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METACOGNITION-BASED DISCOVERY LEARNING: EFFECTS ON CRITICAL THINKING AND COGNITIVE ABILITY IN DYNAMIC FLUID STUDY

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ABSTRACT

This examination assesses the success of metacognition-based discovery studying fashions in improving students' essential questioning talents and cognitive talents inside the context of dynamic fluid concepts, whilst also exploring the relationship among these variables. Applying a quantitative quasi-experimental method with a nonequivalent manipulate group layout, the research sampled grade xi students from a country high school in bandung city, with magnificence XI-2 assigned as the experimental group and sophistication XI-4 as the manage institution. Statistics were accumulated via pre-tests and post-exams to evaluate the scholars' critical thinking skills and cognitive skills. The results suggest that the metacognition-based totally discovery getting to know model drastically stronger the scholars' overall performance as compared to conventional teaching techniques, suggesting its potential as an powerful pedagogical approach in science training. Cognitive competencies have been measured the usage of a 13-question a couple of-desire test, even as crucial wondering abilities had been assessed via a 7-question multiple-choice take a look at. Information analysis employed n-gain, impact length, linear regression, and correlation evaluation. Outcomes discovered massive improvement in each cognitive competencies and important wondering abilities within the experimental magnificence (N-Gain values of 0.70 and 0.68, respectively) as compared to the control class (N-Gain values of 0.44 and 0.36). The metacognition-primarily based discovery studying version established a sturdy have an impact on on both cognitive talents and critical thinking competencies, with high impact sizes of 1.83 and 1.85, respectively. Furthermore, a slight correlation (0.4) was found between cognitive abilities and critical thinking skills. This reasearch provides evidence that metacognition-based approaches effectively enhance both cognitive and critical thinking competencies in physics education, offering valuable insights into their interrelationships.

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1. INTRODUCTION

The 21st century is marked by the emergence of the Industrial Revolution 4.0, which places knowledge at the forefront of development. This era is distinguished by rapid advances in information and technology. To cultivate human resources capable of thriving in this competitive landscape, the concept of Education 4.0 has been introduced (Mardhiyah et al., 2021). Among the essential competencies for 21st-century learners is critical thinking, which is one of the 4C skills identified as crucial for effective learning (Redhana, 2019). The development of critical thinking abilities empowers students to improve their analytical, evaluative, and reasoning abilities, preparing them to address the growing complexities of the Industrial Revolution 4.0. Thinking skills can be used to find and understand ideas, interpret meanings, and solve problems in a good and structured manner. Therefore, these skills are important in creating quality human resources, able to compete healthily through their abilities and skills (Mardhiyah et al., 2021), and ultimately can adjust in the face of a very fast changing world.

Critical thinking is a fundamental requirement across all educational curricula, especially emphasized within the unbiased curriculum. The 2013 curriculum is designed to cultivate a era that is efficient, modern, innovative, and correctly engaged, with the capacity to make contributions meaningfully to society, the state, the country, and worldwide civilization (Kemdikbud, 2018). One of the essential demands is to create a era that is skilled in vital questioning and has excellent personalities so that they are able to face competition within the technology of globalization. One of the essential demands is to create a generation that is professional in vital thinking and has a great personality in order that they may be able to face opposition inside the era of globalization (Wiryanto et al., 2021). The impartial curriculum emphasizes important questioning via the combination of the pancasila student profile. This profile outlines the precise attributes of indonesian inexperienced persons as lifelong folks who are not most effective professional and informed but additionally constantly exercise the principles of Pancasila in their daily behavior. The pancasila student profile is based round six core dimensions: faith in and devotion to god almighty, noble character, appreciation of worldwide variety, collaborative capabilities, independence, vital reasoning, and creativity (Kemendikbudristek, 2024).

Ennis (2011) found out that critical thinking is a process of reflection that emphasizes decisions that want to be mad and common. Consistent with this, Asniar (2022) describes critical thinking as a reflective skill used to decide an action that needs to be taken. Meanwhile, (Soon Yen Foo & Quek (2019) shows that crucial wondering entails a reflective, systematic, and rational cognitive technique and method in making selections. Changwong (2018) suggests that vital wondering is an highbrow process that formulates ideas, programs, examines, synthesizes, and additionally evaluates various records derived from remark, reasoning, enjoy, or remarks as a method for questioning and acting. As a result, vital questioning is a cognitive skill in making rational decisions via knowledge, decoding, and comparing information from a given hassle or phenomenon.

However, in practice, Indonesian students' critical thinking skills remain relatively low. Data from the 2022 PISA assessment revealed that Indonesian students scored an average of 383 in the science domain, significantly below the global average of 485. Consequently, Indonesia ranked 67th out of 81 participating countries (OECD, 2023). The PISA assessment evaluates students' higher-order thinking skills, including their capacity for critical thinking. Addressing this issue requires a greater emphasis on developing students' crucial thinking skills through intentional exercise and instructional support (Suprayitno, 2019). Those findings underscore the urgent want to enhance critical thinking abilties amongst indonesian students.

Several research findings consistently indicate that students' critical thinking skills remain significantly underdeveloped. For instance, a study by Permata (2019) on high school students in Bandung revealed that their critical thinking abilities were relatively low across all assessed indicators. The percentages for each component were as follows: 36.80% for elementary clarification, 40.80% for basic support, 32.00% for inference, 30.67% for advanced clarification, and 36.80% for strategy and tactics. Similar findings were reported by Sundari & Sarkity (2021), Who observed that the common stage of college the development of students' critical thinking in a high school in sidoarjo also remained low. The highest score was recorded in the simple explanation component at 67.42 (moderate category), while the components of basic skills and strategy/tactics each scored 65.15 (moderate). In contrast, the further explanation component scored 50.76 (low), and the conclusion-making component was the lowest at 26.52 (very low). These results suggest that students' low critical thinking performance may be attributed to instructional strategies that do not adequately support the development of higher-order thinking. Furthermore, Nurjanah (2022) found that students' critical thinking abilities related to dynamic fluid concepts in physics were also generally low across all assessed dimensions.

Ufairiah (2020) carried out a field investigation by interviewing physics teachers to explore the dynamics of the learning process within the classroom setting. The findings revealed that teaching is still predominantly carried out using conventional, teacher-centered approaches, resulting in one-way knowledge transmission. Consequently, students face difficulties in applying physics concepts to real-world problems, tend to forget what they have learned, and struggle to identify and analyze scientific phenomena. These challenges contribute to their low levels of critical thinking. The absence of effective teaching methods that encourage higher-level thinking in the classroom is a major factor contributing to the limited development of students' critical thinking. Therefore, it is essential to implement learning models or strategies that actively foster both cognitive and critical thinking skills, specifically inside the context of physics schooling.

Numerous studies have shown the effectiveness of different teaching models in improving students' critical thinking abilities. The implementation of STEM-based discovery learning (Fadlina et al., 2021), problem-based learning supported by concept maps (Masdalipa et al., 2017), and guided inquiry approaches (Sarifah & Nurita, 2023) has been shown to significantly improve students' ability to think critically. Moreover, students' critical thinking development is also influenced by the use of structured student worksheets (LKPD) and hands-on experimental activities, as evidenced by (Pratiwi & Yulkifli, 2019). Additionally, Bakri (2024) found that the application of metacognitive strategies contributes to an increase in students' critical thinking abilities, setting them within the medium proficiency category. These findings suggest that combining active learning models with metacognitive support and experimental engagement can effectively foster higher-order thinking in students.

The study's results are presented in this manuscript as the usage of a metacognition-based discovery learning teaching model in physics lessons with the purpose of improving students' critical thinking skills. Bruner's theory of constructivism provides the foundation for the solution presented in this manuscript. Bruner assumes that knowledge is created by connecting new information with previously learned information and is obtained through an interactive process between students and their environment (Kurniawan, 2021). In his learning theory, Bruner stated that students' cognitive development occurs through three stages that are determined by the way they understand the environment, namely the enactive, iconic, and symbolic stages.

Discovery learning is an active learning approach that emphasizes student-led exploration and independent investigation, which leads to deeper understanding and longer retention of knowledge (Sartono, 2019). According to Bruner, knowledge acquired through the process of discovery tends to have a stronger and more enduring impact on learners. This model of learning has been shown to enhance critical thinking, reasoning abilities, and cognitive skills, particularly in the context of problem-solving (Sundari & Fauziati, 2021).

Every phase in the Discovery Learning model, including stimulation, problem identification, data gathering, data analysis, verification, and generalization, helps students develop skills such as observation, asking questions, conducting experiments, reasoning, and communicating (Sartono, 2019; Sinambela, 2017), as emphasized by Pratiwi (Narumi & Kartono, 2021). Discovery learning is an active learning approach that encourages independent investigation and discovery, leading to improved retention of knowledge over time (Sartono, 2019). This model fosters greater student involvement in the learning process, which in turn enhances their critical thinking abilities. Research by Laeni (2022) indicates that the discovery learning model has a positive impact on enhancing critical thinking skills, particularly in the context of momentum and impulse topics. Additionally, Sapitri (2016) study demonstrated that applying the Discovery Learning model to heat-related content result in a noticeable improvement in students' critical thinking skills competencies, with medium-level performance across all indicators.

In addition to discovery learning, metacognitive integration in this model can improve students' critical thinking skills and cognitive abilities. Flavell (1979) posits that metacognition refers to an individual's awareness of his or her very own cognitive processes, which allows students to reflect on the way they learn and choose the most suitable method to achieve learning goals. Metacognitive knowledge helps students adjust their learning strategies as well as develop critical thinking skills to analyze and evaluate information in depth (Khamzah Syawal et al., 2023). The research performed via Fitri (2022) the use of metacognitive strategies in physics gaining knowledge of confirmed the best impact size value of 0.73 and the lowest of 0.45 which proves that the application of metacognitive strategies can enhance excessive-level thinking abilties with the aid of emphasizing the energetic position of students in the getting to know process Bakri (2024).

In this research, the Discovery Learning Model is combined with metacognitive strategies that are integrated at each stage. Students identify problems to find solutions through the discovery of physics concepts experimentally. Metacognitive expertise, which includes declarative information, procedural information, and conditional information, plays a role in honing students' thinking processes in solving problems in physics materials.The specific gap this research aims to fill is the limited understanding of how metacognitive strategies can enhance discovery learning, specifically in dynamic fluid concepts. Previous studies have examined these approaches separately, but this research uniquely integrates them to address challenges students face in comprehending abstract physics principles. What has not been done in the literature is examining the combined effect of these approaches on both cognitive abilities and critical thinking skills within inside the context of dynamic fluid materials.

The following questions represent the problems provided in this observe: the way to enhance cognitive ability and vital thinking abilties after applying a metacognition-based totally discovery learning model to dynamic fluid substances? And the way powerful is the metacognition-based totally discovery studying version to improve students' cognitive abilities and critical thinking skills on dynamic fluid materials? Referring to the theoretical basis used in this study, the hypothesis tested in this study posits that (H_1): a significant difference exists in the enhancement of critical thinking skills and cognitive abilities between students who are taught with the metacognition-based discovery learning model and those who receive conventional teaching methods.

2. METHOD

In this research, a quantitative methodology employing a nonequivalent control group design was implemented. Through convenience sampling methods, two existing eleventh-grade classes were selected from a public senior high school in Bandung City. The experimental group was composed of 34 students, while the control group had 30 participants. The experimental group received instruction using the metacognitive-based discovery learning model as outlined by Sugiyono (2013), whereas the control class was taught using traditional pedagogical approaches. To evaluate the efficacy of the instructional method, identical pretest and posttest assessments were administered to both groups, specifically designed to measure shifts in students' knowledge acquisition and cognitive capabilities. The composition and framework of these assessment instruments are detailed below.

Table 1. Nonequivalent Control Group Research Design

Class	Pretest	Treatment	Posttest
Experiment	O	X	O’
Control	O	-	O’

(Sugiyono, 2013)

Where, O is pretest in the experimental class and control class, O’ is posttest in the experimental class and control class, X is physics learning with metacognition-based discovery learning model

Two test instruments were administered:
1. Cognitive abilities test: 13 multiple-choice questions measuring comprehension (C2), application (C3), and analysis (C4) based on revised Bloom's taxonomy
2. Critical thinking skills test: 7 multiple-choice questions assessing clarification, basic support, inference, advanced clarification, and strategic thinking

Both instruments underwent validity and reliability testing through expert assessment (1 lecturer and 2 teachers) and the Rasch model analysis. The cognitive abilities test showed 42.1% unidimensionality (appropriate category) with reliability measures of person reliability (0.74, "Adequate"), item reliability (0.85, "Good"), and Cronbach alpha (0.89, "Very high"). The critical thinking skills test showed 42.6% unidimensionality with reliability measures of person reliability (0.70, "Adequate"), item reliability (0.72, "Good"), and Cronbach alpha (0.82, "Very high").

Data analysis involved three main steps. First, we measure student improvement using the N-Gain formula, which calculates the ratio between actual gain (posttest score minus pretest score) and maximum possible gain (ideal score minus pretest score) (Hake, 2002). This gave us a value between 0 and 1, which we categorized as high improvement (≥0.70), moderate improvement (0.30-0.69), or low improvement (<0.30). Second, to determine how effective our teaching method was, we used Cohen's d effect size, which compares the difference in improvement between the experimental and control groups. This tells us if the effect of our teaching method was small (0.2-0.5), medium (0.5-0.8), or large (0.8-2.0) (Cohen, 1988). Third, we examined whether students' cognitive abilities were related to their critical thinking skills by calculating a correlation coefficient (rxy). The strength of this relationship was interpreted as negligible (0.00-0.10), weak (0.10-0.39), medium (0.40-0.69), strong (0.70-0.89), or very strong (0.90-1.00) based on Schober and Schwarte's (2018) guidelines.

3. RESULTS AND DISCUSSION

3.1. Improvement of Critical Thinking Skills

To assess students' critical thinking skills, a test instrument comprising multiple-choice questions was given to both the experimental and control groups prior to and after the learning intervention. The pretest measured the students' initial critical thinking ability, while the posttest evaluated the extent of improvement following the instructional treatments. The difference between the pretest and posttest scores was examined through normalized gain (N-Gain) calculations to quantify the relative increase in performance. The findings of this analysis are summarized in Table 5.

Table 5. Improvement of Critical Thinking Skills

Class	Pretest	Posttest	<g>	Category
Experiment	26,89	76,89	0,68	Medium
Control	23,81	51,43	0,36	Medium

As illustrated in Table 5, both the experimental and control groups exhibited improvements in their critical thinking skills, as reflected by the positive normalized gain (N-Gain) scores. The experimental group attained a higher N-Gain value of 0.68, compared to 0.36 for the control group, although both scores fall within the medium category. This outcome implies that the application of the metacognition-based discovery learning model was more successful in strengthening students' critical thinking abilities compared to the conventional instructional approach. The higher gain achieved by the experimental group highlights that prompting students to take part in metacognitive reflection and discovery activities throughout the learning process greatly fosters the enhancement of higher-order thinking abilities.

From a theoretical perspective, this improvement can be interpreted using Bruner's theory of instruction, which emphasizes the importance of active learning and the spiral curriculum. In the experimental class, students were likely to be engaged through discovery-based or structured inquiry activities, encouraging them to interact with concepts repeatedly and at increasing levels of complexity. This aligns with Bruner's notion that learners construct new ideas based on existing knowledge, facilitated by scaffolding from teachers and materials.

Additionally, the development of critical thinking can also be understood through the lens of Flavell's theory of metacognition, which posits that learners become more effective when they are aware of their own thinking processes. The instructional design in the experimental class may have supported students' metacognitive awareness—encouraging them to monitor, evaluate, and adjust their thought strategies during learning tasks. This could explain the significant improvement in their critical thinking performance, as metacognitive regulation is a key component of critical analysis and problem solving. In contrast, the lower gain in the control class may reflect a more traditional, less interactive learning environment that provides fewer opportunities for metacognitive engagement or for revisiting and restructuring knowledge as emphasized by Bruner.

Furthermore, the detailed improvement in each aspect of critical thinking is presented in Table 6.

Table 6. N-Gain Every Aspect of Critical Thinking Skills

Aspects	**Experiment**		**Control**	
	<g>	**Category**	**<g>**	**Category**
Elementary Clarification	0,70	High	0,63	Medium
Basic Support	0,48	Medium	0,09	Low
Inference	0,83	High	0,46	Medium
Advance Clarification	0,54	Medium	0,08	Low
Strategy and Tactics	0,73	High	0,16	Low

The analysis of critical thinking skill improvement across specific aspects is presented in Table 6. The experimental class achieved higher normalized gain (N-Gain) scores in all measured aspects compared to the control class. Notably, the experimental group exhibited particularly high gains in the Inference aspect (N-Gain = 0.83) and the Strategy and Tactics aspect (N-Gain = 0.73), suggesting significant development in students' advanced reasoning and decision-making abilities. These results reinforce the effectiveness of the metacognition-based discovery learning model in enhancing critical components of critical thinking.

Bruner's theory suggests that active learning and scaffolding foster higher-order thinking, which likely contributed to the experimental group's success (McKinnon, 2012). The high gains in these aspects reflect Bruner's emphasis on building complex cognitive skills through progressive learning stages. Additionally, Flavell's metacognition theory supports the notion that students who engage in reflective thinking are better at monitoring and improving their reasoning (Ozturk, 2024). The experimental class likely benefited from metacognitive strategies that helped them enhance their critical thinking processes.

In contrast, the control group showed lower gains, particularly in Basic Support and Advance Clarification, indicating that their learning may have lacked the active engagement and reflective elements needed to improve these critical thinking skills. A graphical representation of the results is shown in Figure 1.

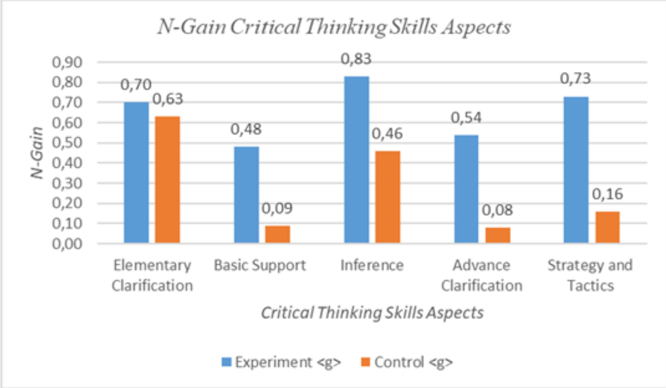

Figure 1. n-gain graph of every aspect of critical thinking skills

3.2. Improvement of Cognitive Ability

To measure the development of students' cognitive skills, a test instrument consisting of multiple-choice questions was administered as a pretest and posttest to both the experimental and control classes. The pretest measured the students' initial cognitive performance, while the posttest evaluated their progress following the instructional interventions. The differences between pretest and posttest scores were examined using normalized gain (N-Gain) calculations to measure the extent of improvement. The findings from this analysis are shown in Table 7.

Table 7. Improvement of Cognitive Ability

Class	***Pretest***	***Posttest***	**<g>**	**Category**
Experiment	23,76	77,15	0,70	High
Control	32,77	63,08	0,44	Medium

The data in Table 7 indicates a significant improvement in cognitive ability among students in each the experimental and control groups. However, the experimental class achieved a higher normalized gain (0.70, categorized as high) compared to the control class (0.44, categorized as medium). This suggests that the instructional strategies applied in the experimental class were more effective in enhancing students' cognitive skills.

To understand this result theoretically, we can refer to Bruner's theory of cognitive development, particularly his emphasis on three forms of representation: enactive (action-oriented), iconic (image-driven), and symbolic (language-dependent). The teaching approach in the experimental class may have utilized these representational modes in a progressive and integrated manner—allowing students to engage with content through hands-on activities, visual models, and abstract reasoning (Davishahl et al., 2020). This process supports cognitive growth by helping learners internalize concepts through multiple channels, thus resulting in greater cognitive gains.

Moreover, Flavell's theory of metacognition can further explain the observed improvement (Moritz & Lysaker, 2018). According to Flavell, students who are aware of their own cognitive processes are more capable of directing their learning effectively. Instruction in the experimental class may have promoted metacognitive techniques like self-questioning, planning, monitoring comprehension, and evaluating outcomes—each of which contributes to deeper cognitive processing and better performance in posttest assessments.

The lower gain in the control group may suggest that students were engaged in more passive forms of learning, with limited opportunities for reflection and strategic thinking. This highlights the importance of instructional design that not only delivers content but also cultivates awareness of the learning process itself. A more detailed breakdown of the n-gain values for each aspect of cognitive ability is illustrated in Figure 2.

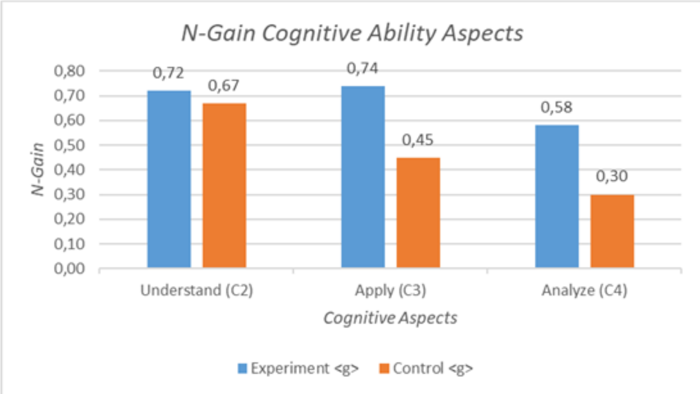

Figure 2. N-Gain Graph of Every Aspect of Cognitive Ability

3.3. Effectiveness of Metacognitive-Based Discovery Learning Models

The efficacy of the metacognition-based discovery learning model turned into evaluated to determine the quantity to which this technique can improve college students' cognitive abilities and critical thinking skills inside the context of fluid dynamics material.

To support this, statistical analyses were conducted, including normality tests, homogeneity tests, and hypothesis testing, all performed using IBM SPSS Statistics 29 software.

To assess whether the sample data drawn from the populace was normally distributed, a normality test was conducted. Given that the range of samples in this study exceeded 50, the Kolmogorov-Smirnov test was applied using SPSS software. The results of the critical thinking skills normality test are offered in Table 8.

Table 8. Results of the Critical Thinking Skills Normality Test

Data Source	Kolmogorov-Smirnov			Interpretation
	Statistic	Df	Sig.	
N-Gain Experimental Class	0,176	34	0,009	Abnormal
N-Gain Control Class	0,226	30	0,000	Abnormal

Table 8 shows that the experimental group's N-Gain scores yielded a Kolmogorov-Smirnov statistic of 0.176 with a significance value (Sig.) of 0.009 (df = 34), while the control group's N-Gain scores produced a Kolmogorov-Smirnov statistic of 0.226 with a significance value of 0.000 (df = 30). Since the significance values for both the experimental and control groups were below 0.05, it can be concluded that the distribution of the N-Gain data for critical thinking skills in both classes does not follow a normal distribution. These findings indicate that the improvement data for students' critical thinking skills in both groups were not normally distributed. As a result, non-parametric statistical tests were deemed more appropriate for subsequent comparative analyses to assess the effectiveness of the metacognition-based discovery learning model. Following this, the results of the normality test for the N-Gain scores of cognitive ability are presented in Table 9.

Table 9. Cognitive Ability Normality Test Results

Data Source	**Kolmogorov-Smirnov**			**Interpretation**
	Statistic	**Df**	**Sig.**	
N-Gain Experimental Class	0,116	34	0,200*	Normal
N-Gain Control Class	0,149	30	0,090	Normal

A normality test was also conducted on the student's cognitive ability improvement scores (N-Gain) to assess the suitability of parametric statistical procedures for subsequent analyses. Table 9 presents the results of this assessment.

The Kolmogorov-Smirnov test results in Table 9 reveal that the experimental class's N-Gain scores produced a statistic of 0.116 with a significance value of 0.200 (df = 34), while the control class's N-Gain scores yielded a statistic of 0.149 with a significance value of 0.090 (df = 30). Since both significance values are above the 0.05 threshold, it can be inferred that the N-Gain data for cognitive ability improvements in both groups are normally distributed.

Thus, the assumption of normality for the cognitive ability data has been met, allowing for the use of parametric statistical tests in subsequent analyses aimed at examining differences between the experimental and control groups regarding the impact of the metacognition-based discovery learning model.

Subsequently, a homogeneity test was conducted to assess whether the sample came from populations with homogeneous variances. Table 10 presents the results of the homogeneity test for critical thinking skills.

Table 10. Results of the Homogeneity Test of Critical Thinking Skills

Data Source	**Levene Statistic**	**df1**	**df2**	**Sig.**
Average N-Gain of Experimental and Control Classes	12,622	1	62	0,000

To further assess the comparability of the experimental and control groups, a homogeneity of variance test was conducted on the N-Gain scores for critical thinking skills. The results are presented in Table 10. As shown in Table 10, Levene's test produced a Levene Statistic of 12.622, with degrees of freedom $df_1 = 1$ and $df_2 = 62$, and a significance value (Sig.) of 0.000. Since the significance value is below 0.05, it can be concluded that the variances between the experimental and control groups are not homogeneous.

Considering the lack of variance homogeneity, any variations in critical thinking skill growth between the two groups should be investigated using non-parametric statistical approaches to account for the violation of homogeneity assumptions. Table 11 shows the homogeneity test findings for N-Gain scores related to cognitive ability.

Table 11. Results of Cognitive Ability Homogeneity Test

Data Source	**Levene Statistic**	**df1**	**df2**	**Sig.**
Average N-Gain of Experimental and Control Classes	14,638	1	62	0,000

As shown in Table 11, the N-Gain scores for cognitive abilities in both the experimental and control groups produced a significance value of 0.000, which is below the 0.05 threshold (0.000 < 0.05). This outcome indicates a substantial difference in variance between the two groups, confirming that the data distribution is not homogeneous.

In light of the violations of both the normality and homogeneity assumptions, the Mann-Whitney U test was employed as an appropriate non-parametric alternative to compare the cognitive ability improvements between the groups. This test was conducted at a significance level of 0.05 to evaluate whether the differences were statistically significant. All hypothesis testing procedures were carried out using IBM SPSS Statistics 29 software. Table 12 presents the results of this analysis.

Table 12. Results of the Mann-Whitey Test (U) Critical Thinking Skills

Data Source	Assymp.Sig. (2 tailed)	Decision
N-Gain experimental class and control class	0,000	H_0 rejected

Considering the non-normal distribution and the absence of variance homogeneity in the critical thinking skills data, the Mann-Whitney U test was used to assess if there was a significant difference in the improvement of critical thinking skills between the experimental and control groups. The outcomes of this analysis are presented in Table 12. As illustrated in Table 12, the Mann-Whitney U test produced an Asymp. Sig. (2-tailed) value of 0.000. Because this value is below the 0.05 significance level, the null hypothesis (H_0), which asserts that there is no significant difference between the two groups, must be rejected.

This result indicates that the metacognition-based discovery learning model had a statistically significant and positive influence on improving students' critical thinking skills, showing greater effectiveness than the traditional learning method applied in the control class. The subsequent analysis regarding cognitive ability improvement is summarized in Table 13.

Table 13. Mann-Whitey (U) Cognitive Ability Test Results

Data Source	Assymp.Sig. (2 tailed)	Decision
N-Gain experimental class and control class	0,000	H_0 rejected

Considering that the cognitive ability data met the normality assumption but to maintain consistency with the analysis of critical thinking skills, a Mann-Whitney U test was also conducted to assess the differences in cognitive ability improvement between the experimental and control groups. The results of this test are shown in Table 13. As indicated in Table 13, the Mann-Whitney U test produced an Asymp. Sig. (2-tailed) value of 0.000. Since this significance value is below the 0.05 threshold, the null hypothesis (H_0), which asserts that there is no significant difference in cognitive ability improvement between the two groups, is rejected.

These results suggest that applying the metacognition-based discovery learning model resulted in a significant enhancement of students' cognitive abilities compared to the conventional learning method used in the control group. To further assess the effectiveness of the metacognition-based discovery learning model, Cohen's d effect size was used to compare the experimental and control groups. The findings of this analysis are shown in Table 14.

Table 14. Effect Size Results of Experimental and Control Classes

	d effect size	**Interpretation**
Critical thinking skills	1.85	High
Cognitive abilities	1.83	High

To measure the extent of the variations identified between the treatment and comparison groups, effect size estimations were carried out for both students' critical reasoning abilities and cognitive capacities. The findings are displayed in Table 14.

As shown in Table 14, the effect size (d) for critical thinking skills was 1.85, and for cognitive abilities, it was 1.83. According to Cohen's (1988) criteria, an effect size greater than 0.80 is considered high. Therefore, both critical thinking skills and cognitive abilities improvements demonstrated a high effect size.

The findings imply that implementing the metacognition-based discovery learning approach had a notable and meaningful influence on enhancing students' critical reasoning skills and cognitive competencies, with both enhancements categorized as having a large effect size.

3.4. The Relationship between Cognitive Ability and Critical Thinking Skills

An association between students' critical reasoning proficiency and cognitive abilities was examined through a linear correlation analysis. The n-gain scores for critical thinking skills and cognitive abilities from the experimental class were used to calculate the correlation coefficient. The results yielded a correlation coefficient of 0.40, with a significance level of α = 0.05 and a sample size (n) of 34 students, resulting in a critical value r_{table} of 0.339. Since the calculated correlation coefficient (r-calculated) is larger than the critical value r_{table}, implying a good relationship between cognitive capacity (X) and critical thinking abilities (Y). The r-value falls within the range of 0.40 – 0.69, which is classified as a moderate correlation.From a pedagogical perspective, this moderate correlation (0.40) suggests a meaningful, albeit not overwhelming, relationship between cognitive abilities and critical thinking skills. This indicates that while improvements in cognitive abilities tend to align with enhancements in critical thinking, the relationship is not deterministic. Practically, this implies that while teaching methods that enhance cognitive abilities may contribute to better critical thinking, educators should also apply specific strategies targeted at developing critical thinking, rather than relying solely on cognitive development to achieve optimal outcomes.Additionally, a simple regression analysis produced the regression equation Y = 0.09 + 0.83X. The linearity of the regression was tested using $F_{TC} = -1{,}60$ and $F_{0.95\,(\frac{12}{20})} = 2.28$ with a significance level of α = 0.05. Since $F_{TC}(-1{,}60) < F_{0{,}95\,(\frac{12}{20})} = 2{,}28$. The regression equation is considered linear. This suggests that a 1% increase in cognitive ability corresponds to a 0.83% increase in critical thinking skills. Given the positive regression coefficient, it can be concluded that cognitive ability (X) exerts a unidirectional influence on critical thinking skills (Y), meaning that as cognitive ability increases, critical thinking skills will also improve.

An examination of the findings demonstrated that although both participant cohorts—those exposed to the metacognition-based discovery learning model and those receiving conventional instruction—showed moderate gains in critical thinking skills, the group utilizing the metacognitive approach achieved a substantially higher level of improvement compared to their counterparts. This aligns with the findings of Meriyana (2020), which suggests that using the Discovery Learning model can enhance students' critical thinking skills. When compared to students using traditional learning methods, students using the Discovery Learning approach demonstrate greater cognitive skills. The approach requires students to conduct scientific experiments, thereby developing their ability and skills to gather and interpret information through critical thinking exercises that adhere to scientific procedures (Martaida et al., 2017).

The outcomes of the data analysis demonstrate that students' critical thinking skills were positively impacted by the metacognitive-based discovery learning model on dynamic fluid materials. This model encourages students to actively formulate problems, conduct experiments, engage in group discussions, and communicate with other groups (Laeni, 2022). The discovery learning model emphasizes direct learning carried out by students, allowing them to find concepts based on the data they obtain.

Cognitive capacity was found to be positively correlated with students' critical thinking skills, implying that cognitive capability can assist students in improving their critical thinking, implying that cognitive capability can assist students in improving their critical thinking. Cognitive abilities within the medium category influence critical thinking skills. The correlation among cognitive ability and critical thinking in this study aligns with the findings of Raturoma & Laisnima (2023) who reported that critical thinking influences learning outcomes by 89%. Additionally, Laily (as cited in Babullah & Nugraha, 2023) emphasizes that strong cognitive abilities are essential for the enhancement of advanced critical thinking skills.

Furthermore, the emphasis on critical thinking skills and cognitive capacities at each step of learning is one of the reasons that contribute to the metacognitive-based discovery learning model's high effectiveness rating. This study's learning stages include the following:

1. Stimulation

Learning begins by asking questions that offer stimulus for students to suppose and recognize issues. From the questions given, students are trained to understand the hassle and give a simple explanation (elementary clarification) according to the student's understanding or prior knowledge. In this case, students identify the known and the unknown (declarative knowledge). At this stage, the researcher displays figures and videos about the application of physics materials in daily life. The stimulus given to students makes students motivated to solve the presented problems. When students are motivated and play an lively position in discovery, the resulting learning process will be very good.

2. Problem Statement

After identifying the questions, students are then given the opportunity to formulate a hypothesis. Students are encouraged to express their opinions about the initial hypothesis (declarative knowledge). The hypothesis formulation process assists students in formulating hypotheses by prompting them to critically identify and analyze a variety of occurrences or phenomena relevant to the topic. Students are therefore taught to evaluate arguments in order to formulate hypotheses at this point (elementary clarification).

3. Data Collecting

At this stage, students work on the LKPD that has been given and conduct experiments using the PhET application to collect data or information to demonstrate the validity of the hypothesis. To gather the required information, students are required to understand the data collection stage (procedural knowledge). At this stage, students are trained to watch and consider the findings of observations (basic support). Students will find concepts or theories that encourage students' curiosity, so that students think critically in accepting concepts or theories in learning.4. Data Processing. After collecting data through experiments, students process data and discuss with their group friends to analyze the data obtained and then record it in LKPD. At this stage, students elaborate the analysis`s results by exploring the relationship between variables and explaining in detail how the data supports or rejects the hypothesis (advance clarification). Students apply the concepts they find to solve various problems in the LKPD. The experiments carried out can reconstruct their knowledge so that their cognitive abilities increase (conditional knowledge).

4. Verification

Students carefully review the findings of data analysis to support the hypothesis` accuracy that has been formulated. Proof of the results was obtained through presentation activities and discussions with group friends. This stage trains students' critical thinking skills because during presentations and class discussions, various questions will arise, both from fellow group members and from other groups. The student who is asked will express his or her views, while the other students will give a response or rebuttal. Through this activity, students can discover for themselves the concepts and principles of the subject matter studied (conditional knowledge). Through the discussion process, students can conclude strategies that are relevant to the problems that exist in the LKPD and develop tactics to overcome these problems effectively (strategy and tactics).

5. Generalization

At this stage, the teacher guides the class in making inferences from the completed learning process. The conclusions obtained are used as a general principle by paying attention to the results of the verification that has been achieved.

Thus, students' critical thinking skills and cognitive abilities on dynamic fluid materials can be improved by using metacognitive-based discovery learning models since the learning stages are executed extremely well and always involve students so that students understand the problems given and are able to solve these problems. Students find solutions to problems by conducting experiments, discussions and questions and answers so that they are trained to ask questions, argue and conclude, or it can be said that students are taught to think critically.

The findings of this study are strongly supported by previous research. Laeni (2022) provides compelling evidence regarding how the discovery learning model improves critical thinking skills through active student engagement. Her study revealed that students who designed challenges, conducted experiments, and participated in collaborative discussions demonstrated significant improvements in multidimensional aspects of critical thinking. Specifically, within the subject of momentum and impulse, she reported increases in analytical reasoning (27.4%), evidence evaluation (31.2%), and logical argument construction (24.8%)—dimensions that closely align with those assessed in the present study.

Further validation is provided by Fitri (2022), whose meta-analysis on the implementation of metacognitive strategies revealed effect sizes ranging from 0.45 to 0.73. Her analysis demonstrated a consistent, positive relationship between the intensity of metacognitive interventions and improvements in thinking skills. The medium-level improvement observed in our study corresponds with Fitri's median effect size of 0.59, indicating that the effectiveness of our intervention falls within the expected range. Moreover, Fitri identified planning, monitoring, and evaluation as key mechanisms of metacognition—components that were explicitly embedded in our experimental scaffolding.

In addition, Bakri's (2024) research offers contextual support for the normalized gain score of 0.65 (classified as medium) obtained in our study. Bakri demonstrated that metacognitive strategies are particularly impactful in physics education because they facilitate students' ability to transition between abstract concepts and concrete applications. His findings showed that students receiving metacognitive training exhibited a 34% greater capacity to transfer learning to novel problem contexts compared to control groups. This transferability is essential for cultivating authentic critical thinking skills, extending beyond rote memorization and test preparation.

Taken together, these studies construct a robust theoretical framework that elucidates not only the effectiveness of our intervention but also the mechanisms through which the integration of discovery learning and metacognitive strategies led to substantial improvements in students' critical thinking skills.

4. CONCLUSION

This study confirms that the metacognition-based discovery learning model substantially improves students' critical thinking skills and cognitive abilities in dynamic fluid materials. As hypothesized, the experimental group outperformed the control group, achieving n-gain values of 0.68 (medium) for critical thinking and 0.70 (high) for cognitive abilities. The high effect size values (1.85 and 1.83 respectively) demonstrate the substantial impact of this intervention on student learning outcomes. A modaretely positive relationship between cognitive abilities and critical thinking skills is indicated by the correlation coefficient of 0.40, aligning with Bruner's constructivist theory that active discovery supported by metacognitive awareness fosters deeper understanding and higher-order thinking. The structured discovery learning phases, integrated with metacognitive strategies, provided students with meaningful engagement opportunities while promoting reflection on their cognitive processes. This approach directly addresses the problem identified in the introduction regarding low critical thinking skills among Indonesian students in physics education. By teaching students to monitor, plan, and evaluate their thinking, this model helps them grasp abstract concepts and apply them to complex problems. These results support innovative instructional strategies that develop 21st-century competencies within Education 4.0 and the Indonesian Independent Curriculum framework. For future research, several avenues merit further exploration. Investigating the long-term retention of critical thinking and cognitive skills developed through this model would provide insights into its sustained impact. Moreover, examining its effectiveness across different physics topics and other domains within science education could expand its applicability. Adaptations for diverse learning environments, such as online and blended modalities, also represent a valuable direction for enhancing its scalability. Additionally, the development of tailored metacognitive prompts and scaffolding techniques specific to various physics concepts could further strengthen instructional design. Finally, integrating this model into teacher education programs would support its broader adoption and contribute to the cultivation of critical and reflective educators capable of fostering 21st-century skills among learners.

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