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Integration of PhET Simulations and Animated Videos in Discovery-Based E-Worksheets to Enhance Critical Thinking Skills

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ABSTRACT In the digital era, critical thinking skills are essential for students to navigate complex challenges. However, these skills in science education remain a concern. This study examines the effectiveness of discovery learning-based electronic worksheets (e-worksheets) integrating PhET simulations and animated videos in enhancing students' critical thinking skills. A quasi-experimental design with a nonequivalent control group was employed, involving 60 eighth-grade students from Junior High School X Yogyakarta. The experimental group used discovery learning-based e-worksheets, while the control group used conventional printed worksheets. Data was collected using a critical thinking test with 10 questions covering five indicators. Results showed significant improvements in the experimental group (N-gain = 0.23), while the control group declined (N-gain = -0.18). The experimental group's mean score increased from 42 to 56, whereas the control group declined from 41 to 37. The highest improvement was in the "providing arguments or explanations" indicator (N-gain = 0.425). The Mann-Whitney test indicated significant differences between groups ($p < 0.05$), with the experimental group achieving a higher mean rank (39.45) than the control group (21.55). These findings suggest that integrating digital tools in discovery learning effectively enhances students' critical thinking skills in science education.

Keywords Animated video, Critical thinking skills, Discovery learning, E-worksheets, PhET.

1. INTRODUCTION

The emergence of the digital age has fundamentally transformed how science is taught and learned in educational institutions today. As societies face increasingly complex global challenges, the ability to think critically has emerged as a fundamental competency that must be developed in the twenty-first century (Gunadi et al., 2022; Laar et al., 2020). Within Indonesia's educational framework, this emphasis on critical thinking is reflected through the implementation of Higher Order Thinking Skills (HOTS)-based instruction, designed to equip students with the necessary capabilities to navigate modern-day challenges (Khaeruddin & Amin, 2020).

An analysis of research trends over the past twenty years reveals growing emphasis on critical thinking skills in education. From 2000 to 2021, studies focusing on critical thinking have not only increased in number but also diversified in scope and methodology. While scholarly contributions from Western academic institutions tend to receive more citations and recognition, research in this field spans globally. Among various research areas, pedagogical approaches to developing critical thinking capabilities emerge as the predominant focus of academic investigation (Dong et al., 2023). To develop advanced criticat thinking skills, students must master two fundamental aspects of thinking. First, they need to understand and recognize the distinct components that make up their thought processes. Second, they must develop the ability to evaluate how effectively they employ these various thinking components in practice (Paul & Elder, 2006).

The capacity for critical thinking encompasses a complex set of cognitive abilities that enable individuals to conduct thorough information analysis, assess various viewpoints, and reach evidence-based conclusions (Fisher, 2011). When integrated into classroom instruction, these critical thinking skills create lasting benefits for students' educational journey, particularly by enhancing their ability to comprehend and dissect logical frameworks and arguments (Raj et al., 2022). Given its fundamental

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importance, educational institutions should prioritize the cultivation of critical thinking capabilities through both innovative pedagogical strategies and robust assessment methods that effectively track and measure students' cognitive development.

Recent assessments reveal concerning trends regarding Indonesian students' critical thinking capabilities, highlighting a significant challenge in the nation's educational landscape. The 2022 Programme for International Student Assessment (PISA) results paint a troubling picture, with Indonesia ranking 73rd among 81 participating countries in science proficiency. The country's average score of 395 falls significantly short of the OECD mean of 485, and more worryingly, represents a decline from the previous score of 396 in PISA 2018 (OECD, 2023). This regression underscores the urgent need for educational reform in Indonesian science instruction.

Further evidence of this cognitive skills gap emerges from recent academic research. A study by Widyapuraya et al (2023) specifically identifies deficiencies in critical thinking abilities among middle school students. Multiple researchers attribute this educational challenge to traditional teaching methodologies that heavily emphasize teacher-centered instruction. Contemporary studies indicate that limited student engagement and passive learning environments significantly contribute to underdeveloped analytical skills among learners (Arviani et al., 2023; Widyapuraya et al., 2023).

Learning innovations are needed to overcome these problems, which can facilitate the development of students' critical thinking skills. One of the things that can be used is learning using e-worksheet discovery learning which is integrated with digital technology. Discovery learning puts students at the center of learning by encouraging them to play an active role in exploring concepts, solving problems, and finding solutions through inquiry-based activities that are in line with the principles of developing critical thinking skills (Karan, 2023). Discovery learning engages learners in hands-on learning experiences, allowing them to build understanding independently through observation, experimentation, and reflection. Digital technologies have become instrumental in transforming and enhancing educational practices, serving as vital tools that facilitate effective teaching and learning interactions. The integration of modern information systems, communication platforms, and technological resources creates dynamic pathways for knowledge transfer and skill development in educational settings. (Kumar, 2024).

E-worksheets designed with a discovery learning approach allow students to engage in an active and constructive learning process. Azhar et al (2024) research findings revealed that integrating PhET simulations within discovery learning methodology proved to be an effective approach for enhancing students' critical thinking skills. In line with that, Discovery learning makes students able to think more critically in solving a discovery (Manurung & Pappachan, 2025). The integration of digital technology such as PhET simulations and animated videos in learning can improve students' understanding of concepts and critical thinking skills (Anisa & Astriani, 2022; Anwar et al., 2023). However, there are still limitations in previous research related to the simultaneous use of PhET simulations and animated videos in discovery learning-based e-worksheets.

While prior research has explored the use of PhET simulations, animated videos, and e-worksheets individually, limited attention has been given to the integrated use of these three digital tools within a discovery learning framework. This study seeks to bridge that gap by designing e-worksheets that simultaneously incorporate PhET simulations, animated videos, and structured discovery activities, offering a cohesive digital environment aimed at enhancing students' critical thinking skills.

This research focuses specifically on the topic of simple machines, particularly levers, which are included in the eighth-grade science curriculum. This topic was selected due to persistent misconceptions among students in distinguishing between the fulcrum, load, and effort points (Christina et al., 2022; Rohmah et al., 2021). Misconceptions in this fundamental topic can impede students' understanding of more advanced scientific concepts. Therefore, teaching simple machines through interactive and visualized approaches is crucial for conceptual clarity and critical reasoning.

The theoretical foundation for this integration is grounded in constructivist learning theory, which posits that learners actively construct knowledge through meaningful experiences (Saarsar, 2018; Vygotsky, 1978; Zajda, 2023). Discovery learning, supported by interactive technologies such as PhET simulations and animated videos, aligns with this constructivist view by fostering active engagement, inquiry, and conceptual understanding (Flora et al., 2020; Saudelli et al., 2021).

Considering the aforementioned imperatives, this research seeks to determine the effectiveness of digital worksheets that incorporate PhET simulations and animated content, structured around discovery-based learning principles, in enhancing students' critical thinking skills during science learning. Also, looking at the influence of e-worksheets on students' critical thinking skills. This investigation aspires to provide meaningful insights into the development of innovative pedagogical approaches that enhance learners' critical cognitive competencies in today's technology-driven educational landscape.

Based on the background and research objectives, this study is guided by the following research questions: (1) How effective is the use of discovery learning-based e-worksheets integrated with PhET simulations and animated videos in improving students' critical thinking skills? (2) Is there a significant influence of the digital e-worksheet intervention on students' critical thinking skills compared to conventional learning? and (3) To what extent does the integration of PhET simulations and animated videos affect the improvement of students' critical thinking skills in science learning?

1. This study contributes to science education by offering an instructional framework that combines discovery learning with digital innovation. The integration of simulation and visual tools into discovery learning not only enhances student engagement but also improves critical thinking skills that are essential for scientific reasoning (García-Carmona, 2023). By aligning with 21st-century learning demands, this research provides actionable insights for science educators seeking to develop critical thinking in middle school students through technology-enriched discovery learning environments.

2. METHOD

The research methodology employs a quantitative framework, utilizing a quasi-experimental approach characterized by a nonequivalent control group structure (Best & Kahn, 2006). This methodological choice reflects the practical constraints of working with pre-existing class groups rather than randomly assigned subjects.

This research involving human participants was conducted in accordance with ethical standards. Ethical approval was obtained from the school principal of Junior High School X, and informed consent was secured from all participating students and their teacher before data collection commenced.

The participants of this study were 60 eighth-grade students from Junior High School X in Yogyakarta, consisting of 30 students in the experimental group (Class VIII-B) and 30 students in the control group (Class VIII-C). The experimental class comprised 11 male and 19 female students, while the control class consisted of 13 male and 17 female students. The students' ages ranged from 13 to 14 years old. The selection was made using purposive sampling based on teacher recommendations regarding student characteristics and classroom balance.

The research encompasses all eighth-grade students enrolled at Junior High School X Yogyakarta during the 2023/2024 academic session, distributed across four distinct classes. The selection of participants followed a purposive sampling methodology, taking into account the students' baseline capabilities as recommended by their science teacher. From the available classes, two were identified as research participants: Class VIII-B, comprising 30 students, was designated as the experimental group, while Class VIII-C, also containing 30 students, served as the control group (Table 1).

Table 1 Nonequivalent control group design

Class	Pretest	Treatment	Posttest
Experiment	0_1	X	0_2
Control	0_3	–	0_4

Information:
0_1 = Pretest of the experimental class
0_2 = Posttest the experimental class
0_3 = Control class pretest
0_4 = Posttest control classes
X = Treatment with PhET-integrated discovery learning-based e-worksheets and animated videos
– = Conventional learning with printed worksheet

The intervention was carried out for one week. The PhET simulations and animated videos used in this study were selected based on their relevance to the eighth-grade science curriculum and the concepts targeted in the e-worksheets. Guided by the principles of meaningful learning within the discovery learning framework, the selection emphasized content accuracy, interactivity, visual clarity, and potential to stimulate student. Animated videos were specifically used to help stimulate students to better understand the problems presented in learning activities, thereby enhancing their engagement and facilitating deeper conceptual comprehension.

The assessment of critical thinking skills in this research employs a set of ten multiple choice questions, constructed to align with five fundamental indicators of critical thinking skills, specifically: identifying, analyzing, evaluating, drawing conclusions and making decisions, providing arguments or explanations (Facione, 2015; Fisher, 2011; Sanders & Moulenbelt, 2011). Each indicator is represented by two questions. The distribution of questions and subtopics respectively is as follows:

a. Identifying (2 questions):
   - Sub Topic 1: Identifying tools that utilize the lever principle (e.g., bottle opener)
   - Sub Topic 2: Selecting effective simple machines for specific problems (e.g., moving a rock)

b. Analyzing (2 questions):
   - Sub Topic 1: Calculating required effort using lever arm data and force
   - Sub Topic 2: Computing mechanical advantage of a tool based on arm lengths

c. Evaluating (2 questions):
   - Sub Topic 1: Assessing the effectiveness of a lever configuration based on applied force and object weight
   - Sub Topic 2: Evaluating the correctness of conceptual statements about levers

d. Drawing conclusions and making decisions (2 questions):
   - Sub Topic 1: Interpreting data from an experiment to determine tool efficiency

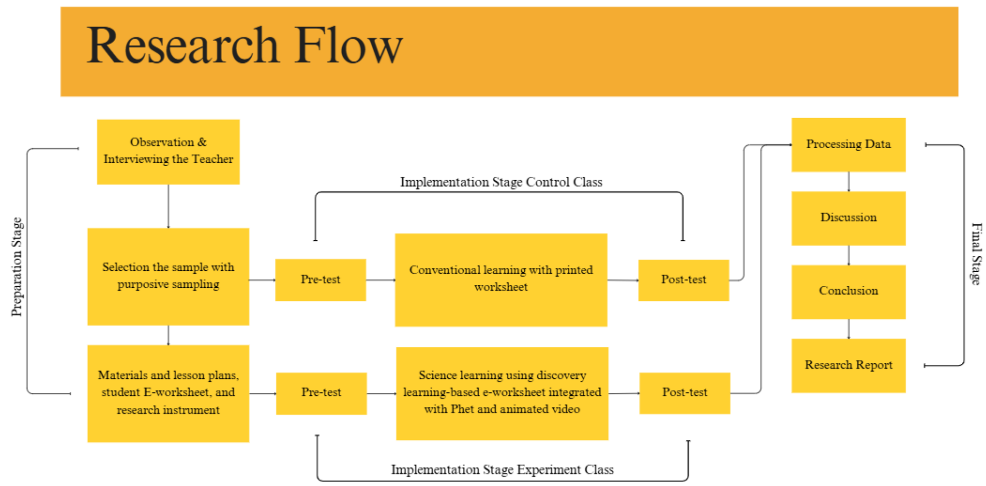

Figure 1 Research flow design

- Sub Topic 2: Deciding on the optimal lever configuration based on physical parameters

e. Providing arguments or explanations (2 questions):

- Sub Topic 1: Explaining why a tool (e.g., bottle opener) works better than manual force
- Sub Topic 2: Explaining the effectiveness of long vs. short crowbars based on the simple machines principle of levers

Each question was contextualized around the topic of levers, a type of simple machine covered in the eighth-grade science curriculum. The items required students not only to recall information but also to reason, evaluate, and apply conceptual understanding—core components of critical thinking.

The critical thinking test instrument was validated through a two-step process. First, expert judgment was conducted by two subject matter experts in science education, who assessed the items based on three aspects: content/substance, construction, and language. Revisions were made based on their feedback to ensure clarity, relevance, and alignment with the research objectives.

Second, empirical validation was carried out using SPSS. The validity test used Pearson's Product Moment correlation to assess the correlation between each item and the total score. The results indicated that all items had a correlation coefficient (r-count) greater than the critical r-value at a significance level of 0.05, demonstrating that all test items were valid.

The assessment of the effectiveness of e-worksheets based on PhET integrated discovery learning and animated videos uses N-gain values. The N-gain equation can be seen in the following equation.

$$\text{N-gain} = \frac{S_{posttest} - S_{pretest}}{S_{maximum} - S_{pretest}}$$

Furthermore, the results of the calculations obtained are interpreted based on the category in Table 2.

Table 2 N-gain interpretation category

Value	Category
N-gain > 0.7	High
0.3 < N-gain ≤ 0.7	Medium
N-gain ≤ 0.3	Low

(Hake, 1999)

Then, to see if there is a difference in critical thinking skills between the experimental class and the control class, an analysis test was carried out using an independent sample t-test. If the prerequisite test is not met, then use the Mann-Whitney test. To better understand the research flow, it can be seen in figure 1.

The research flow diagram illustrates the systematic approach employed in this study, structured across three main phases: Preparation Stage, Implementation Stage, and Final Stage.

In the Preparation Stage, researchers began with observation and interviews with the science teacher to gather contextual understanding of the learning environment. Based on this, purposive sampling was conducted to select two comparable eighth-grade classes. Subsequently, researchers developed all necessary materials, including lesson plans, student e-worksheets, animated video, PhET simulations, and research instruments.

The Implementation Stage involved two groups: the experimental class and the control class. Both groups initially completed a pre-test to measure baseline critical thinking skills. The experimental group then received learning through discovery learning-based e-worksheets integrated with PhET simulations and animated videos. In contrast, the control class underwent conventional instruction using printed worksheets within a discovery learning model commonly employed by science teachers. Upon completion of the learning activities, both groups

Figure 2 discovery learning e-worksheet integrated with virtual laboratory (phet) and animated video on simple aircraft materials

were administered a post-test to assess changes in critical thinking skills.

In the Final Stage, researchers analyzed the collected data using appropriate statistical methods, interpreted the results, and conducted a comprehensive discussion to explain the effectiveness of the intervention. Conclusions were drawn based on empirical findings, and all outcomes were compiled into a detailed research report. This structured flow ensured a rigorous investigation into how integrating digital tools within discovery-based learning environments compares to traditional methods in enhancing students' critical thinking abilities.

3. RESULT AND DISCUSSION

3.1 Learning Process

The selection of simple aircraft material is based on observations that have been made and adjusted to the learning materials that will be learned by students. In addition, there are still frequent misconceptions about simple aircraft materials, where students have difficulty distinguishing the location of fulcrum points, load points, and power points on types of levers (Christina et al., 2022; Fahrunissa et al., 2023; Rohmah et al., 2021)

The pretest was carried out on the experimental class and the control class as the initial stage before learning simple aircraft material. Then, on Wednesday, October 23, 2024, in the first and second hours, learning was carried out in the experimental class using e-worksheet discovery learning integrated with PhET and animated videos. Learning in the control class was carried out the next day using the learning model and media commonly used by science teachers at SMP N X Yogyakarta. The posttest is given to both classes after the entire learning process is completed. The learning steps of the experimental class and the control class can be seen in table 3 and table 4.

Figure 3 Student activities in the experimental class using discovery learning e-worksheet integrated with virtual laboratory (phet) and animated videos

The learning of the experimental class using e-worksheet discovery learning integrated with a virtual laboratory (PhET) and an animated video on the Simple Airplane material of the lever part can be seen in figure 2. Meanwhile, the learning activities in the experimental class can be seen in figure 3.

Based on the research that has been carried out using Discovery-Based E-Worksheets integrated with PhET and animated videos on students' critical thinking skills, several results are obtained that will be systematically described. The data obtained showed an improvement in students' critical thinking skills. These findings provide a comprehensive overview of critical thinking skills that will be further analyzed in the following discussion.

3.2 Effectiveness of E-Worksheet on Students' Critical Thinking Skills

The effectiveness of e-worksheets based on PhET integrated discovery learning and animated videos can be seen from how much the N-gain score increased as seen in the table 5.

Table 5 Critical thinking skills n-gain score

Treatment	Average		N-gain	Category
	Pretest	Posttest		
Experimental Classes	42	56	0.23	Low
Control Classes	41	37	-0.18	Low

The examination of N-gain scores revealed contrasting outcomes between the two groups. The experimental group demonstrated modest improvement in critical thinking skillas, achieving an N-gain value of 0.23, which falls within the lower enhancement bracket. In contrast, the control group exhibited a decline, with an N-gain value of -0.18, also categorized in the lower range. Despite both groups being classified in the same category, notable differences appear in their final results. The experimental group's mean scores progressed from 42 in the pretest to 56 in the posttest, indicating positive development.

Conversely, the control group's performance declined from an initial mean of 41 to 37 in the final assessment.

When comparing the N-gain score of 0.23 with similar studies, it aligns with results reported in related works. For example, Saputra et al. (2021) reported an N-gain of 0.21, and Sudirman et al. (2024) found improvements between 0.2–0.3 when using technology-supported discovery learning. These studies support the interpretation that critical thinking interventions, especially those conducted over short durations, often yield incremental gains in score but may still exert meaningful pedagogical impact.

This measured pace of progress aligns with established research indicating that critical thinking development requires sustained engagement and time, as highlighted in recent studies (Kusuma et al., 2024; Narayanan & Zainal, 2022). The early development of critical thinking skills plays a vital role in shaping individuals' life competencies. These fundamental cognitive skills enable people to exercise sound judgment, articulate their perspectives effectively, and develop innovative approaches to problem-solving (Cisterna-Zenteno et al., 2022). By cultivating these critical thinking skills from a young age, individuals become better equipped to navigate complex decisions and contribute meaningful solutions to challenges throughout their lives.

These findings corroborate the research by Saputra et al (2021), which demonstrated that Discovery Learning approaches integrated with digital media can enhance students' critical thinking skills, even when improvements appear incremental. In addition, the implementation of e-worksheets in the learning process has proven to be effective in developing and improving students' critical thinking skills, thereby helping them in analyzing, evaluating, and solving various problems systematically (Sudirman et al., 2024). Moreover, the use of virtual laboratories offers an alternative to overcome the limitations of physical laboratory facilities and infrastructure. The use of PhET simulation media as a substitute for real experiments has proven to be effective, which is reflected in the improvement of learning outcomes and the level of student activity during the learning process in the classroom (Simbolon & Silalahi, 2023). How much critical thinking skills have improved in each indicator can be seen in the table 6.

A more detailed analysis of each critical thinking skills indicator shows varied and interesting results to study. The highest increase in the experimental class occurred in the indicator of " Providing arguments or explanations" with an N-gain of 0.425, which was indicated by an increase in the score from 37.5 to 64.1. This significant increase indicates that the use of PhET simulations and animated videos is effective in helping students construct and communicate their scientific arguments. This increased argumentability can be explained because students gain hands-on experience through interactive simulations, which allows them to observe and understand scientific phenomena in a more concrete way. In line with the research of Sudatha & Simamora (2021) which found that dynamic visualization through interactive simulations can support the learning process. This is reinforced by the findings of Sudirman et al (2024) which show that the application of e-worksheets as an interactive learning medium is proven to improve students' ability to argue logically and systematically.

The "analyzing" indicator took second place with an N-gain of 0.226, indicated by an increase in the score from 51.6 to 62.5. This improvement indicates that discovery learning-based electronic worksheets have successfully facilitated students in developing their analytical skills. Exploration activities through PhET simulations allow students to identify important variables, analyze relationships between variables, and understand key concepts in the phenomena studied. This is in line with the research of Muhammad et al (2022) which found that discovery learning-based e-worksheets integrated with technology can improve students' analytical skills in science learning. Furthermore, the use of animation has been proven to significantly improve students' analytical skills, which is shown through the suitability of systematic analysis formats and the development of structured and high-quality analytical thinking in solving various learning problems (Kwangmuang et al., 2024)

The "evaluate" indicator has increased with an N-gain of 0.174 (from 28.1 to 40.6). This improvement in evaluation ability proves that students have been able to develop skills to assess their own learning performance better (Seden et al., 2023) In addition, learning based on discovery learning can improve students' evaluation skills,

Table 6 N-gain score of each indicator of critical thinking skills

Critical Thinking Skills Indicators	Experimental Classes				Control Classes			
	Pretest	Posttest	N-gain	Category	Pretest	Posttest	N-gain	Category
Identifying	51.6	57.8	0.129	Low	26.6	35.9	0.127	Low
Analyzing	51.6	62.5	0.226	Low	43.8	40.6	-0.056	Low
Evaluating	28.1	40.6	0.174	Low	34.4	31.3	-0.047	Low
Drawing conclusions and making decisions	29.7	37.5	0.111	Low	40.6	21.9	-0.315	Low
Providing arguments or explanations	37.5	64.1	0.425	Medium	46.9	42.2	-0.088	Low

Tabel 7 Analysis based on sub-topic

Class		Identifying		Analyzing		Evaluating		Drawing conclusions and making decisions		Providing arguments or explanations	
		Sub Topic 1	Sub Topic 2	Sub Topic 1	Sub Topic 2	Sub Topic 1	Sub Topic 2	Sub Topic 1	Sub Topic 2	Sub Topic 1	Sub Topic 2
Eksperiment	Pretest	50.00	53.13	34.38	68.75	34.38	21.88	31.25	28.13	43.75	31.25
	Posttest	62.5	53.125	62.5	62.5	50	31.25	43.75	31.25	78.125	50
Control	Pretest	28.13	25.00	21.88	65.63	40.63	28.13	34.38	46.88	62.50	31.25
	Posttest	31.25	40.63	25.00	56.25	31.25	31.25	21.88	21.88	50.00	34.38

where students review statements used in expressing ideas, thoughts, opinions, or perceptions (Rahmawati et al., 2021)

While "identifying" reached an N-gain value of 0.129 (from 51.6 to 57.8). In the indicator of identifying problems, although the improvement is relatively low, the data shows that students have a fairly good initial score (51.6) compared to other indicators. This moderate increase can be attributed to the PhET simulation feature and animated videos that help students visualize abstract science problems into more real (Banda & Nzabahimana, 2021) The ability to identify problems is an important basic skill in the development of critical thinking, where identification is the main foundation for a person to analyze an event (Heard et al., 2020)

The "draw conclusions and make decisions" indicator achieved an N-gain of 0.111 with an increase in score from 29.7 to 37.5. Although the increase was lowest among all indicators, it still showed the positive impact of the learning interventions provided. These results are in line with the research of Drastisianti et al (2024) which shows that the implementation of PhET simulations in the learning process has a positive impact on improving students' ability to make conclusions, although the increase recorded is relatively small. In line with that, the use of virtual laboratories can also improve students' decision-making abilities (Abdelmoneim et al., 2022). Once a person has managed to draw a conclusion from an event, then the step that is synonymous with it is decision-making. Decision-making is the process of making choices by identifying decisions, gathering information, determining conclusions and assessing alternative resolutions (Subedi, 2022) Improvements in all of these indicators, albeit in the low category, show a consistent pattern that technology-enriched discovery-based learning can facilitate the development of various aspects of critical thinking skills (Muhammad et al., 2022). An analysis of improving critical thinking skills based on each sub-topic can be seen in table 7.

The analysis of students' critical thinking skills was further detailed based on two subtopics for each indicator. This breakdown provided a clearer understanding of how students progressed in specific cognitive processes across different learning content. In the "Analyzing" indicator, both subtopics showed strong improvements in the experimental class: Sub Topik 1 (calculating effort) increased from 34.38 to 62.5, and Sub Topik 2 (mechanical advantage) remained high at 62.5, indicating consistent understanding after the intervention. This aligns with findings from Kefalis & Skordoulis (2025), who emphasized that digital simulations allow learners to manipulate variables and observe the effects dynamically, thereby reinforcing analytical skills through experimentation. Similarly, in the "Providing arguments or explanations" indicator, Sub Topik 1 improved significantly from 43.75 to 78.13, while Sub Topik 2 rose from 31.25 to 50.00. This suggests that the simulation and animated videos were particularly effective in helping students construct logical reasoning and articulate cause-effect relationships.

In contrast, subtopics under the "Evaluating" and "Drawing conclusions and making decisions" indicators displayed more modest improvements. For example, in Evaluating Sub Topik 2, scores only increased from 21.88 to 31.25, and in Drawing Conclusions Sub Topik 2, the rise was from 28.13 to 31.25. These lower gains may reflect the complexity of these tasks and students' difficulty in transferring conceptual understanding into evaluative or strategic decisions. This is consistent with the study by Zohar & Barzilai (2013), which found that evaluation and decision-making are higher-order cognitive skills that require prolonged exposure and structured scaffolding to develop effectively.

Several classroom challenges contributed to these uneven outcomes. Observations during the learning sessions noted that some students were distracted—engaging in conversations, using their phones for non-educational purposes, and lacking focus, especially during interactive exploration phases. These behavioral issues likely hindered deeper cognitive engagement with more complex tasks, thereby limiting the potential improvement in certain subtopics. Similar challenges in managing student engagement during technology-enhanced instruction have been noted by Bano et al (2018), who emphasized the need for integrating digital discipline strategies alongside interactive learning tools to sustain attention and learning outcomes.

3.3 Influence of E-worksheets on Students' Critical Thinking Skills

The next test carried out is a data normality test to find out whether the distributed data is normal or not. The results of the data normality test can be seen in the table 8.

Table 8 Data normality test results

Class	Shapiro-Wilk		
	Statistic	df	Sig.
Experimental Class Pretest	0.915	30	0.020
Experimental Class Posttest	0.929	30	0.046
Control Class Pretest	0.891	30	0.005
Posttest Control Classes	0.879	30	0.003

The next research analysis uses the Shapiro-Wilk test to determine the normality of the data. The data of the experimental class obtained a significance value of 0.020 in the pretest and 0.046 in the posttest, while the control class showed a value of 0.005 for the pretest and 0.003 for the posttest. Considering that all significance values are below the threshold of 0.05, it can be concluded that the data distribution does not follow the normal data pattern, so the test continues with a non-parametric method, namely the Mann-Whitney test (Emerson, 2023). Because the normality test shows that the data is abnormally distributed. So, the statistical test used is the Mann-Whitney test. The data of Mann-Whitney test results can be seen in the following table 9.

Table 9 Mann-whitney test results

Kelas	N	Mean Rank	Sum of Ranks	Nilai U	Z	Asymp. Sig. (2-tailed)
Eksperimen	30	39,45	1183,50	181,500	-	0.000
Kontrol	30	21,55	646,50		4,039	

The findings through the Mann-Whitney test revealed that there was a meaningful gap between the achievement of the experimental and control classes, reflected in the Asymp. (2-tailed) value of 0.000 which was well below the significance threshold of 0.05 (Sriwidadi, 2011). The achievement of the experimental class using integrated electronic worksheets recorded a mean rank of 39.45, outperforming the control class which only reached a mean rank of 21.55. This gap suggests a difference in the use of discovery-based electronic worksheets enriched with PhET simulations and animated videos in honing students' critical thinking skills towards the use of conventional worksheets. Thus, there is an influence on the use of PhET-integrated discovery learning e-worksheets and animated videos.

The e-worksheet developed has been proven to encourage students to go beyond conventional learning. The effectiveness of digital learning media has indeed been proven to improve students' critical thinking skills, where the use of learning media is better than conventional learning (Fitria et al., 2023; Marnita et al., 2021; Wardani et al., 2024). The integration of PhET simulations provides a virtual experimentation space that enriches the learning experience. In line with the research of Haleem et al (2022) which revealed that the integration of technology in learning, including virtual laboratories, plays a strategic role in developing students' competencies needed to adapt to the demands of the digital era, especially in terms of higher-order thinking skills.

Then, to find out how much the effect of the intervention on the difference between the two groups can be seen from the size effect. Cohen's value of d of 1.19 indicates a large effect according to conventional interpretation (0.2 = small, 0.5 = medium, 0.8 = large) (Brydges, 2019). These statistically significant results confirm that the use of discovery-based worksheets integrated with PhET simulations and animated videos has a powerful and meaningful influence on improving students' critical thinking skills in science learning.

The successful implementation of discovery-based electronic worksheets is inseparable from its characteristics that facilitate independent learning and discovery. These outcomes align with Hilmia et al (2022) research, which emphasizes how electronic worksheets facilitate critical thinking development by providing a more dynamic learning experience and enabling students to independently construct knowledge. The incorporation of PhET simulations and animated videos within electronic worksheets has demonstrated effectiveness in helping students visualize abstract scientific concepts (Samitra et al., 2023). PhET simulations create opportunities for students to engage actively in learning exploration, thereby enhancing their educational achievements (Liswar et al., 2023). Through the discovery learning approach, students develop analytical capabilities, evaluation skills, and the ability to draw conclusions based on evidence gathered during their learning journey (Khasinah, 2021). Interactive learning tools, particularly PhET simulations and animated videos, serve as crucial elements in establishing a learning environment that nurtures the development of higher-order thinking skills, including critical thinking abilities (Sastradewi, 2022; Verawati & Sukaisih, 2021).

This study is subject to several limitations. The sample size was relatively small (30 students per group), which limits generalizability. The intervention duration was limited to one week, which may not have been sufficient to fully develop critical thinking skills. Furthermore, the implementation was conducted by the same teacher for both groups, which may introduce bias, particularly in the delivery of digital content and instructional engagement.

Educators aiming to develop students' critical thinking skills can consider integrating PhET simulations in the exploration or experimentation phase and using animated videos during concept stimulation. These tools can be embedded in e-worksheets that guide students through discovery learning processes—encouraging active engagement, data analysis, and reasoning.

In alignment with global educational priorities, this study supports the PISA framework's emphasis on 21st-century skills, particularly critical thinking, scientific reasoning, and digital competency (OECD, 2023). The findings suggest that using interactive technologies within structured pedagogical models like discovery learning can effectively address deficits in cognitive skill development in science education.

4. CONCLUSION

The integration of discovery learning-based e-worksheets with PhET simulations and animated videos was effective in enhancing students' critical thinking skills, as reflected by an N-gain of 0.23 in the experimental group, while the control group experienced a decline (-0.18), thereby addressing the first research question. A significant influence of the intervention was confirmed through the Mann-Whitney test ($p < 0.05$), with the experimental group achieving a higher mean rank (39.45) than the control group (21.55), thus answering the second question. The third research question was addressed by identifying that the most improved critical thinking indicator was "providing arguments or explanations" (N-gain = 0.425), indicating the strong impact of visual and interactive media on reasoning skills. Furthermore, the large effect size (Cohen's d = 1.19) reinforces the substantial educational impact of the intervention. Future studies should extend the intervention duration, involve diverse science topics and student populations, and consider integrating adaptive or gamified digital features to further strengthen the development of critical thinking.

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