Jurnal Penelitian Pendidikan IPA

http://jppipa.unram.ac.id/index.php/jppipa/index

The Role of Metacognitive Scaffolding in Fostering Creative Thinking and Conceptual Mastery in Physics: A Comparative Study Across Educational Level

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Received: July 16, 2025
Revised: August 13, 2025
Accepted: September 25, 2025
Published: September 30, 2025

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DOI: 10.29303/jppipa.v11i9.12197

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Abstract: The study explores the importance of concept mastery in physics education for developing 21-st century skills, focusing on the role of metacognitive scaffolding in enhancing creative thinking. Data were collected from publications indexed by Google Scholar over the past 10 years from 2015 to 2025, using the Publish or Perish tool. Through a systematic literature review using PRISMA guidelines, data from Google Scholar was analyzed using VOSviewer software, covering publication types, sources, and frequently occurring keywords in related studies. In-depth analysis of several key articles indicates that metacognitive scaffolding has a significant positive impact on enhancing student's creative thinking abilities and concept mastery at different educational levels, supported by the role of teachers. However, there is a potential decline in similar research seen in publications related to physics concepts mastery and creative thinking, which trends to decrease in 2025. Key themes include metacognitive scaffolding, critical thinking, concept mastery, and physics education in various educational levels.

Keywords: Education level; Metacognitive scaffolding; Physics education

Introduction

In the context of evolving education, metacognitive scaffolding has become an important pedagogical strategy to enhance student's self-regulation abilities (Jumaat & Tasir, 2016). This strategy includes the development of interactive teaching material (Badri et al., 2019; Yersi et al., 2025; Yosa et al., 2025) and various teaching techniques, such as reflective questioning (Sijmkens et al., 2023; Yelli, 2021), learning journals (Rahmat et al., 2021), concept mapping (Wodaj, 2020), classroom discussion (Firmansyah et al., 2025), problem-solving models (Kamelia & Pujiastuti, 2020; Patonah & Novita, 2025), constructive feedback (Hsissi et al., 2014), metacognitive skill simulation strategies (Steward, 2000), and role-playing games (Raharja et al., 2025; Saprudin et al., 2017). These techniques are designed to encourage students to reflect on their own thinking processes, enabling deeper engagement with the material being learned.

Through structures guidance, teacher plays a crucial role in helping student develop essential skill such as self-assessment, strategic planning and adaptive reasoning (Arifin, 2022; Widiantie et al., 2025; Wisdayana et al., 2025). This skill not only support student's understanding of complex concepts but also is highly relevant in the context of physics education (Masfufa et al., 2025), where understanding often abstract concepts is crucial. By promoting of metacognitive processes, teachers can create an interactive learning development, enabling students to not only absorb information but also critically evaluate

How to Cite:
Kesaulya, N., Parno, Purwaningsih, E., & Sunaryono. (2025). The Role of Metacognitive Scaffolding in Fostering Creative Thinking and Conceptual Mastery in Physics: A Comparative Study Across Educational Level. *Jurnal Penelitian Pendidikan IPA*, *11*(9), 178–187. https://doi.org/10.29303/jppipa.v11i9.12197

their understanding and learning strategies (Rodli & Widiastutik, 2024; Sari et al., 2024). This approach is expected to significantly improve student's academic outcomes.

Creative thinking is the driving force behind innovation and problem-solving, enabling students to tackle challenges with originality (Alkhatib, 2019; Alzoubi et al., 2016; Gregory et al., 2013; Karunarathne & Calma, 2024; Yazar Soyadı, 2015), and involves not only the application of acquired knowledge but also the ability to synthesize information and generate new solutions to complex problems (Asriadi & Istiyono, 2020; Riberio, 2023). Besides that, equally important is the concept of conceptual mastery, which refers to student's ability to comprehend and apply basic principles in various context (Doyan et al., 2024). A strong conceptual mastery enables students to connect different ideas, apply theoretical knowledge to practical situations, and engage in high-level thinking. Studies show that students with a solid conceptual foundation are better prepared to tackle new problems and are less prone to misunderstandings-issue that are particularly common in physics education. Therefore, integrating metacognitive scaffolding helps develop creative thinking and strengthens conceptual mastery, creating a synergistic effect that enhances overall learning outcomes (Dessie et al., 2023; Kurniawan et al., 2024).

The subject of physics at the junior high school plays a crucial role for students, introducing basic concepts such as force, motion and energy (Kusumadani et al., 2025). At this stage, students develop scientific inquiry skills and critical thinking, which are essential for understanding complex principles in higher education. Through practical experiments and collaborative projects, students enhance their interest in physics and foster creativity. This creativity is important as it allows students to approach problems from various perspectives, develop innovative solutions, and connect physics concepts to real-life situations. Mastering these basic concepts prepares students for more challenging curricula in high school. Furthermore, in high school, students are required to achieve competence through optimal mastery of physics concepts to participate effectively in secondary educations. Therefore, physics learning should be designed to facilitate the achievement of this mastery (Abdurrahman et al., 2018). Understanding physics concepts enhances student's analytical skills, problem-solving abilities, and foster creativity for innovations in higher education (Zaini et al., 2025). Student delve into complex topics that demand a profound grasp of fundamental principles and the relationship between concepts. They learn to apply their knowledge to conduct scientific research and experiments, as well as to comprehend intricate natural phenomena. Effective pedagogy id crucial at this stage to ensure students develop a strong foundation in physics.

This systematic review aims to analyze and synthesize current research on how metacognitive scaffolding can enhance creative thinking and conceptual mastery in physics education across different educational level. By examining multiple student's cognitive processes and learning results. Ultimately, this review offers evidence-based suggestions for teacher and policymaker on incorporating metacognitive scaffolding into physics curricula to cultivate innovative and conceptually adept learns.

Method

This study is a descriptive and analytical which aims to understand and describe research of metacognitive scaffolding in fostering creative thinking and conceptual mastery in physics educations. The data were collected from sources indexed by google scholar (Hallinger & Nguyen, 2020) using the Publish and Perish tool. The search on google scholar utilized keywords "metacognitive scaffolding in creative thinking and conceptual mastery in physics education" across three educational levels: "junior high school", "senior high school", and "higher education or university". An initial search yieldes, the analysis focus on 1.000 documents indexed by google scholar covering the publication range 2015 to 2025. In this study, we applied the PRISMA (Preferred Reporting for Systematic Reviews and Meta-Analyses_ guidelines to filter the data obtained through Publish or Perish which include the stage of identification, screening, eligibility, and inclusion to ensure transparency and replicability. From the final selection of studies, relevant data were extracted using a structured coding sheet with key information included title, educational level *junior high school, senior high, or higher education), types of study, focus area, implementation of metacognitive scaffolding to explain explicit strategies or frameworks used and main findings and implications.

Result and Discussion

Based on google scholar search using keywords related to the effect of metacognitive scaffolding on creative thinking and conceptual mastery in Physics across educational level, we found 14,000 articles, including research articles, review articles, and proceedings from the past 10 years (2015-2025). To avoid excessive bias, we selected a few key articles as primary references, totaling 13 articles. From this data, we present a table illustrating the role of metacognitive scaffolding at three educational levels: junior high school, senior high school, and higher education, each in a separate table.

In this study, as presented in Table 2, we found that the significance of innovative learning strategies, particularly metacognitive scaffolding approaches, in enhancing concept mastery and higher-order thinking skills in physics across different educational levels. In the modern educational landscape, critical, reflective, and creative thinking skills are highly valued, underscoring the relevance of employing metacognitive and problem-solving-based learning strategies. The study titled "Gender Issues in Achievement and Retention among Secondary School Students Taught Thermal Energy Using Metacognitive Scaffolding Teaching Strategy" revealed that the implementation of advanced organizers, modeling, and metacognitive problem-solving strategies led to notable improvements in student achievement and retention, with no significant gender-based differences observed. This finding supports the notion that metacognitive scaffolding aids students in regulating their cognitive processes, thereby deepening their conceptual understanding (Michalsky, 2024).

Table 1. Metacognitive Scaffolding to Conceptual Mastery and Creative Thinking in Junior High School

Article Title	Method	Significant Outcomes	Types of MS	Implication	References
The Effect of Predict-Observe-Explain (POE) Strategy on Students' Conceptual Mastery and Critical Thinking in Learning Vibration and Wave	One-group pretest-posttest design	Significant enhancement in conceptual mastery (N-gain of 0.29) and critical thinking improvement from 1.30 to 2.07.	Predicting, Observing, Explaining	Conceptual Mastery and Critical Thinking	(Furqani et al., 2018),
Practicality of Learning Devices Based on Conceptual Change Model to Improve Concept Mastery of Students in the Gas Kinetic Theory Material	Development research (4D model)	Learning devices based on the conceptual change model are very practical for improving students' concept mastery in gas kinetic theory.	Hypothesis generation, Reflection, Problem-solving	Hypothesis generation, Reflection, Problem-solving	(Susilawati et al., 2022)
Depth of Science Learning Materials in Schools and Student Concept Mastery	Qualitative study (descriptive analysis)	Teacher's material delivery was not in-depth, leading to low student mastery of concepts; students performed better on concepts with clear, focused delivery.	Reflection, Concept mapping, Peer discussion	Emphasizes the need for teachers to structure material delivery to enhance student understanding.	(Laelandi et al., 2022)

Note: MS refers to metacognitive scaffolding

Table 2. Metacognitive Scaffolding to Conceptual Mastery and Creative Thinking in Senior High School

Article Title	Method	Significant Outcomes	Types of MS	Implication	References
An interactive e-book for physics to improve students' conceptual mastery	Quasi-experiment (one group pretest-posttest design)	Significant improvement in conceptual mastery with N-gain scores of 0.79 (high) for equilibrium and 0.66 (medium) for rotational dynamics.	Multimedia content (audio. Video. animations). problem-solving activities	Enhances conceptual mastery in physics, emphasizing the effectiveness of interactive e-books in learning.	(Harjono et al., 2020)
The effectiveness of physics learning tools based on discovery model with cognitive conflict approach toward student's conceptual mastery	Quasi-experiment (one group pretest-posttest)	Significant improvement in conceptual mastery, with an average n-gain of 67.58%. highest increases in remembering and understanding.	Problem identification. hypothesis generation. reflection	Effective in enhancing conceptual mastery in physics through innovative learning approaches.	(Gunawan et al., 2021)
The implementation of generative learning	Quasi-experimental	Significant improvement in mastery	Hypothesis generation.	Effective in enhancing	(Maknun, 2015)

Article Title	Method	Significant Outcomes	Types of MS	Implication	References
model on physics lesson to increase mastery concepts and generic science skills of vocational students	(pretest-posttest design)	of physics concepts and generic science skills; N-gain scores indicate medium to high improvement.	problem-solving. reflection	conceptual mastery and generic science skills in vocational education.	
Generative learning models assisted by virtual laboratory to improve mastery of student physics concept	Quasi-experimental (pretest-posttest design)	Significant improvement in physics concept mastery; N-gain scores indicate high improvement in cognitive levels C1 to C6.	Hypothesis generation. problem-solving. Reflection	Effective in enhancing mastery of physics concepts through the integration of virtual laboratories.	(Dewi et al., 2020)
Revolutionizing physics education: enhancing high school students' understanding of standing wave concepts through mictester-based smartphone experiments	Pre-experimental design (pretest-posttest)	Significant improvement in students' understanding of standing wave concepts; N-gain score of 0.364 indicates moderate improvement.	Hypothesis generation. experimentation. reflection	Effective alternative for teaching standing waves using smartphones, enhancing conceptual understanding.	(Liunokas & Asbanu, 2023)
Development of physics learning media based on guided inquiry model to improve students' concepts mastery and creativity	Research and development (4d model)	Learning media based on the guided inquiry model is valid, practical, and effective in improving students' conceptual mastery and creativity.	Hypothesis generation. problem-solving. reflection	Teachers can effectively use this media to enhance students' understanding of physics concepts.	(Susilawati et al., 2021)
Gender issues in achievement and retention among secondary school students taught thermal energy using metacognitive scaffolding teaching strategy	Quasi-experimental (non-randomized control pretest-posttest design)	Students taught with metacognitive scaffolding had higher achievement and retention scores; no significant gender differences in performance.	Advanced organizers. modeling. problem-solving strategies	Supports the adoption of metacognitive scaffolding to improve student outcomes in physics, regardless of gender.	(Agu & Iyamu, 2020)

Note: MS refers to metacognitive scaffolding

Table 3. Metacognitive Scaffolding to Conceptual Mastery and Creative Thinking in Senior High School

Article Title	Method	Significant Outcomes	Types of MS	Implication	References
Hybrid learning model: its impact on mastery of concepts and self-regulation in newton's second law material	Quasi-experimental design (2x3 factorial)	Hybrid learning improves concept mastery compared to non-hybrid learning; self-regulation positively impacts understanding	Questioning. reflection journal. peer discussions	Conceptual Mastery	(Doyan et al., 2024)

Note: MS refers to metacognitive scaffolding

In the meantime, learning with generative models and virtual laboratories, as seen in the study with high school students in Mataram, has proven to be effective (Dewi et al., 2020). This approach allows students to actively construct knowledge through activities like hypothesis generation, problem-solving, and reflection. It aligns with the principles of social constructivism, emphasizing social interaction and appropriate guidance to accelerate students' development. Furthermore, studies using the Predict-Observe-Explain (POE) strategy demonstrate that active student engagement in predicting phenomena, observing experiments, and explaining results significantly improves conceptual understanding and critical thinking. POE acts as a form of cognitive and metacognitive scaffolding, encouraging internal questioning and reflective dialogue among students Interactive physics e-books are a valuable tool for enhancing concept mastery among students (Liunokas & Asbanu, 2023). These media resources offer dynamic visualizations that make abstract concepts more tangible and easier to grasp. Research by Al Mamun et al. (2024) suggests that the combination of visual, narrative, and interactive elements aligns with the cognitive theory of multimedia learning.

This approach aids in the integration of information into both working memory and long-term memory, ultimately enhancing learning outcomes. The findings suggest that integrating metacognition-based strategies and technology in physics learning is crucial. Teachers should create activities that focus on both conceptual content and how students assess and control their understanding. This approach helps students become independent learners who can tackle lifelong learning challenges. Success in improving conceptual mastery and thinking skills in physics relies not only on teaching methods but also on teachers' ability to provide appropriate scaffolding tailored to students' cognitive and metacognitive needs. Teachers should not just deliver information but also act as facilitators who recognize and accommodate different learning styles and cognitive readiness levels. Effective scaffolding should be adaptable and responsive, offering guidance, reflective questions, feedback, and opportunities for independent exploration. Teachers should also teach students metacognitive thinking strategies like planning, monitoring, and evaluating their learning processes. Without teachers' skill in applying scaffolding, even innovative interventions may not be effective. Therefore, teachers' professional development in metacognitive pedagogy is essential for meaningful and lasting improvements in physics education.

Table 4. Metacognitive Scaffolding to Conceptual Mastery and Creative Thinking in Senior High School

Article Title	Method	Significant Outcomes	Types of MS	Implication	References
Scaffolding in geometry based on self-regulated learning	Quasi-experimental (pretest-posttest design)	Scaffolding positively affected students' achievement in mathematics; students with high self-regulated learning performed better than those with lower levels.	Problem-solving, monitoring, reflective questioning	Supports the integration of scaffolding and self-regulated learning in geometry education to enhance student performance.	Bayuningsih et al., 2017)
Visualization and metacognitive scaffolding in learning from animations	Mixed methods (experiments with quantitative assessments and qualitative feedback)	Static visualizations led to better learning outcomes than dynamic animations; metacognitive prompts increased cognitive load without improving learning.	Cognitive prompts, reflection, self-monitoring	Highlights the need for careful design of visualizations and metacognitive support in educational settings to enhance learning effectiveness.	(Deibl et al., 2023)

Note: MS refers to metacognitive scaffolding

In this study, we also evaluated how metacognitive scaffolding affects other subject outside of physics education (table 4). The findings revealed that metacognitive scaffolding significantly influences academic performance, especially in mathematics education. A study on geometry learning in junior high school students demonstrated that metacognitive scaffolding strategies, such as problem-solving cues and reflective questions, improved student performance, particularly among those with high levels of self-regulated learning. This indicates that metacognitive scaffolding enhances student's ability to plan, monitor, and evaluate their thinking processes, crucial for understanding geometric reasoning. Integrating self-regulated learning strategies into instructional design aligns with previous research emphasizing the role of reflective thinking in enhancing conceptual mastery and mathematical reasoning. However, a study on multimedia-based mathematics instruction found that static visualization was more effective of designing metacognitive interventions that consider load and learning readiness.

Although the two studies above (table 4) indicate the potential transferability of metacognitive scaffolding strategies to other object, such as mathematics, the limited number of sources does not provide a sufficiently robust empirical basis for broad generalizations. To clarify the relationship between our findings and existing literature, this discussion is structured around key thematic insight from the reviewed studies, rather than re-stating the content of the result section. Most notably, the review revealed consistent positive correlations between the use of metacognitive scaffolding and improvements in student's conceptual mastery and creative thinking within physics education. Furthermore, analysis of study design revealed that quasi-experimental and mixed-method approaches were the most frequently employed, often combining pre/post-tests with qualitative reflection to assess conceptual shifts and metacognitive engagement. However, relatively few studies longitudinal designs, suggesting a gap in understanding the sustained impact of metacognitive scaffolding over time.

Nevertheless, caution must be exercised when interpreting cross-disciplinary relevance. Although preliminary findings hint at possible benefits in other STEM fields, such as mathematics, further systematic investigations are required to substantiate such claims. Future study should aim to expand the scope of review across the multiple databases and include a broader range of disciplines to validate the potential transferability of metacognitive scaffolding strategies.

How Metacognitive Scaffolding Influence Creative Thinking for Students in Physics?

Metacognitive scaffolding—defined as structured supports that foster students' awareness and regulation of their cognitive processes—has emerged as a crucial pedagogical tool to enhance higher-order thinking skills, including creative thinking (Ali et al., 2025), particularly in complex disciplines like physics (Rivas et al., 2022). In the context of physics education, creative thinking is not merely the generation of novel ideas, but the ability to conceptualize, model, and solve non-routine problems through flexible cognitive processes (Indarasati et al., 2019). Metacognitive scaffolding enhances this capacity by promoting learners' ability to monitor, evaluate, and adapt their problem-solving strategies in novel and dynamic situations (Arianto & Hanif, 2024). Firstly, metacognitive scaffolding guides students in formulating hypotheses, planning solution steps, and evaluating alternative representations—skills crucial in physics problem-solving. For example, when students are encouraged to reflect on their reasoning pathways and articulate their problem-solving steps, they begin to identify multiple solution trajectories, fostering divergent thinking, a core component of creativity. Empirical studies have demonstrated that students exposed to metacognitive prompts show improved performance in open-ended and ill-structured physics problems, where creativity is essential (Doyan et al., 2024; Wider & Wider, 2023). In addition, metacognitive scaffolding fosters epistemic curiosity, which is critical in scientific creativity. By encouraging learners to question the nature and origin of their knowledge, scaffolding strategies help students to explore physics phenomena beyond algorithmic solutions, driving them toward conceptual innovation. Such approaches align with constructivist principles, where knowledge construction is seen as an active, self-regulated, and iterative process (Carmo, 2020). Moreover, physics tasks that embed metacognitive scaffolds—such as conceptual change texts, modeling tasks, or reflective journals—create cognitive dissonance that challenges students' preconceptions, a necessary condition for creative restructuring of knowledge. This disruption often prompts the search for novel conceptual representations and fosters analogical reasoning, another critical marker of creativity in science learning (Yang et al., 2025). Importantly, the efficacy of metacognitive scaffolding in promoting creative thinking is also moderated by the learners' metacognitive maturity and the scaffolding's adaptability (Veenman & van Cleef, 2019). Scaffolds must not be overly directive; instead, they should evolve in complexity, gradually transferring the responsibility of self-regulation to the learner—a process known as the "fading" principle in scaffolded instruction. This approach nurtures autonomy, which is essential for creative exploration in physics contexts where uncertainty and abstraction are common.

How it Affects Conceptual Mastery in Physics?

Conceptual mastery in physics involves more than the recall of formulas or procedures; it requires students to grasp the underlying principles governing physical phenomena and to apply these principles flexibly across varied contexts (Doyan et al., 2024). Metacognitive scaffolding—pedagogical support that helps learners plan, monitor, and evaluate their learning processes—has proven effective in promoting this kind of deep, transferable understanding. Metacognitive scaffolding enhances conceptual understanding by encouraging students to reflect on how they learn, not just what they learn. This reflective engagement leads to a deeper restructuring of conceptual frameworks, which is essential in physics where many concepts (e.g., force, energy, electricity) are counterintuitive and abstract. In physics education, students often default to algorithmic problem-solving without understanding the conceptual basis of formulas. Metacognitive scaffolding intervenes in this "procedural trap" by prompting learners to pause and articulate the why behind each step. This shift from surface-level to deep processing aligns with constructivist learning theories, where knowledge is actively constructed rather than passively received. Empirical studies have shown that students who receive metacognitive scaffolding outperform their peers on conceptual assessments. For instance, Apata (2024) demonstrated that scaffolding prompts embedded in inquiry-based physics activities led to significant gains in students' conceptual reasoning, especially when prompts encouraged them to predict, justify, and evaluate their understanding. Similarly, Clark et al. (2011) found that metacognitive scaffolding during simulations improved learners' ability to apply Newtonian mechanics concepts in novel situations, indicating a more robust conceptual grasp.

Conclusion

Metacognitive scaffolding plays a vital role in improving students' understanding of concepts and fostering creative thinking skills in physics education at different academic levels. This review highlights the benefits of this strategy for students in junior high school, senior high school, and higher education, particularly in enhancing reflection and knowledge application. The research trend on critical thinking and concept mastery in physics education, as indexed by Google Scholar from 2015 to 2024, has shown fluctuating increases. However, it is anticipated that in 2025, the research focus on metacognitive scaffolding effect on critical thinking and conceptual mastery in physics education may decline due to the emergence of diverse instructional models.

Acknowledgments
We would like to thank Dr. A. Latununuwe, M.Si from the Physics Education Laboratories for their support and resources during this research. Our gratitude also goes to Prof. Dr. I. H Wenno, M.Pd, the Dean of the Faculty of Teacher Training and Education at University of Pattimura, Ambon, for their guidance and encouragement. Lastly, we extend our heartfelt thanks to all the participants of this study, whose contributions were invaluable to our research.

Author Contributions
N.K.: Conceptualization, Software, Visualization, Methodology, Writing – original draft, Writing –review & editing. P: Formal analysis, Investigation, Review. E.P: Conceptualization, Software, Review, Methodology. S: Conceptualization, Methodology.

Funding
This research does not receive funding.

Conflicts of Interest
The authors declare that there are no conflicts of interest associated with this publication.

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