

Students' metacognition knowledge and skills during physics problem-solving process

Zeynep Dulger^{ID*} and Feral Ogan-Bekiroglu^{ID†}

Science and Mathematics Education Department, Physics Education Division, Marmara University, Istanbul, 34852, Turkey



(Received 13 February 2025; accepted 3 June 2025; published 17 July 2025)

This study examined how students utilized metacognition while solving physics problems. A case study design was implemented, involving 30 11th-grade students. Data were collected by using open-ended physics problems, with a think-aloud strategy applied during the process. Both quantitative and qualitative analyses were conducted using the metacognition during problem-solving rubric, classifying students as either experts or novices. The findings revealed several key insights: First, the majority of high school students fall into the novice category, struggling with the application of metacognitive knowledge and skills while solving physics problems. Second, expert students demonstrate strong evaluation and planning skills but limited metacognitive knowledge and monitoring abilities. Third, novice students exhibit major deficiencies in metacognitive knowledge and monitoring. Fourth, assessment practices focusing heavily on final results may hinder the development of deeper metacognition and problem-solving skills. Fifth, metacognitive knowledge and monitoring are crucial for generating successful solutions for scientific problems, especially in high-complexity tasks. Last, familiarity with the content and the complexity level of the problem may influence students' success in problem solving. The metacognition rubric developed for this research may serve as a valuable tool for future studies in the field.

DOI: [10.1103/PhysRevPhysEducRes.21.020106](https://doi.org/10.1103/PhysRevPhysEducRes.21.020106)

I. INTRODUCTION

Metacognition and problem solving are fundamental components of 21st-century skills [1–3]. Metacognition refers to an individual's awareness of their learning process, including the knowledge and skills required to learn effectively and the ability to determine when and how to apply them successfully [4–8]. This cognitive ability enables individuals to achieve specific goals and regulate their problem-solving processes [9,10]. Metacognition consists of two key elements: metacognitive knowledge and metacognitive skills [11]. Metacognitive knowledge pertains to an individual's understanding of their own cognitive processes, while metacognitive skills involve the strategies used to regulate learning and problem solving [12]. These skills play a critical role in the interaction between the individual, the task, and the strategies employed, ultimately enhancing one's ability to understand and apply knowledge effectively [4,13–15].

Problem solving, as described by Popper [16], is an inherent part of human life. It is the process of addressing

and resolving challenges by finding viable solutions [17,18]. In the context of science and physics education, problem solving facilitates deeper learning and the development of essential skills [19–22]. A primary goal of physics education is to help students develop a profound understanding of concepts and apply them effectively in problem-solving scenarios [23,24].

Various factors influence problem-solving abilities, with domain knowledge and metacognition being among the most critical [17]. Metacognition enables students to manage their cognitive processes and enhances their ability to solve problems efficiently and effectively [25–29]. The type and quality of metacognitive skills used during problem solving significantly impact learning outcomes [30]. Students with well-developed metacognitive abilities are better equipped with essential problem-solving skills [31]. Several studies have explored the relationship between metacognition and problem solving [32–40]; however, research specifically examining how students employ metacognition while working on physics problems remains limited. Therefore, this study aims to investigate the ways in which students utilize their metacognitive knowledge and skills during physics problem solving.

II. CONCEPTUAL FRAMEWORK

Metacognitive knowledge is relatively stable and develops over time, enabling individuals to reflect on their cognitive processes [41]. In contrast, metacognitive skills

*Contact author: lilithzd7@gmail.com

†Contact author: fbekiroglu@marmara.edu.tr

are dynamic and involve higher-order cognitive processes used to regulate learning tasks [42,43]. These skills include planning, monitoring, and evaluation, each of which plays a crucial role in learning and problem solving [15]. Planning involves selecting appropriate strategies and structuring a plan for learning [44]. Monitoring refers to an individual's ability to oversee and regulate their cognitive strategies during problem solving [41]. Evaluation entails assessing one's learning process and outcomes to ensure understanding and accuracy [7,45]. Differences in metacognitive skills significantly affect problem-solving efficiency and effectiveness [14,29,46,47]. That is, one student is conscious of those skills being utilized in different problems, and another student has the skills to select and adapt them for problem solving [48].

Problem solvers, depending on their level of expertise, construct a mental representation of a problem and organize relevant domain knowledge before solving it [41]. Experts approach problems by focusing on fundamental principles and systematically applying their knowledge to develop solutions [49–56]. In contrast, novices tend to concentrate on surface-level features rather than underlying conceptual frameworks [41,57,58]. Because experts possess a more comprehensive and structured knowledge base, they are better able to apply and transfer their understanding across different problem-solving scenarios [59–61]. This study categorizes students as either experts or novices based on their metacognitive abilities.

III. LITERATURE REVIEW ABOUT THE ROLE OF METACOGNITION IN PROBLEM SOLVING

Neto and Valente [62] suggest that a metacognitively oriented approach to problem solving fosters a synergy between scientific concepts and critical thinking skills. Researchers have employed both qualitative and quantitative methods to examine the impact of metacognition on problem solving. Rozencwajg [63], for example, explored the extent to which students' metacognitive awareness influences their conceptual understanding and problem-solving performance. Taasooobshirazi and Farley [64] tested a model of expertise in physics problem solving and found that metacognitive planning significantly influenced the choice of strategies, ultimately affecting problem-solving success. Prather *et al.* [65] examined novice programmers' challenges and found that some students instinctively enhanced their problem-solving tools when explicit support for metacognitive awareness was lacking. Other studies have also highlighted the benefits of metacognitive awareness in problem solving [66–69].

The literature review indicates that metacognition is an important component that contributes to students' learning and problem solving in any discipline, and when students use their metacognition while solving content-related problems, the probability of solving problems correctly increases. However, despite the evidence supporting the

role of metacognition in problem solving, the related literature does not show how students apply metacognitive strategies to science-related problems. Further research is needed to understand the nature of the relationship between metacognition and problem solving. Therefore, this study aims to address the following research questions:

1. How do students use their metacognitive knowledge and skills when solving physics problems?
2. How do expert and novice students approach problem-solving scientifically?

IV. METHODOLOGY

A case study design was used in this study. The case study is a genre of qualitative method that involves the identification of a specific situation in a small group and offers an in-depth analysis [70]. The participants of the study were 30 students who were volunteers among 103 11th-grade students studying in an urban public high school. Their age ranged from 17 to 18. The 30 students were numbered S1 to S30. They had different academic achievements in physics courses and expressed interest in pursuing different career plans. Therefore, it was assumed that their cognitive and metacognitive levels were different from each other.

Data were collected by using a questionnaire that consisted of open-ended physics problems about the “photoelectric effect” concept. A table of specifications was prepared to evaluate the content validity of the questionnaire. The levels of problems—understanding, applying, analyzing, and evaluating—were structured based on Bloom's Taxonomy. The think-aloud strategy was applied to obtain the data. This strategy involves participants verbalizing their thoughts aloud while performing a task [71], enabling the capture of momentary data [72]. The participants were required to think loudly while solving the problems and their performances were video recorded. The students' recordings took approximately 25–30 min. The researcher, who collected all the data, was their physics teacher.

Metacognitive mental models, behaviors, strategies, and performances of expert and novice problem solvers were determined with the help of a literature review and shown in Table I. Competences in “Metacognition during problem-solving rubric” (see Table II) were created by taking cognition and behaviors given in Table I into account. In order to generate the items in the rubric, the metacognitive process during problem solving was analyzed and written step by step. The items were verbalized as knowledge and skills. Then, the scoring levels in the rubric were prepared, and the draft version was generated. The rubric was submitted to two experts for content validation. According to the feedback from the experts, some minor corrections were made and the final version of the rubric was generated. Metacognition during problem solving was described under the following four dimensions: metacognitive knowledge, planning, monitoring, and evaluation. Metacognitive knowledge refers to individuals' conscious thinking about their

TABLE I. Experts and novices' cognition and behaviors during problem solving process.

Expert problem solvers	Novice problem solvers
a) They have the ability to solve the problem by being aware of their own cognitive processes and reflecting on their thoughts [76]. (metacognitive knowledge) a) They are able to recall appropriate domain knowledge and strategy with little cognitive effort because they have extensive and largely unified, correlated domain knowledge [59]. b) They have multiple representations. They move quickly between their representations, particularly to understand the problem [78,79]. c) They can easily identify the underlying structure of domain problems because they focus on the structure of the problem. [59,80]. So, they can reconstruct the problem when they need [61]. d) They obtain qualitative information by making a detailed plan for the solution [77]. Thus, they select the appropriate problem-solving procedure to solve the problem and apply it [59]. (planning) a) They use metacognition better to monitor their own processes after solving the problem [59]. b) They are better at monitoring and organizing their own initiatives [80]. (monitoring) a) They solve the problem fast [79]. b) They use their past experience to evaluate the solution [61]. (evaluation)	a) They lack the ability to think about problem-solving processes and reflect on what they know [66]. a) They have superficial domain knowledge. They have difficulty in establishing relationships between subjects [77]. b) Since they approach the problem superficially, they often do not consider understanding the problem [79]. Since they move slowly through their representations. They show little cognitive effort when recalling appropriate domain knowledge and strategy [59,78]. c) Since they focus on the superficial features of the problem, they try to solve the problem without a qualitative description [77,80]. d) Since they plan superficially, they do not make much use of problem-solving procedures [59,77]. a) They have low monitoring skills and problem-solving effort [80]. a) They solve the problems slowly [78].

abilities and behaviors in their own learning processes [4,73,74]. Metacognitive skills, including planning, monitoring, and evaluation, on the other hand, are applied to solve the problem and to check the correctness of the response by students who identify inconsistencies and contradictions in the solution of a problem [59]. There are five items under each dimension of the rubric. The lowest score that can be obtained from the rubric is zero, and the highest score is 20. The students' transcripts from the video recordings were analyzed by using this five-point scale rubric. Two researchers analyzed the students' knowledge and skills during their problem-solving process separately and came up with 88% agreement. The reliability measured by Cohen's κ was 0.74 revealing that the coding done for the students' metacognition had adequate reliability [75].

Due to the fact that one student's score from the rubric can be between 0 and 20 and each dimension has an equal number of items, the maximum score was divided in half and the students whose scores were below 10 were coded as novices and the students whose scores were 10 or above were coded as experts. In the end, 20 students were characterized as novices, and 10 students were characterized as experts.

Pearson correlation coefficient analysis was performed to understand the relationship between expert-novice problem solvers' metacognition and their physics problem-solving achievement. To categorize the students' competencies in each dimension and determine their metacognition levels, the mean scores (ranging from 0 to 5) were divided into four intervals: 0–1.25 as low, 1.26–2.50 as emerging, 2.51–3.75 as proficient, and 3.76–5.00 as high.

A detailed answer key was prepared in order to identify the students' answers to five physics problems either scientifically or nonscientifically. The answers given by the students were coded as scientific when their responses were consistent with the scientific conceptualization. For instance, for the following question: "How is photoelectricity used in automatic doors used in shopping malls and supermarkets? Explain why?", S9's answer, i.e., "these doors have photocell circuits. Himm... if I draw the figure like this... This is the cathode; opposite is the anode... There is a kind of metal surface at the cathode and light falls on it. Let me show you on the diagram... This light takes electrons from the metal. Photocell circuits are found in the doors of shopping malls. When we come in front of these doors, the sensor detects us.

TABLE II. Metacognition during problem-solving rubric.

Dimension	Expected knowledge and skills	5	4	3	2	1	0
Metacognitive knowledge	- Knows the factors that influence their own strategies and performance as a learner - Knows when and why to use problem-solving strategies - Knows concepts and opinions related to cognitive events - Knows which strategy to use and how to use it in cognitive events - Knows the levels at which they can use their knowledge and skills	Shows five items of he expected knowledge	Shows four items of the expected knowledge	Shows three items of the expected knowledge	Shows two items of the expected knowledge	Shows one item of the expected knowledge	No sign of any knowledge
Planning	- Defines the problem - Expresses the relationships in the structure of the problem - Makes a detailed plan to solve the problem - Controls plan for solving the problem - Determines appropriate strategies for solving the problem (drawing a figure, using keywords, visualization, determining the formula, etc.)	Shows five skills of the expected skills	Shows four skills of the expected skills	Shows three skills of the expected skills	Shows two skills of the expected skills	Shows one skill of the expected skills	No sign of any skill
Monitoring	- Tracks the accuracy of performance - Makes predictions about the next performance - Checks the effectiveness of learning strategies - Determines errors in performance - Gives feedback regarding incomplete and incorrect learning and behavior	Shows five skills of the expected skills	Shows four skills of the expected skills	Shows three skills of the expected skills	Shows two skills of the expected skills	Shows one skill of the expected skills	No sign of any skill
Evaluation	- Expresses thoughts about the tasks and strategies that affect learning - Expresses the improvement of performance and the quality of the knowledge gained - Analyses the solution and expresses the result numerically or verbally - Expresses the efficiency of the learning outcomes and the process - Makes arrangements for future learning with past experiences	Shows five skills of the expected skills	Shows four skills of the expected skills	Shows three skills of the expected skills	Shows two skills of the expected skills	Shows one skill of the expected skills	No sign of any skill

Let me think a little...There was light in this circuit, right, teacher? Yes, yes, I think that light hits us. I just told you the way I just said.... Then the circuit closes and the door opens for us" was coded as scientific. For the same problem, S17's answer, i.e., "There is a sensor on the door. When the frequency of the light on the sensor suddenly changes, the door opens" was coded as nonscientific as the student's answer was scientifically incorrect. For the question, i.e., "red and violet light are incident separately on the metal surface at the cathode of a photoelectric circuit. Which color of light is more successful in removing electrons from the metal surface? Explain why?", the following answer belonged to S19 was coded as scientific: "I think purple light. Because the energy of violet light is higher than the energy of red light. As far as I remember, the photon's ability to remove electrons from the metal surface depends on the energy of the light and it should be more than the electron on the metal surface." On the contrary, for the same problem, S30's answer, i.e., "I don't think either of them can. Maybe with a green light" was coded as nonscientific because the student's answer did not match the scientific answer in the answer key. The second researcher randomly selected answers from 10 students to assess the reliability of this coding. When two researchers compared their coding, they reached 93% agreement. The reliability measured by Cohen's κ was 0.77 indicating that the coding for the students' answers to the physics problems had adequate reliability [75].

V. RESULTS AND DISCUSSION

A. Students' metacognitive knowledge and skills while solving physics problems

Results indicate that while approximately one-third of the students (33%) were classified as experts, two-thirds (67%) were identified as novices. The mean values of metacognitive knowledge and skills demonstrated by the experts and novices during physics problem solving are presented in Table III.

The experts exhibited a high level of evaluation skills ($X = 4.50$; see Table III). Specifically, they analyzed their solutions, explained results both numerically and verbally, articulated their thoughts regarding the tasks and strategies employed, and made adjustments for future learning based on past experiences. In addition, the experts demonstrated a proficient level of planning ($X = 3.60$). In other words, they

defined the problems, explained the internal relationships within them, and developed plans and appropriate strategies to solve them. The findings further revealed that the expert students particularly focused on the planning phase and the accuracy of the solutions they produced. The findings of this study are consistent with those of Taasobshirazi and Farley [81], who found that experts' planning skills had a significant impact on successful problem solving. The results also align with the findings of Tachie [82], who argued that students corrected their initial mistakes during problem solving and employed evaluation strategies throughout the process as they worked to understand the problems.

However, the experts showed only surface-level metacognitive knowledge ($X = 2.30$) and exhibited limited monitoring skills ($X = 1.90$) during problem solving. That is, while they were aware of their cognitive ability to solve problems, their capacity to self-monitor throughout the process was underdeveloped. Consequently, their metacognition levels in the metacognitive knowledge and monitoring dimensions were classified as emerging. Metacognitive knowledge refers to students' understanding of goals and tasks, as well as their insights into their own thinking processes [15]. This study argues that the experts' limited awareness of their own characteristics and the strategies influencing their performance negatively impacted their monitoring abilities. Since both metacognitive knowledge and monitoring are dimensions closely tied to individual characteristics, it is considered natural for these two dimensions to influence one another.

There was considerable variation among the experts across dimensions. For example, 40% (S7, S9, S24, and S25) scored low (1 or 2) in both metacognitive knowledge and monitoring, yet high (4 or 5) in planning and evaluation. Additionally, while S26 and S28 scored 1 in planning, they scored 5 in evaluation. S26 also achieved the second-highest monitoring score (3) by recognizing gaps in his understanding and providing self-feedback. Only S4 achieved the highest scores across all dimensions, solving problems by recalling prior knowledge and integrating it effectively.

The key distinction between the novices and experts lay in their performances in the planning and evaluation dimensions. The novice students demonstrated emerging-level skills in these areas ($X = 1.60$, $X = 1.70$ respectively). Although they showed some intent to plan, their approaches lacked structure, and while they occasionally recognized errors, they were unable to explain them. These

TABLE III. Metacognition knowledge and skills of the experts and novices. Note X , mean; SD, standard deviation.

	Expert (X)	Expert (SD)	Novice (X)	Novice (SD)
Metacognitive knowledge	2.30	1.49	0.05	0.22
Planning	3.60	1.51	1.60	1.43
Monitoring	1.90	1.29	0.10	0.45
Evaluation	4.50	0.85	1.75	1.65

findings are consistent with Desoete [83], who found that evaluation skills effectively distinguish below-average performers in problem solving from their peers. The novices largely failed to employ metacognitive knowledge and self-monitoring during problem-solving ($X = 0.05$, $X = 0.10$ respectively) by lacking awareness of their personal strengths, weaknesses, and learning strategies, and proceeding without actively monitoring their progress. The novices often provided superficial answers and attempted to jump directly to solutions without deep reflection. This tendency may be attributed to the heavy emphasis on summative assessment in the high school education system—where exam results heavily influence final grades—and the multiple-choice format of the university entrance exam.

Some novices (S1, S3, S13, and S30) (20%) scored 0 across all dimensions, while S16 and S17 scored 0 in all dimensions but achieved 4 in planning. For instance, S3 completed the problem quickly, yet his incorrect answer prolonged the solution process. He remarked:

...to its frequency... Because, for example, if the numbers were small, the light... Hmmm, the current would be less. For example, if the changing amount is larger, then the flow will be greater...

B. Expert and novice students' physics problem solving

According to Table IV, none of the experts were able to solve all five physics problems. Their metacognitive knowledge and monitoring performance were notably lower than their skills in other dimensions, which may have limited their ability to determine when and how to apply their knowledge and reduced their capacity for self-evaluation. Only half of the experts (S4, S9, S19, S26, and S28) solved up to three problems.

Despite being categorized as an expert, S8 failed to solve any problems. Although he attempted to use planning strategies and guide himself through the problem-solving process, he struggled during the recall phase and confused the knowledge he possessed, leading to incorrect answers despite following the general problem-solving approach. Furthermore, none of the experts solved the third and fifth problems correctly. These problems, classified at the

evaluation level—the second-highest level of Bloom's taxonomy—required advanced cognitive skills. In contrast, 80% of the experts answered the fourth problem correctly, which related to a real-life phenomenon (photoelectricity in automatic doors) and was categorized at the application level. Familiarity with the content may have contributed to their success. Similarly, 70% of the experts answered the first problem (understanding level) correctly, and 60% answered the second problem (analysis level) correctly. Even though the experts evaluated the strategies used in the problem-solving process and corrected their mistakes by analyzing their own performance [84], these results indicate that proficiency in planning and evaluation alone was insufficient to provide scientific solutions to high-level cognitive physics problems. In another study conducted by Bereiter and Scardamalia [85], it was observed that as the difficulty of a task or problem increased, the number of skills demonstrated by experts decreased. These findings argue that differences in problem difficulty might let expert students encounter challenges, particularly in dimensions related to their personal characteristics.

The results in Table IV revealed that 40% of the novice students (S5, S6, S12, S13, S14, S20, S22, and S30) failed to answer any physics problems scientifically, while only 20% (S11, S15, S18, and S21) managed to answer two problems correctly. The second and fourth problems were solved by only 30% of the novices. A lack of metacognitive knowledge and monitoring skills likely contributed to the novices' difficulties in finding scientific solutions. This finding aligns with previous research demonstrating a significant positive relationship between problem-solving strategies and monitoring [86]. Monitoring involves evaluating performance both prospectively (before solving the problem) and retrospectively (after completing the solution) [87]. Retrospective evaluation, in particular, encompasses self-assessment at each stage: understanding the problem, planning and executing the solution, and evaluating the process [88]. Similarly, this study supports the findings of Ali *et al.* [89], who emphasized the critical role of monitoring in successful physics problem solving.

According to research by Muir *et al.* [90], to develop expertise, students must utilize their metacognitive and problem-solving skills. These results are in agreement with this study, which revealed the lack of these skills in novices.

TABLE IV. Responses of expert and novice problem solvers to physics problems. Note F , frequency value; %, percent value.

Problems	Expert scientific (F , %)	Expert nonscientific (F , %)	Novice scientific (F , %)	Novice nonscientific (F , %)
First	7, %70	3, %30	4, %20	16, %80
Second	6, %60	4, %40	6, %30	14, %70
Third	0, %0	0, %0	0, %0	0, %0
Fourth	8, %80	2, %20	6, %30	14, %70
Fifth	0, %0	0, %0	0, %0	0, %0

TABLE V. Correlation between expert-novice metacognition and problem-solving achievement.

		Problem-solving achievement
Expert-novice metacognition	Pearson correlation	0.632
	Significance (two-tailed)	0.000
	<i>N</i>	30

Another study by Fernandez *et al.* [91] found that some students focused on superficial aspects of the problem and attempted to solve it without following a proper problem-solving process. This may help explain the deficiencies observed among the novices in this study. Furthermore, a study by Tachie [82] found that students who activated their metacognitive skills during problem solving achieved higher scores. Similarly, this study identified the activation of metacognitive skills as a key differentiator between experts and novices.

Results from the Pearson correlation coefficient analysis presented in Table V showed a significant, positive, and moderate relationship between expert-novice metacognition and physics problem-solving achievement ($r = 0.63$, $p = 0.00$). The experts produced more scientifically accurate answers than the novices. Consequently, experts demonstrated a broader and more advanced range of problem-solving skills compared to novices. This finding underscores the role of metacognition in fostering deeper comprehension and higher success rates in scientific problem solving. Physics problem-solving success was strongly linked to metacognitive competence: Experts were more likely to produce scientifically accurate responses. They effectively applied prior knowledge, recognized problem structures, and used systematic approaches to reach solutions. Novices struggled to structure their reasoning, often relying on surface-level features rather than deep conceptual understanding. Their inability to monitor and regulate their thought processes resulted in frequent errors and ineffective problem-solving strategies.

VI. CONCLUSIONS AND SUGGESTIONS

This study highlights the critical role of metacognition in physics problem solving and reveals significant disparities between expert and novice students. The following conclusions knowledge and monitoring are crucial for generating successful solutions for scientific problems, especially in high-complexity tasks. Finally, familiarity with the content and the complexity level of the problem may influence students' success in problem solving.

A key implication of this study is the pressing need to integrate can be drawn from the study: First, the majority of

high school students fall into the novice category, struggling with the application of metacognitive knowledge and skills while solving physics problems. Second, expert students demonstrate strong evaluation and planning skills but limited metacognitive knowledge and monitoring abilities. Third, novice students exhibit major deficiencies in metacognitive knowledge and monitoring. Fourth, assessment practices focusing heavily on final results may hinder the development of deeper metacognition and problem-solving skills. Fifth, metacognitive training in physics education to enhance students' problem-solving skills and overall learning outcomes. The research indicates that students with limited metacognitive awareness are less likely to solve problems scientifically, underscoring the necessity of explicit instruction in metacognitive strategies. While some students can intuitively develop these skills, the majority require structured interventions, such as guided reflection and self-explanation exercises, to enhance their problem-solving performance. Moreover, the study's findings suggest that a deeper focus on self-monitoring could bridge the gap between expert and novice students. Given that experts tend to neglect this crucial skill, educators should emphasize self-assessment techniques that encourage students to track their thought processes and adjust their strategies accordingly. Additionally, further investigation is needed to explore how metacognitive scaffolding and adaptive learning environments can be leveraged to foster long-term improvements in students' problem-solving abilities.

Despite its contributions, this study has limitations, including its reliance on a small sample size and a focus on a single physics topic. Future research should examine a broader range of scientific disciplines and problem types to determine whether similar metacognitive patterns emerge. Longitudinal studies could also provide deeper insights into how students develop and refine their metacognitive abilities over time. In conclusion, metacognition is a fundamental determinant of problem-solving success in physics. Educators must prioritize the development of metacognitive skills to enhance students' scientific reasoning and problem-solving efficiency. Without deliberate instructional efforts, students may continue to struggle with fundamental cognitive processes, ultimately hindering their ability to engage in complex scientific thinking.

Metacognition is a crucial aspect in problem solving and can improve problem solving performance and facilitates science learning [92,93]. Therefore, this study contributes to the related literature particularly. The metacognition rubric developed for this research would be used in similar research.

DATA AVAILABILITY

The data are available from the authors upon reasonable request.

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