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Students' Scientific Reasoning in Physics through Procedural and Conceptual E-Scaffolding in Modelling Instruction: A Quasi-Experimental Study

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Abstract

Procedural and conceptual e-scaffolding has been shown to be effective for assisting novice learners in understanding new concepts. Its integration with modelling instructions (E-MI) raises expectations for improving scientific reasoning (SR) in students whose level is still a concern in Indonesia. A quasi-experimental study was conducted to find out if there was a difference between e-scaffolding and a regular modelling instruction (MI) class; how integration affected the shift in students' SR levels; and the effect size on students' SR in physics. A total of 70 first-year high school science class students in East Java, Indonesia participated in this study, and were randomly divided into two groups with different treatments. The experimental group with E-MI ($n = 35$) and the control group with MI ($n = 35$) received a 15-item scientific reasoning test ($\alpha = 0.828$), and the data were analysed by t-test. The difference in SR between the E-MI and MI group was found to be statistically significant. As a result, students who learned physics through E-MI exhibited higher levels of SR compared to students who took only an MI course. In the E-MI group, elevating the SR level for students at the transitional level was relatively easier than for students at the concrete level. Integrating procedural and conceptual e-scaffolding in modelling instructions also had a large influence on students' SR in physics. In conclusion, the findings of this study underscored the importance of technology in education. E-scaffolding facilitated the augmentation of students' SR levels, excluding the operationally concrete SR levels.

Introduction

According to the United Nations Educational, Scientific and Cultural Organization (UNESCO, 2021), individuals' trust in science is contingent on their perception of the world's scientific process. Hence, society needs individuals capable of observing, interpreting, and effectively communicating scientific phenomena. Each citizen requires a culture of scientific reasoning (SR) to nurture such a scientific atmosphere. SR is the foundation of fundamental cognitive abilities (Fischer et al., 2014) in science education for thinking and reasoning (Ding et al., 2016). Whether in science, engineering, or social contexts, Zafitri et al., (2019) contend that SR plays a crucial role in resolving complex, authentic problems. SR requires scientific inquiry skills such as analysis, hypothesis formulation, problem-solving, and deriving appropriate conclusions (Kalinowski & Willoughby, 2019; She & Liao, 2010) from the perspective of higher-level logical reasoning. Additionally, SR influences other cognitive skills such as conceptual understanding (Nieminen, 2012), argumentation (Fischer et al., 2014), and problem-solving (Alshamali, 2016; Hejnová et al., 2018).

The majority of upper secondary students' SR skills are still deemed to be subpar in Indonesia. Ninety four percent of students are still at the concrete reasoning level, 5.7% are at the transitional level, and only 0.3% of students reach the formal reasoning level (Tajudin & Chinnappan, 2015). In addition, Widarti and Winarti (2019) discovered that no students reached the formal reasoning level, while 65.52% of students remained at the operational concrete reasoning level. Hence, it is imperative to implement effective learning strategies to improve students' SR (Illes et al., 2019).

Theoretical Framework

Scientific reasoning (SR) refers to the set of fundamental skills required in scientific activities, such as exploring issues, formulating hypotheses, and evaluating investigation results (Bao et al., 2009; Erlina et al., 2018). Lawson, (2010) identified six SR indicators: Conservation Reasoning (CR), Proportional Reasoning (PPR), Control of Variable (COV), Probabilistic Reasoning (PBR), Correlation Reasoning (COR), and Hypothetic-deductive Reasoning (HDR). Piaget's theory further classifies SR into three developmental stages: concrete operational, transitional, and formal operational reasoning (Aini et al., 2018; Widarti & Winarti, 2019). Higher levels of SR enable students to better adapt to various abstract problems (Brahmia et al., 2021; Zimmerman & Klahr, 2018). Research by Fabby and Koenig (2015) highlights that the levels of SR skills develop cyclically, with early SR skills influencing subsequent levels (Oogarah-Pratap et al., 2020).

Various learning models have been employed to develop SR, including application-oriented SR models (Vaesen & Houkes, 2021), guided inquiry learning (Andersen & Garcia-Mila, 2017), active learning techniques (experiments and debates), scientific animations (Al-Balushi, 2017), and modeling strategies (Göhner & Krell, 2022). Among these, Modelling Instruction (MI) has gained significant attention (Campbell et al., 2015). MI is an active physics learning environment (Commeford et al., 2022) and constructivist-based instruction that enhances students' independent reasoning (Barlow et al., 2014) through modeling and investigative activities, utilising multiple representations to construct knowledge (Jumadin et al., 2017; Lestyaningtyas et al., 2017; Ropika et al., 2019).

MI has primarily been studied for its effect on various aspects of students' knowledge and skills, such as on conceptual understanding (Campbell et al. 2015). Recent research has expanded to include self-efficacy (Dou et al., 2018; Selau et al., 2018), epistemological beliefs (McPadden et al., 2020), problem-solving, and attitudes toward mathematics (Koç & Elçi, 2022). Concerning technology integration, Nguyen and Santagata, (2021) compared paper modeling and computer modeling in a lesson on park ecosystems and mulch experiments. The results showed that computer modeling effectively stimulated students to explain scientific evidence and ideas systematically. Similarly, Vasconcelos and Kim, (2020) created a Scratch integration of coding in MI, demonstrating that block-based coding simulations used as scaffolds improved students' simulation and scientific design skills.

Despite extensive research on MI, the integration of scaffolding in MI to enhance SR remains underexplored. Handayanto et al. (2024) found no significant differences in SR between inquiry-based classes with or without e-scaffolding, except for students with low prior knowledge. In this study we introduce two scaffolding types: conceptual scaffolding, which provides guidance to help students describe and establish connections between concepts (Wu et al., 2016), and procedural scaffolding, which provides guidance for solving a problem using steps or questioning sentences (Saman et al., 2018).

This study addressed several research gaps. Firstly, integrating scaffolding into MI can support students struggling with physics, particularly through ICT-based e-scaffolding, which has proven effective in guiding students to develop strategies for enhancing their knowledge (Heijnes, 2018; Koes-H et al., 2020; Malone & Schuchardt, 2020; Stammen et al., 2018). Research indicates that providing e-scaffolding in collaborative learning environments helps students actively engage in reasoning and accurately comprehend physics concepts (Wu et al., 2016). As per Balqis et al., (2019), SR encompasses both procedural and conceptual cognitive aspects. Thus, implementing procedural and conceptual e-scaffolding is suitable for supporting students facing difficulties, and offering initial assistance while encouraging critical thinking and problem-solving (Saman & Handayanto, 2017). In particular, conceptual and procedural e-scaffolding can enhance the quality of students' cognitive knowledge (Doo et al., 2020; Liu & Adams, 2017) and potentially foster the development of SR. Consequently, students' argumentation and deductive reasoning skills are expected to improve. Secondly, there is limited literature on secondary school settings, with only one study conducted in a senior high school (Malone & Schuchardt, 2020). Thirdly, we utilise the physical domain to cultivate students' SR (Bao, 2009), since it has been identified as influencing students' SR (Opitz et al., 2022). Fourthly, the study's context is predominantly dominated by Western countries. We contend that the Asian context offers a unique perspective.

Finally, the results of our synthesis indicate that integrating procedural and conceptual e-scaffolding with MI is an innovative instructional strategy. Developing thinking skills toward science requires teachers and schools to design appropriate learning innovations. Procedural and conceptual e-scaffolding are two types of scaffolding that are suitable for helping novice learners to understand new concepts. When procedural and conceptual e-scaffolding in modeling instruction (E-MI) is implemented, students' learning difficulties in physics can be reduced and managed. In addition, the impediment to students' development of SR presented by inappropriate pedagogical practice can be mitigated. The researchers hypothesise that E-MI significantly improves students' SR, offering a practical approach to fostering scientific reasoning in physics education.

Research Questions

Consequently, the following research questions are addressed in this study:

1) Is there a difference in SR between students in procedural and conceptual e-scaffolding in an e-scaffolding modelling instruction (E-MI) class and students in a regular modelling instruction (MI) class?
2) How do the levels of students shift between procedural and conceptual e-scaffolding in modeling instruction (E-MI) and regular modelling instruction (MI) classes before and after the intervention?
3) Does the implementation of procedural and conceptual e-scaffolding in modelling instruction (E-MI) affect the SR of physics students?

Methods

Participants

The participants were first-year students from one high school in East Java, Indonesia during the 2019/2020 academic year. Initially, the study was approved to include all first-year students, comprising six classes with a total of 216 students. However, due to learning conditions, the school restricted participation to only two classes. The final participants consisted of 70 students (aged 15-17 years) enrolled in the science major. This major was selected because the student participants receive more intensive science courses, including physics, compared to other majors. The 70 participants were randomly allocated to the control and experimental group, with 35 participants in each group.

Design and Procedure

A quasi-experimental design was used in this quantitative study. Two groups were given a pre-test before and a post-test after the intervention and then were compared (Creswell, 2014). This study lasted for 12 weeks, with two weeks devoted to the pre-test, eight weeks (16 sessions) dedicated to the intervention's implementation, and two weeks devoted to the post-test.

Each student in the experimental group learned physics using an MI strategy supported by procedural and conceptual e-scaffolding. The Moodle Learning Management System (LMS) was used as the e-learning platform to integrate that scaffolding into students' worksheets. The learning design procedure for the experimental group is illustrated in Figure 1. Meanwhile, the control group participants learned physics using MI, but without e-learning and e-scaffolding. Therefore, in this study, the experimental group was labeled E-MI and the control group was labeled MI. The study's design and the measures given to the two groups are presented in Table 1, and the stages are depicted in Figure 1.

Table 1: Design of Study

Pre-test Measures	Group	Instructional Method	Post-test Measures
Scientific Reasoning ability	E-MI	Using procedural and conceptual e-scaffolding	Scientific Reasoning ability
	MI	Regular teaching methods	

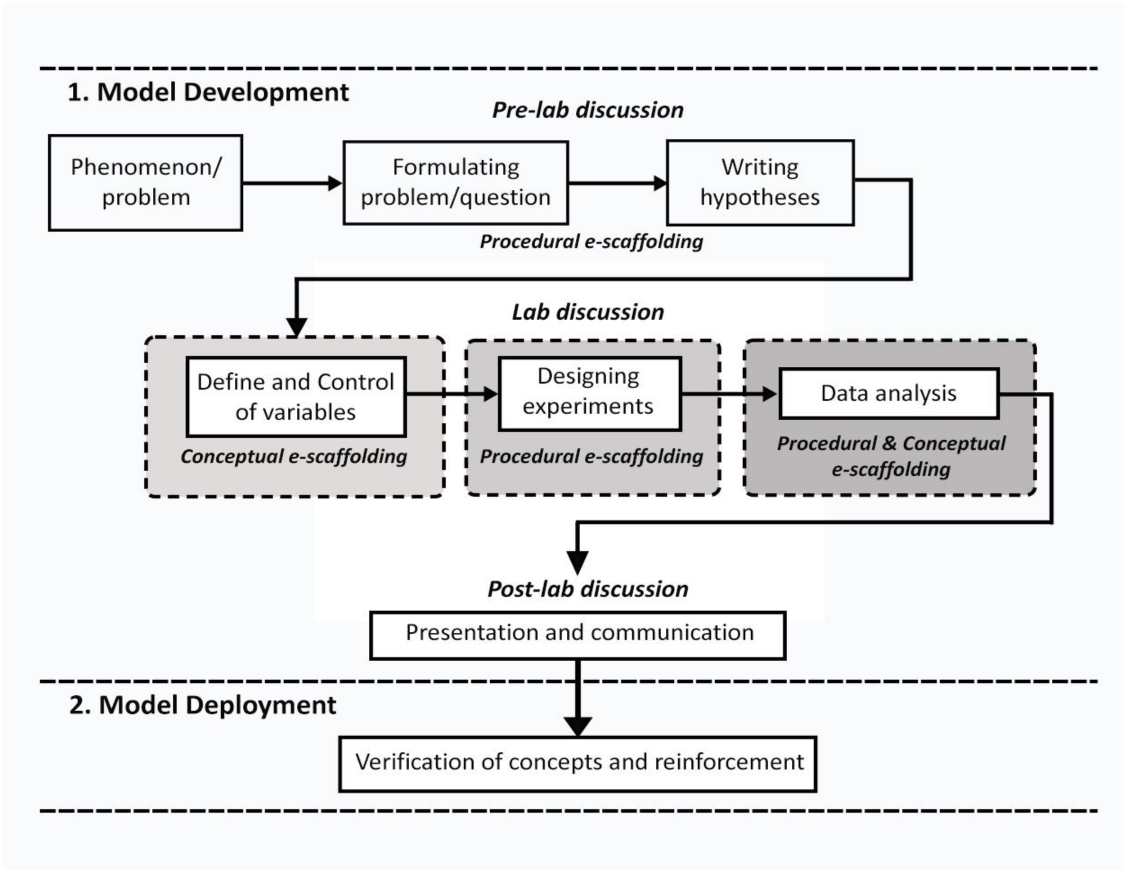

Figure 1: Procedural and conceptual e-scaffolding learning design in modeling instruction

Scientific Reasoning Test

To measure students' scientific reasoning abilities in physics, Lawson's CTSR form (2000) was modified and used as a pre-test and post-test. The modifications to the test questions used were adapted from a combination of Han (2013) and Zhou (2016), and the scientific reasoning indicators were adjusted to suit content requirements. In this study, scientific reasoning test questions on the topic of Newton's laws were modified and adapted.

This test consisted of 15 questions that assessed physics reasoning abilities, such as conservational reasoning, control of variables, proportional reasoning, correlational reasoning, probabilistic reasoning, and deductive hypothesis reasoning. Each question comprised two levels: content questions in the form of multiple-choice items and open-ended questions for reasoning. Each student's answer was assigned points (0-5) for each item based on their reasoning and choice of answers. The estimated Cronbach alpha reliability for this test instrument is 0.828 (n = 207). Furthermore, the method used to classify the total score based on SR level criteria is shown in Table 2.

Table 2: Criteria for Level Scientific Reasoning

Total Score	Level
0% - 33%	Operational Concrete
34% - 67%	Transitional
68% - 100%	Operational Formal

Data Collection

All participants and schools approved the entire implementation and the procedures of this study. Data were collected through scientific reasoning tests related to Newton's laws. Pre-measurement of scientific reasoning ability (SR pre-test) was conducted before the intervention. Then, post-measurement of scientific reasoning ability (SR post-test) was conducted after the treatment to analyse and compare the improvement of students' scientific reasoning abilities in physics, especially on the topic of Newton's laws.

Data Analysis

For general data, such as mean and standard deviation, descriptive statistical data analysis techniques were used. The technique was also employed to determine the distribution of students' SR levels and the number of students who had level shifts. To examine the difference in students' SR between the two classes, an independent t-test comparative analysis was conducted. Previously, the assumptions for the t-test were checked and found to be appropriate. A statistically significant difference in SR ability between the E-MI group and the MI group was considered to exist if a sig. p value < 0.05 was obtained from the analysis. Furthermore, Cohen's d effect size value was used to determine the effect of procedural and conceptual e-scaffolding on each dependent variable.

Results and Discussions

Comparison of Students' Scientific Reasoning in Physics

During implementation, procedural and conceptual e-scaffolding indirectly improved students' performance and learning outcomes, including scientific reasoning. The results obtained through descriptive statistical analysis in both classes showed that the mean score of the experimental group was higher than that of the control group. Figure 2 illustrates the comparison of the mean pre-test and post-test between the experimental and control groups. The results of the pre-test SR measurement revealed that students in the E-MI group had a mean score of 22.2 (SD = 6.92), while the MI group had a mean score of 22.3 (SD = 5.58). After receiving the intervention, the mean score of students in the E-MI group increased to 43.20 (SD = 6.45), whereas the MI group had a lower mean score of 37.63 (SD = 6.68). The implementation of procedural and conceptual e-scaffolding in modelling instruction for the experimental group demonstrated positive results, with the group's average increasing by 21 points compared to their initial SR (pre-test SR). In contrast, the control group's average increased by only 15.4 points from their initial SR.

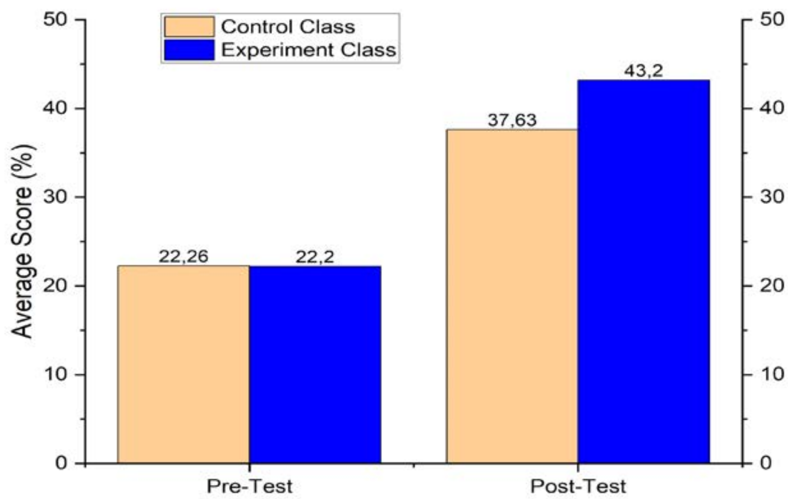

Figure 2: Comparison of mean pre-test and post-test scores between the experimental and control groups

Table 3 shows that there was no difference in the initial SR (pre-test) between students in the two groups ($p > 0.05$). The negative t-value and mean difference in the pre-test SR results also reinforced the comparison results shown in Figure 2, which means that the mean pre-test SR scores of the E-MI group were lower than those of the MI group. The mean score comparison showed that the initial SR of the control group students was slightly higher (by 0.06 points) compared to the experimental group. The t-test analysis in Table 3 also shows the essential result on the post-test SR, which is a significance value smaller than 0.05. This means that there is a significant difference in SR between the E-MI and MI groups after the intervention. In addition, the mean difference value of 5.571 indicates that the experimental group, that learned physics with procedural and conceptual e-scaffolding in modeling instruction, had a higher mean post-test SR score (5.571) than the control group. Again, this outcome also reinforces the result of the difference in the mean post-test SR in Figure 2.

Table 3: Independent t-Test Results

Test	t	df	Sig.	Mean Difference	SE Difference
Pre-test	-.038	68	.970	-.057	1.502
Post-test	3.550	68	.001	5.571	1.570

This research found that the E-MI group, which utilised web-based procedural and conceptual scaffolding, demonstrated a greater increase in the physics SR scores, suggesting that such scaffolding provides a more complex and effective learning experience. This aligns with prior studies on e-scaffolding in physics learning (Deejring, 2015; Kim et al., 2018; Lin & Singh, 2015; Saputri & Wilujeng, 2017). Despite the fact that our study did not investigate scaffolding in the control group, we argue that direct scaffolding by the teacher or peers may occur. However, procedural and conceptual e-scaffolding proved more effective in addressing individual student needs due to its flexibility, enabling precise identification of learning difficulties and enhancing instructional efficiency (Belland, 2017; Kim et al., 2018; Koes-H et al., 2019). Although conceptua1 e-scaffolding had a stronger statistical impact than procedural e-scaffolding (Doo et al., 2020), their combined use significantly improved students' SR. Thus, E-MI learning effectively enhanced students' SR in physics-related subjects.

The control group's results, which utilised MI without e-scaffolding, were comparable with Sutarno's (2014) findings, where only a few students reached the formal operational level despite receiving the treatment during the learning process. Similarly, Balqis et al. (2019) and Fawaiz et al. (2020) reported that over 50% of high school students' SR in science subjects, specifically physics, remained at the transitional or even concrete operational level. These findings underscore the complexity of developing SR, which requires a dual competency-based approach—procedural (scientific inquiry) and conceptual (scientific modeling) (Krell et al., 2022). While the control group showed improvement, it was less pronounced than in the technology-enhanced class, indicating that inquiry-based learning models such as MI alone are insufficient for optimal cognitive development.

The Shifting Level of Students' Scientific Reasoning

The comparison of students' physics SR levels in the E-MI and MI groups is shown in Table 4. Analysis of the total post-test score revealed that 63% of the experimental group students reached the formal operational SR level after learning with E-MI. This result was significantly higher than the SR level of the experimental group students at the time of the pre-test and the SR level of the control group students at the time of the post-test, which was only 23%. This significant difference strengthened the results of the previous analysis.

Table 4: Comparison of the Level of Scientific Reasoning in Physics of Students in the Two Groups

	E-MI Group		**MI Group**	
Level of Scientific Reasoning	**Pre-test (%)**	**Post-test (%)**	**Pre-test (%)**	**Post-test (%)**
Concrete	37	0	43	0
Transitional	60	37	57	77
Formal	3	63	0	23

Figure 3 illustrates that a number of students experienced a level shift, while others did not. It can be observed that more students in the control group shifted from the concrete level to the transitional level. In contrast, nearly 43% of the students in the experimental group, who received procedural and conceptual e-scaffolding in MI, experienced a shift from the transitional level to the formal level.

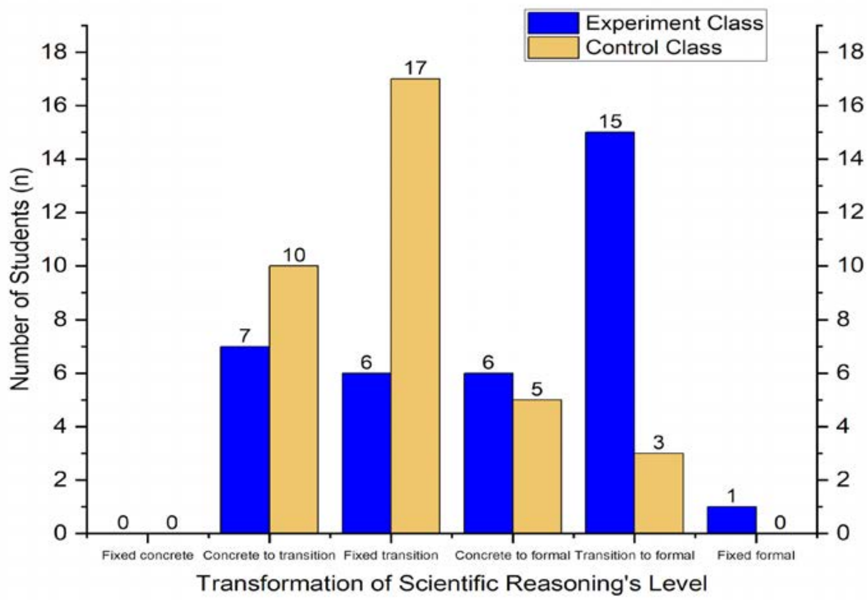

Figure 3: Shift in scientific reasoning levels for experiment and control class students

A significant proportion of students experienced a level shift, with those at the transitional level showing greater improvement compared to those at the concrete operational level. We argue that this shift in the E-MI group is linked to students' self-efficacy and their attitude towards e-scaffolding. Although we did not directly collect self-efficacy data, prior research indicates that students with a higher SR tend to have more positive perceptions of their academic abilities (Bandura, 1997; Nyberg et al., 2022) and greater confidence in using technology (Kuo & Belland, 2019). E-scaffolding attempts to gradually transfer responsibility to students, fostering autonomy and supporting optimal development of SR. However, students at the concrete operational level exhibited limited progress, likely due to a lower self-efficacy belief and less favourable attitudes toward technology (Kuo & Belland, 2019). These students often avoided challenging tasks, which hindered their SR development (Nyberg et al., 2022). While this assumption requires further investigation, our finding highlights that the improvement of SR levels was not linear and depended on scaffolding integration (Andersen & Garcia-Mila, 2017). Notably, the integration of procedural and conceptual e-scaffolding with MI strategy significantly shifted SR levels, though students who were formal reasoners in the pre-test remained unchanged in the post-test, consistent with the findings by Marušić and Zorica, (2012).

Conversely, in the control group, shifts from the concrete to the transitional level were more common than from the transitional to the formal operational level. This suggests that MI alone is not yet strong enough to elevate students' SR levels. Without additional support, students struggled to identify theoretical elements, connect cause-and-effect using theory, or model phenomena effectively (Cabello et al., 2021). Thus, while MI contributed to SR development, its impact was limited without targeted scaffolding.

The Effect of E-MI on Students' Scientific Reasoning in Physics

The results of the effect size analysis calculation yielded a Cohen's d value of 0.84, indicating the large influence of procedural and conceptual e-scaffolding in MI on students' scientific reasoning in physics. This study revealed a considerable difference between the SR skills of students who learned with E-MI and those who learned only with MI. These findings are consistent with Basu et al. (2017) and Mulder et al., (2016) who discovered that e-scaffolding in MI affected students' cognitive development, particularly in constructing conceptual models and enhancing SR. The disparity in SR level improvement between the groups can be attributed to the use of procedural and conceptual e-scaffolding by the experimental class, and is consistent with those of Koes-H et al. (2019) and Kim et al. (2018), who reported superior cognitive abilities among students utilising such scaffolding.

Furthermore, procedural and conceptual e-scaffolding not only helps students in overcoming challenges but also trains their cognitive processes. Procedural and conceptual e-scaffolding effectively assists students to design experiments, understand procedures, and clarify concepts, while conceptual scaffolding supports information processing and simplifies complex ideas (Aslam et al., 2017; Falloon, 2017; Rahmatiah et al., 2015; Susilowati et al., 2018). Procedural e-scaffolding fosters systematic thinking, whereas conceptual e-scaffolding builds on learned concepts (Brown & Wilkinson, 2018; Rahmatiah et al., 2015). These findings are consistent with Liu and Adams, (2017), who demonstrated that e-scaffolding in appropriate instructional strategies enhances task completion, problem-solving, and cognitive skill development. For example, in constructing and interpreting graphs for Newton's Second Law experiments, students in the E-MI group received structured procedural guidance, unlike the MI group, which relied on teacher prompts. This structured support explains why procedural and conceptual e-scaffolding significantly strengthened students' SR skills in this study.

Conclusion

During the 12-week study period, both MI and E-MI were capable of increasing SR levels. However, the overall results indicate that integrating procedural and conceptual E-MI is more effective at assisting students with their difficulties and training their SR skills in physics. As a result of learning physics with procedural and conceptual E-MI, students' SR improved significantly. Incorporating procedural and conceptual e-scaffolding in MI positively affected students' SR skills, resulting in significantly higher SR skills for students who learned physics with E-MI compared to those who learned physics only with MI. The difference in the level of improvement between the two classes was also highly significant, with students who had attained the formal operational level in the experimental class experiencing greater growth.

In addition, the researchers would like to highlight recommendations that may be useful for teachers and future researchers. There is a need for a more comprehensive assessment of scientific skills (including criteria for SR and self-efficacy) in physics education. Knowledge enhancement and reasoning improvement are two distinct goals, and it is anticipated that future research will further investigate the influence of the integration of E-MI on other scientific skills (beyond SR), thereby yielding a more comprehensive range of research insights. In addition, it is anticipated that future research will further investigate the influence of the integration of E-MI on other scientific skills (beyond SR), thereby yielding a more comprehensive range of research insights. In addition, future researchers are encouraged to dig deeper and determine the effect of other e-scaffolding incorporated with MI on the level shifting of SR in physics students. Education technology researchers and developers are encouraged to design learning technologies specifically tailored for students with concrete SR levels.

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