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Enhancing Real-World Physics Problem-Solving Skills through Mind Map-Based Scaffolding: The Role of Metacomponents among Pre-University Students

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ABSTRACT

Physics problem-solving is essential in physics education, yet many pre-university students struggle to apply concepts to real-world contexts. This study examines the effectiveness of integrating mind map-based scaffolding with metacomponents to enhance real-world physics problem-solving skills (RWPPS). A quasi-experimental pre-test–post-test non-equivalent group design involved 253 students at Universiti Malaysia Sabah. The experimental group used mind maps to define problems, organize information, and plan strategies with guided scaffolding, while the control group received conventional lectures. Data from open-ended RWPPS assessments showed that the experimental group significantly outperformed the control group, with improvements across all metacomponent sub-skills, especially monitoring. Normalized gain results indicated higher learning gains in the experimental group, highlighting the approach's effectiveness in fostering structured and reflective problem-solving.

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1. INTRODUCTION

One of the primary goals of physics education is to ensure that students can apply fundamental principles to identify and solve real-world problems. Problem-solving is central to physics learning, as it not only reflects students' conceptual understanding but also enhances their achievement and engagement in the subject [1]. Students who actively engage in real-world problem-solving are more likely to connect classroom learning with real-life experiences, thereby fostering greater motivation and interest [2, 3].

Despite the recognized importance of these skills, physics remains one of the most challenging subjects for students at both secondary and tertiary levels [4-6]. Students encounter significant difficulties in managing multiple forms of representation simultaneously, including mathematical formulas, graphical data, conceptual explanations, and experimental information [7-11]. This complexity has contributed to declines in both student performance and enrollment in physics-related programs [11]. In Malaysia, for instance, STEM enrollment decreased by 11.64% between 2020 and 2021, with similar trends reported internationally, indicating a broader educational challenge [12].

To effectively address these challenges, a promising approach is to enhance students' real-world physics problem-solving (RWPPS) skills. This approach requires students to integrate conceptual knowledge with higher-order thinking skills, enabling them to analyze and solve authentic, complex problems that involve navigating multiple representations and making critical decisions [3, 13, 14]. Beyond theoretical understanding, RWPPS plays a crucial role in preparing students to apply physics knowledge in real-life situations. In everyday contexts, individuals must interpret information, make decisions, and solve problems that are often ill-structured, context-dependent, and lack explicit solution pathways. RWPPS helps students connect abstract physics concepts with real-world phenomena such as motion, forces, energy use, and system behavior, thereby fostering practical reasoning and informed decision-making. Previous studies have shown that engaging students in real-world problem-solving enhances their ability to transfer knowledge across contexts and supports critical and reflective thinking aligned with 21st-century competencies [15-18]. Therefore, emphasizing RWPPS is essential not only for academic achievement but also for preparing students to address complex challenges in daily life and future STEM-related careers.

However, solving real-world physics problems imposes substantial cognitive demands, as such problems are often ill-structured and require students to process extensive texts, interpret complex diagrams, manipulate mathematical expressions, and relate solutions to authentic real-life contexts [19-23]. Engaging in this type of problem-solving not only deepens students' conceptual understanding of physics but also fosters essential 21st-century skills, including critical thinking, creativity, and collaboration [24].

To address these challenges, scaffolding plays a critical role by providing structured support while maintaining the authenticity of the problem [13, 24, 25]. Its significance is grounded in Vygotsky's theory of the zone of proximal development (ZPD), which posits that learners can perform beyond their independent capabilities when supported by a more knowledgeable individual, such as a teacher or peer. Within this framework, scaffolding functions as a temporary bridge that enables students to transition from guided assistance to independent problem-solving with greater confidence [26]. In physics education, scaffolding is essential for fostering meaningful engagement with complex, ill-structured problems while promoting students' independence and self-efficacy.

Furthermore, Sternberg's Triarchic Theory of Intelligence emphasizes the role of metacomponents as higher-order executive processes that guide problem-solving and decision-making [27]. These metacomponents include problem identification, problem definition, strategy construction, information organization, resource allocation, monitoring, and evaluation. Such processes are particularly important in addressing complex, ill-structured problems like RWPPS, as they enable learners to systematically plan, monitor, and evaluate their problem-solving strategies [27].

In this regard, the process can be effectively facilitated through the use of mind maps, which have emerged as practical scaffolding tools that support students' cognitive processes [28-30]. Mind maps enable students to organize information visually, illustrate relationships among concepts, and promote both convergent and divergent thinking [31-35]. Visual representations help students develop clearer mental models when interpreting physics concepts.

When effectively integrated with Sternberg's metacomponents, mind maps assist students in navigating each stage of problem-solving within a coherent framework, from identifying and defining problems to constructing strategies, organizing information, allocating resources, monitoring progress, and evaluating outcomes [28, 36, 37]. This structured approach not only makes the problem-solving process more transparent and manageable but also enhances conceptual understanding, promotes metacognitive regulation, and encourages deeper engagement in solving real-world physics problems. Contextual and problem-based learning environments can strengthen students' critical thinking and analytical reasoning when addressing real-world scientific issues [38].

Despite this strong theoretical foundation, there remains a lack of empirical studies examining the combined effects of mind map-based scaffolding and metacomponent processes in improving RWPPS skills among pre-university students. In Malaysia, where physics performance and STEM enrollment are declining, there is an urgent need for innovative instructional approaches that extend beyond conventional lecture-based methods.

Addressing this gap, the present study investigates the effects of a mind map-based scaffolding intervention designed to enhance metacomponent processes in real-world physics problem-solving. The primary objective of this study is to examine the effectiveness of mind map-based scaffolding in supporting metacomponents to improve pre-university students' real-world physics problem-solving skills. This research aims to provide valuable insights into instructional strategies that enhance students' engagement and performance in physics learning. The findings are expected to contribute to physics education research by offering empirical evidence on how structured scaffolding strategies support the development of systematic and reflective real-world physics problem-solving skills among pre-university students.

2. METHODS

2.1. Research Design

This study employed a quasi-experimental pre-test–post-test non-equivalent group design. Within this design, an experimental group (EG) and a control group (CG) were used to compare the effects of the mind map-based scaffolding intervention. The EG received instruction supported by mind map-based scaffolding aimed at enhancing metacomponent processes in real-world physics problem-solving, whereas the CG was taught using conventional lecture-based methods.

The quasi-experimental design was selected due to practical and ethical considerations inherent in authentic educational settings. Participants were drawn from intact lecture groups, and random assignment to experimental and control conditions was not feasible without disrupting existing instructional arrangements. Such conditions are common in educational research, making quasi-experimental designs particularly suitable for evaluating instructional interventions in real classroom contexts. Therefore, this approach was considered an appropriate and robust methodological choice for addressing the objectives of the study.

2.2. Participant

This study employed a quasi-experimental pre-test–post-test non-equivalent group design. In this design, EG and CG were used to compare the effects of the mind map-based scaffolding intervention. The EG received instruction supported by mind map-based scaffolding aimed at enhancing metacomponent processes in real-world physics problem-solving, whereas the CG was taught using conventional lecture-based methods.

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2.3. Intervention Procedure

The intervention was carefully designed to compare the effects of conventional lecture-based instruction with a mind map-based scaffolding approach in enhancing students' RWPPS skills. As illustrated in **Figure 1**, both the EG and the CG followed the same sequence of physics topics over eight weeks. Week 1 involved the administration of the pre-test (RWPPS 1), followed by six weeks of instruction covering kinematics (Weeks 2–3), force, momentum, and impulse (Weeks 4–5), work, energy, and power (Week 6), and dynamics and statics (Week 7). The intervention concluded in Week 8 with the administration of the post-test (RWPPS2). While the CG received conventional lecture-based instruction emphasizing conceptual explanations and worked examples, the EG was taught using an intervention format that integrated scaffolding with mind maps and explicitly supported metacomponent processes.

Figure 2 illustrates the mind map-based scaffolding intervention format implemented in the EG. This format was designed based on Sternberg's metacomponent processes and integrates mind maps as scaffolding at each stage of problem-solving. At the beginning of each session, the lecturer presented real-world physics problems grounded in everyday contexts. Students were then guided to identify the main issue and sub-problems using a mind map, facilitating a clear representation of relationships among concepts.

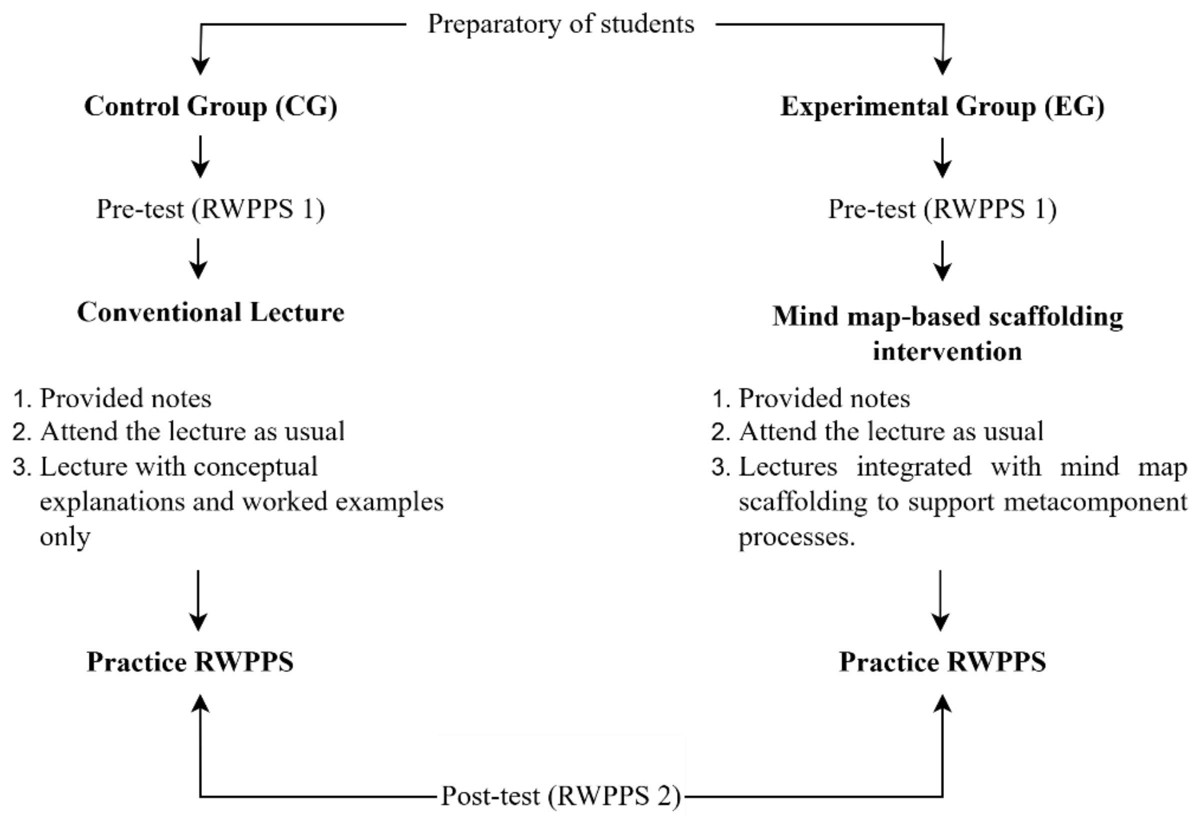

Figure 1. Chronology of educational modalities provided to students in conventional versus intervention lectures.

Following this initial phase, students organized the steps required to solve the problem and allocated resources using the mind map framework. Group collaboration was emphasized as students worked together to refine and expand their mind maps, exchange ideas, and develop solution strategies. Throughout the process, the lecturer acted as a facilitator, providing scaffolding through prompts and guiding questions without directly offering solutions. This approach ensured that students actively constructed their own problem-solving pathways while receiving adequate support to overcome challenges.

In the final stage of each instructional cycle, students evaluated and reflected on their solutions by using mind maps to visualize the effectiveness of their strategies and to monitor whether each step of the metacomponent processes had been addressed. Over the six weeks, scaffolding was gradually reduced as students demonstrated increased independence in using mind maps to plan, monitor, and evaluate their solutions. In contrast, students in the CG engaged with the same content but did not benefit from scaffolding or mind maps, relying solely on conventional lecture methods, which limited their active engagement. This systematic integration of mind map-based scaffolding ensured that the EG engaged meaningfully in real-world problem-solving processes. By incorporating Sternberg's metacomponents into the instructional design, the intervention aimed to enhance students' ability to analyze, plan, and evaluate solutions to complex real-world physics problems beyond rote application of formulas.

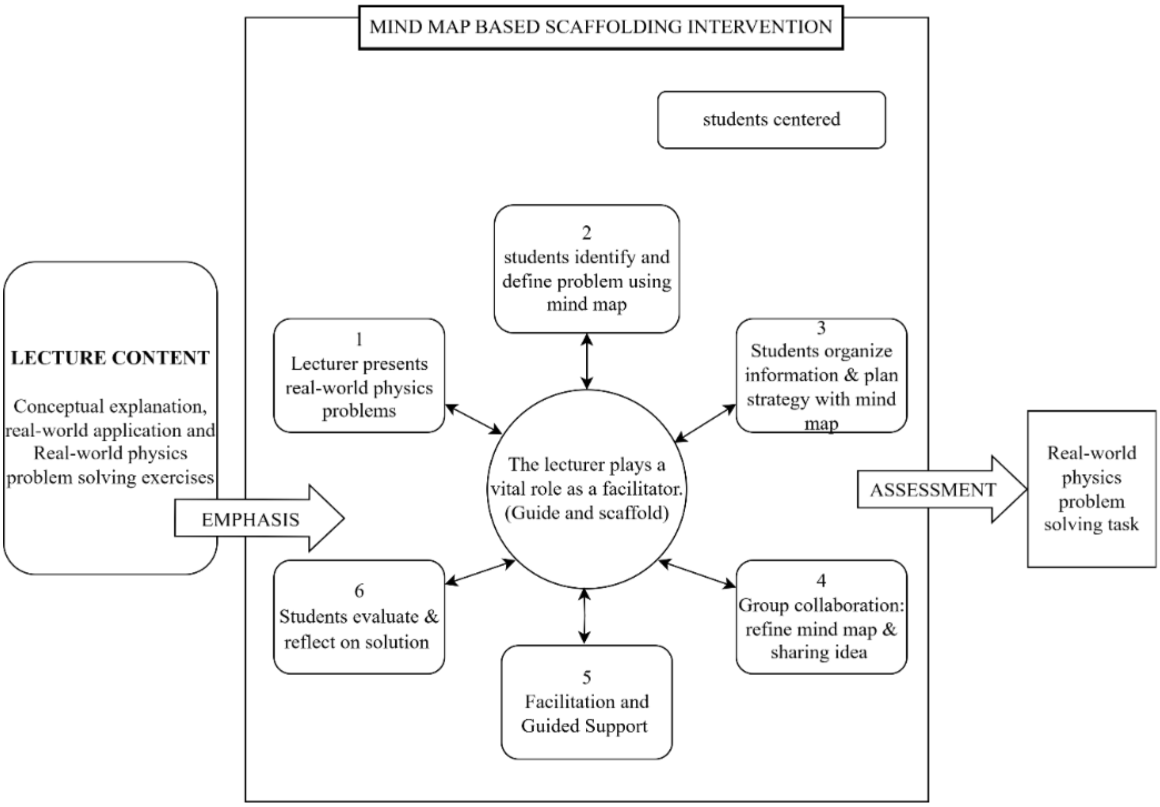

Figure 2. Mind map-based scaffolding intervention format for the EG.

2.4. Instruments

This study utilized two main instruments: the Real-World Physics Problem-Solving 1 (RWPPS1) for the pre-test and the Real-World Physics Problem-Solving 2 (RWPPS2) for the post-test. Both instruments consisted of open-ended, ill-structured problem-solving tasks designed to assess students' skills in real-world physics problem-solving. RWPPS1 and RWPPS2 each comprised four questions adapted from the University's problem-solving framework, focusing on the topics of kinematics and force. Each test was administered individually within 90 minutes. The problem contexts were situated in real-world scenarios to engage students in applying conceptual knowledge while developing their problem-solving skills.

To evaluate students' responses, a Real-World Physics Problem-Solving Skill Rubric (RWPPSS Rubric) was employed. This analytical rubric was designed to measure students' skills across seven key processes aligned with Sternberg's metacomponents:
(i) Problem identification;
(ii) Problem definition;
(iii) Strategy formulation and construction;
(iv) Information organization;
(v) Resource allocation;
(vi) Monitoring;
(vii) Evaluation.
The rubric was adapted and refined based on prior studies in physics problem-solving assessment. Students' written solutions were scored according to these indicators to capture the extent of their problem-solving abilities.

The validity of the instruments was established through expert judgment. Two experts in physics education reviewed the RWPPS instruments and the rubric for content validity, clarity, and alignment with the intended constructs. Their feedback played a crucial role in refining both the assessment items and the scoring descriptors. To further strengthen the evaluation process, a pilot study was conducted with a group of students who did not participate in the main study. This group provided valuable insights to ensure that the questions were clear and comprehensible. Additionally, the pilot study confirmed that the allocated time was sufficient and that the problem contexts were relevant and appropriate for pre-university students. Through these procedures, the assessment tools were established as both valid and practical for measuring students' real-world physics problem-solving skills.

2.5. Data Collection and Analysis

Data collection was conducted in two phases: a paper-and-pencil pre-test and a post-test. Both EG and CG completed the Real-World Physics Problem-Solving 1 (RWPPS1) as the pre-test to establish a baseline of students' problem-solving skills. Following the six-week intervention, the Real-World Physics Problem-Solving 2 (RWPPS2) was administered as the post-test to both groups under the same conditions. All assessments were conducted individually within a 90-minute time limit.

Students' written responses were evaluated using the Real-World Physics Problem-Solving Skill Rubric (RWPPSS), which assessed students' skills across seven metacomponent processes: problem identification, problem definition, strategy construction, information organization, resource allocation, monitoring, and evaluation. Each student's solution was scored independently, and the scores were converted into percentage values for analysis and comparison.

Data analysis was performed using SPSS version 29. Descriptive statistics (mean and standard deviation) were calculated to summarize students’ overall performance in both groups. Inferential statistics were employed, including (i) paired-samples t-tests to examine within-group differences between pre-test and post-test scores and (ii) independent-samples t-tests to compare differences between the EG and CG. In addition, Cohen's d effect size was calculated to determine the magnitude of the intervention's impact. Normalized gain (g) analysis was also used to categorize students' learning gains (low, medium, and high) across both groups. These analyses provided a comprehensive understanding of the effects of the scaffolding intervention on enhancing students' real-world physics problem-solving skills.

3. RESULTS AND DISCUSSION

Independent-samples t-tests were conducted to examine whether there were significant differences in real-world physics problem-solving skill scores between EG and CG. The findings reveal a clear difference in overall RWPPS scores between the two groups. As illustrated in **Figure 3**, students in the EG achieved higher mean scores than those in the CG. This pattern is supported by the independent-samples t-test results presented in **Table 1**, which indicate a statistically significant difference between the groups, $t(251) = 5.816$, $p < 0.001$, with a large effect size (Cohen’s $d = 0.73$). The substantial mean difference suggests that the mind map-based scaffolding intervention had a meaningful impact on enhancing students’ ability to solve real-world physics problems beyond the outcomes of conventional lecture-based instruction.

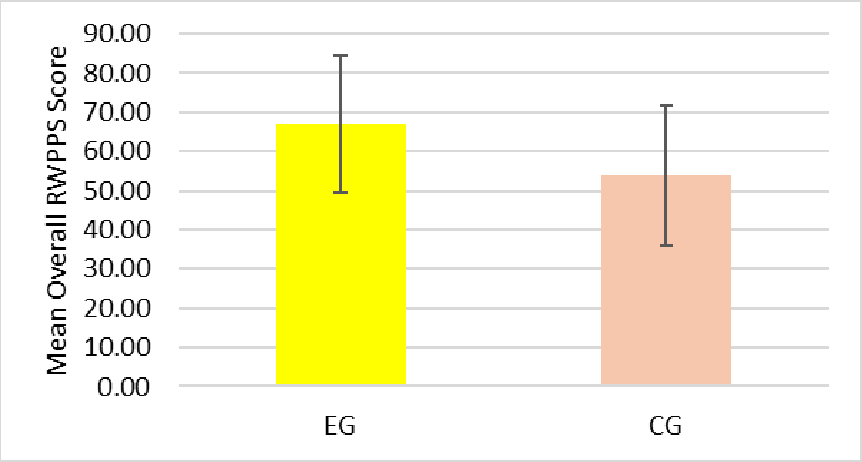

Figure 3. Comparison of mean overall RWPPS scores between the EG and the CG. Error bars represent ±1 standard deviation.

Table 1. Descriptive statistics and independent t-test results between EG and CG on overall RWPPS skill scores.

GROUP	N	MEAN (M)	STANDARD DEVIATION (SD)	T(DF)	P-VALUE	MEAN DIFF.	COHEN'S D
EG	127	67.00	17.54	5.816(251)	<0.001	12.96	0.73
CG	126	54.04	17.91				

A within-group analysis was subsequently conducted using paired-samples t-tests to examine improvements in students' skills within the EG. As shown in **Figure 4**, there is a clear enhancement in students' RWPPS skills following the intervention. The mean score increased substantially from the pre-test (M = 49.38, SD = 15.66) to the post-test (M = 67.00, SD = 17.54). This pattern is supported by the paired-samples t-test results presented in **Table 2**, which indicate a statistically significant increase in RWPPS scores, t(126) = −9.489, p < 0.001. The significant mean difference demonstrates that the mind map-based scaffolding intervention effectively improved students' problem-solving skills over time within the EG.

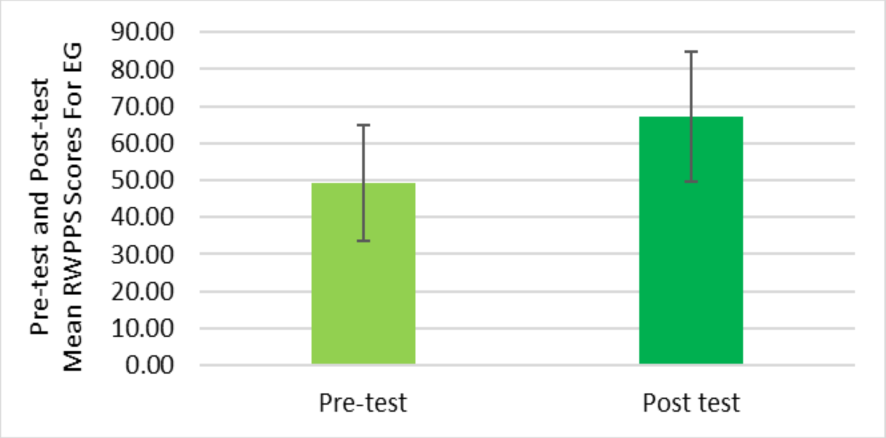

Figure 4. Comparison of Pre-test and post-test mean RWPPS scores for the eg, error bars representing ±1 standard deviation.

Table 2. Paired t-test results of pre-test and post-test for the EG on overall RWPPS skill scores.

GROUP	TEST	N	MEAN (M)	STANDARD DEVIATION (SD)	T(DF)	P-VALUE	MEAN DIFF.
Experimental (EG)	Pre-test	127	49.38	15.66	-9.489(126)	<.001	-17.62
Experimental (EG)	Post-test	127	67.00	17.54			

Further analysis compared the performance of the EG and the CG across the seven subskills of the RWPPS metacomponent. As presented in **Figure 5**, students in the EG outperformed those in the CG across all seven metacomponent skills. The results in **Table 3** show that the mean differences ranged from 1.58 to 2.09, and independent-samples t-tests indicated statistically significant differences at p < 0.001. The effect sizes, measured by Cohen's d, ranged from 0.60 to 0.75. These findings indicate that the intervention was effective in enhancing students' real-world physics problem-solving skills, particularly in higher-order cognitive processes across all dimensions of Sternberg's metacomponents.

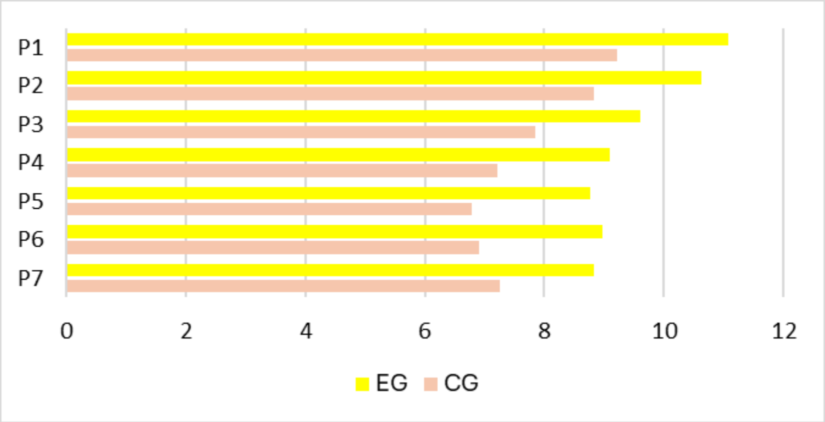

Figure 5. Comparison of mean scores for the seven metacomponent skills in RWPPS between EG and CG.

Table 3. Independent t-test between EG and CG on the seven metacomponent skills in RWPPS.

METACOMPONENT SKILLS	EG MEAN (STANDARD DEVIATION)	CG MEAN (STANDARD DEVIATION)	MEAN DIFF.	T(DF)	P	COHEN'S D
P1 Problem identification	11.08 (2.51)	9.22 (2.61)	1.86	5.77 (251)	< 0.001	0.72
P2 Problem definition	10.63 (2.43)	8.83 (2.59)	1.81	5.72 (251)	< 0.001	0.71
P3 Constructing a strategy	9.61 (2.42)	7.85 (2.62)	1.76	5.54 (251)	< 0.001	0.70
P4 Organizing information	9.09 (2.60)	7.21 (2.67)	1.89	5.70 (251)	< 0.001	0.72
P5 Resource Allocation	8.77 (2.78)	6.79 (2.76)	1.99	5.70 (251)	< 0.001	0.73
P6 Monitoring	8.98 (2.87)	6.90 (2.69)	2.09	5.97 (251)	< 0.001	0.75
P7 Evaluation	8.83 (2.60)	7.25 (2.69)	1.58	4.75 (251)	< 0.001	0.60

In addition, a normalized gain ⟨g⟩ analysis was conducted to assess the extent of students' improvement in RWPPS skills from the pre-test to the post-test. As shown in **Figure 4** and **Table 4**, the distribution of normalized gain levels differed significantly between EG and CG.

In the low-gain category ($g < 0.3$), a majority of CG students (71.4%) were classified at this level, compared to 53.5% of EG students. Conversely, 41.7% of EG students achieved medium-gain levels ($0.3 \leq g < 0.7$), whereas only 27.0% of CG students reached this category. Additionally, 4.7% of EG students attained high-gain levels ($g \geq 0.7$), while only 1.6% of CG students fell into this category.

Although the proportion of students in the high-gain category was relatively small, the difference between the two groups suggests that the intervention effectively elevated some students to a higher level of mastery in applying problem-solving skills to real-world physics problems. Overall, the normalized gain analysis indicates that students in the EG demonstrated greater improvement in their problem-solving skills from the pre-test to the post-test compared to those in the CG. The more balanced distribution of gains across low, medium, and high levels in the EG further highlights the effectiveness of the scaffolding intervention in fostering deeper learning and sustained development of RWPPS skills.

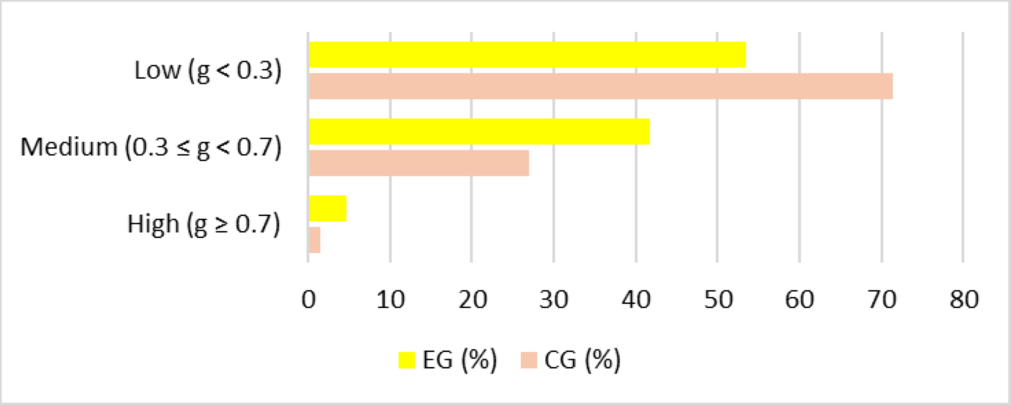

Figure 5. Distribution of normalized gain ⟨g⟩ levels of students in the CG and CG.

Table 4. Normalized gain <g> distribution percentage of students in the EG and CG.

GAIN LEVEL	EG (%)	CG (%)
Low ($g < 0.3$)	53.5	71.4
Medium ($0.3 \leq g < 0.7$)	41.7	27.0
High ($g \geq 0.7$)	4.7	1.6

The purpose of this study was to examine the effects of a mind map-based scaffolding intervention in enhancing students' RWPPS skills. The results provide strong empirical evidence of the intervention's impact on students' RWPPS skill levels. Therefore, this section discusses the findings in relation to existing literature, theoretical perspectives, and implications for physics education.

The independent-samples t-test results in **Table 1** revealed that students in the EG outperformed those in the CG in their RWPPS scores, with a large effect size (Cohen’s d = 0.73). This indicates that the mind map-based scaffolding intervention was not only statistically significant but also practically meaningful in strengthening students’ problem-solving skills. Additionally, the paired-samples t-test results in **Table 2** show a statistically significant improvement within the experimental group, $t(126) = -9.489$, $p < 0.05$, indicating that students’ RWPPS scores increased significantly from the pre-test to the post-test. Together, these findings affirm that the intervention effectively supported the development of both cognitive and metacognitive skills required for real-world physics problem-solving.

These findings are consistent with previous research emphasizing the importance of scaffolding in physics education. Scaffolding has been shown to reduce cognitive overload by breaking complex tasks into more manageable components, thereby providing learners with the structure needed to engage in higher-order thinking [26, 39]. In this study, mind maps functioned as scaffolding tools that enabled students to visualize relationships among concepts and systematically plan their solution strategies, aligning with Vygotsky's theory of the zone of proximal development (ZPD). According to Vygotsky, the ZPD represents the gap between what learners can achieve independently and what they can accomplish with appropriate guidance. Through structured support using mind maps, students were able to solve problems that would otherwise be beyond their capabilities, gradually internalizing processes such as planning, monitoring, and evaluation until they could perform these tasks independently [3]. The findings of this study illustrate this principle, as students in the EG initially relied on guided mind maps but progressively developed independence in applying problem-solving skills. This transition reflects the essence of the ZPD, where instructional scaffolds serve as a bridge from assisted to self-regulated problem-solving in addressing complex, ill-structured physics problems.

Furthermore, the use of mind maps in this study appeared to support several key metacomponent processes involved in real-world physics problem-solving. Through the visual mapping of concepts and relationships, students were able to identify and define the core elements of the problem more clearly before attempting calculations. The structure of the mind maps also helped students organize relevant information and construct appropriate solution strategies, enabling them to allocate cognitive resources more effectively when dealing with complex physics problems. During the problem-solving process, the visual layout allowed students to monitor their steps and evaluate the consistency of their solutions. These findings suggest that mind map-based scaffolding not only supports conceptual organization but also facilitates the activation of multiple metacomponent skills.

In addition, the improvement in EG performance supports Sternberg's assertion that metacomponent processes, such as problem recognition, definition, planning, monitoring, and evaluation, can be explicitly taught and developed through instructional interventions. In this study, these processes enabled students to approach real-world physics problems more systematically rather than relying solely on formulas. Conventional lecture approaches often overlook these higher-order processes, focusing instead on formula application and procedural practice [5, 6]. By integrating scaffolding with mind maps into the instructional design, this study ensured that students actively engaged with these metacomponents, which explains the significant performance gains in the EG compared to the CG. This finding is consistent with some papers [28]. Who demonstrated that learning models incorporating visual tools and metacognitive activities, such as mind mapping, significantly improved students' ability to plan, monitor, and evaluate their learning strategies. Their study emphasized that structured visual scaffolds helped students regulate their thinking processes and make learning more meaningful through reflective engagement. Similarly, in this study, mind map-based scaffolding functioned as a cognitive organizer, guiding students to break down real-world physics problems into manageable components and enabling them to plan and execute solutions more effectively.

The analysis of the seven metacomponent sub-skills further highlights the effects of the intervention. Students in the EG outperformed their CG counterparts across all seven dimensions: problem identification, problem definition, strategy construction, information organization, resource allocation, monitoring, and evaluation. These findings are particularly significant, as they indicate that the intervention not only improved overall performance but also systematically enhanced specific executive processes identified by Sternberg as essential for effective problem-solving [27].

The most notable improvement was observed in monitoring, suggesting that mind map-based scaffolding was particularly effective in helping students oversee their solution processes, identify errors, and adjust their strategies accordingly. Although evaluative processes remain challenging, the observed gains indicate meaningful development in higher-order regulation, which is essential for solving real-world problems. However, the relative progress in evaluation was smaller compared to other sub-skills. This pattern highlights both the strengths of the intervention and the areas where students still require support, emphasizing the importance of sustained scaffolding in developing higher-order metacognitive skills.

The normalized gain analysis provided additional insight into the extent of student improvement. While most students in the CG remained in the low-gain category, those in the EG demonstrated a more balanced distribution across low, medium, and high levels of improvement. A substantial proportion of EG students achieved medium gains, and a small but noteworthy number reached high gains. These findings are consistent with previous studies [40, 41], which reported that structured and active learning interventions in physics tend to produce higher normalized gains compared to conventional instruction. Importantly, although limited, the presence of students in the high-gain category indicates that mind map-based scaffolding can elevate learners to a higher level of competence in solving real-world physics problems—an outcome less likely to be achieved through traditional teaching methods alone.

The intervention in this study also addresses this issue by situating learning within real-world problem contexts and providing cognitive tools to manage complexity. By engaging students with ill-structured problems in a structured manner, the intervention not only enhanced immediate performance but also equipped students with transferable 21st-century skills such as critical thinking, collaboration, and creativity [24]. These broader outcomes are essential for encouraging students to persist in physics and STEM education more generally.

The evidence further supports the view that scaffolding should not be regarded merely as a temporary instructional aid but as an integral component of curriculum design in physics education. The gradual reduction of scaffolding over the six-week intervention encouraged students to assume greater responsibility for their learning, consistent with the principle of progressive autonomy [42]. This approach ensures that students do not remain dependent on external support but instead develop the self-regulatory skills necessary for independent problem-solving. The balanced distribution of gains in the EG provides evidence of this transition, as students progressed from basic improvements toward medium and high levels of mastery.

The findings of this study strongly support the integration of mind map-based scaffolding into pre-university physics instruction. The intervention not only improved overall problem-solving performance but also enhanced students' engagement in real-world problem-solving processes that underpin effective learning. By linking cognitive theory, instructional practice, and empirical evidence, this study demonstrates the potential of innovative scaffolding strategies to address persistent challenges in physics education. The results affirm that developing real-world problem-solving skills requires more than conventional lecture-based approaches; it demands deliberate instructional design that incorporates scaffolding, promotes collaboration, and explicitly fosters higher-order cognitive processes. Such approaches are essential for preparing students not only for academic success but also for the demands of the 21st century, where solving complex real-world problems is a critical competence.

4. CONCLUSION

This study demonstrated clear differences between pre-university students who experienced mind map-based scaffolding and those who received conventional lecture-based instruction. While students in the CG tended to rely on procedural, formula-based approaches, those in the EG engaged more systematically in organizing information, planning strategies, monitoring progress, and reflecting on their solutions when solving real-world physics problems. These differences were reflected in improved post-test scores among students exposed to mind map-based scaffolding, particularly in the areas of problem identification, information organization, resource allocation, and monitoring during real-world physics problem-solving.

The findings suggest that these improvements may be attributed to the deliberate instructional design that integrated scaffolding with structured support for higher-order thinking processes. By making students' thinking processes more explicit and manageable, the integration of mind map-based scaffolding with metacomponent processes enabled learners to cope more effectively with the complexity of ill-structured, real-world physics problems. This approach supported students in moving beyond surface-level problem-solving toward deeper conceptual understanding and more reflective reasoning.

Based on these results, mind map-based scaffolding integrated with metacomponents represents a promising instructional strategy for supporting physics problem-solving in similar pre-university contexts. Such an approach can facilitate the development of transferable problem-solving skills essential for 21st-century education. In conclusion, mind map-based scaffolding offers a valuable pedagogical approach that can be adapted across various topics and contexts in physics education. Future research may extend this work by exploring its long-term effects, scalability in larger cohorts, and integration with other active learning strategies, which are crucial for ensuring that pre-university physics instruction remains relevant, effective, and capable of preparing students to address complex real-world challenges.

5. AUTHORS' NOTE

The authors declare that there is no conflict of interest regarding the publication of this article. The authors confirmed that the paper was free of plagiarism.

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