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The effect of PhET simulations-assisted inquiry-based learning on students' critical thinking skills

Ismu Sukamto[1], Hervin Maulina[2], Rahmah Kumullah[3]
[1] Universitas Negeri Yogyakarta
[2] Universitas Lampung
[3] STKIP Andi Matappa
Correspondence: ismusukamto.2022@student.uny.ac.id

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ABSTRACT
The purpose of this study is to determine the influence of inquiry-based learning on students' critical thinking skills. The study employed a quantitative approach using a quasi-experimental design with a nonequivalent control group. This study involved an experimental class and a control class with a total of 44 students. The data collected were statistically analyzed using an independent sample t-test. Based on data analysis, it was found that inquiry-based learning based on PhET simulations can improve the critical thinking skills of high school students. Inquisition-based learning allows students to act as scientists, using scientific methods to explore natural phenomena, so as to develop students' critical thinking and problem-solving skills. Blending with PhET simulations helps students develop a deeper understanding of scientific concepts by providing visual and interactive ways to explore and test hypotheses.

INTRODUCTION

The development of critical thinking is essential for students to meet the challenges of the 21st century (Sukamto et al., 2022). Critical thinking skills allow individuals to analyze complex problems and design effective solutions (Indrawatiningsih et al., 2019). This skill is especially important in areas where multi-perspective thinking is required to tackle complex problems (Prapulla et al., 2022). By thinking critically, individuals can evaluate various solutions and choose the best method, thus improving the decision-making process (Sáenz-Rodríguez et al., 2021). This skill is essential in professional settings where making the right decisions can lead to better outcomes (Stoesz et al., 2022).

In an academic context, critical thinking skills are positively correlated with learning achievement, suggesting that students who think critically tend to perform better academically (Nasution et al., 2023). For instance, writing assignments that foster critical thinking have been shown to significantly improve students' analytical and inference skills (Quitadamo & Kurtz, 2007). Additionally, critical thinking is also related to better reading comprehension and mastery of concepts (Amanda et al., 2022).

Critical thinking disposition (CTD) also acts as a mediator between problem-solving and creative thinking, enhancing both skills (Koçoğlu & Kanadlı, 2025). This interconnectedness suggests that fostering critical thinking can also boost creativity, which is essential for innovation and artistic endeavor (Prapulla et al., 2022). In addition, critical thinking dispositions significantly mediate the relationship between self-efficacy and problem-solving skills, suggesting that improving critical thinking can improve students' confidence and problem-solving abilities (Tasgin & Dilek, 2023).

Traditional teaching methods often fail to actively engage students, leading to lower critical thinking skills (Chengere et al., 2025; Rahmatan, 2021). Studies have shown that guided inquiry models significantly improve students' critical thinking skills. For instance, one study reported a 29.9% increase in critical thinking skills among 11th-graders using a guided inquiry model (Rosania et al., 2023). Inquiry-based learning can help reduce educational gaps by promoting an active, hands-on learning experience that engages all students, regardless of gender or socioeconomic status (Hedley et al., 2013). This method encourages students to articulate their thoughts and consider different perspectives (Lombardi et al., 2024).

The shift towards a more interactive and flexible learning environment, powered by technology, underscores the need for inquiry-based learning to keep pace with global education trends (Cao, 2022; Marcolino et al., 2019). Therefore, combining PhET simulations with real experiments can provide complementary advantages, improving students' conceptual understanding and critical thinking skills more effectively than using either method alone (Flegr et al., 2023). PhET simulations are advanced tools that can significantly support inquiry-based learning and improve students' critical thinking skills. PhET simulations promote active engagement by allowing students to manipulate variables and observe outcomes, which fosters critical thinking and problem-solving skills (Diab et al., 2024). Integrating PhET simulations with inquiry-based learning has been shown to improve students' critical thinking skills. For instance, students who used PhET simulations within the PBL framework showed significant improvements in their ability to analyze and solve problems (Putranta & Wilujeng, 2019).

Considering the benefits of inquiry-based learning and the use of PhET simulations in learning, researchers need to combine the two as a cohesive treatment in learning. This research is aimed at improving students' critical thinking skills by applying inquiry-based learning assisted by PhET simulations. This research is expected to provide alternative solutions for teachers, curriculum designers, and policy makers to develop innovative learning according to the needs of the 21st century society.

RESEARCH METHODS

Research Design

The study employed a quantitative approach using a quasi-experimental design with a nonequivalent control group (Creswell, 2015). This design was chosen to examine the influence of PhET simulations-assisted inquiry learning. This study involved an experimental class and a control class, where the experimental class was given inquiry learning assisted by PhET simulations and the control class was given inquiry learning assisted by learning videos. In both classes, students worked on critical thinking skills before and after being treated. Treatment was given during 3 meetings on gas kinetic theory material.

Research Sample

The sample was determined using non-probability convenience sampling by considering willingness to participate voluntarily in the study (Braz et al., 2020; Tapia-Gutierrez & Delgado, 2015). A total of number of participants was involved, consisting of 21 people for the experimental class and 23 people for the control class. The research sample was grade XI students at one of the high schools in Surabaya.

Collecting Data

Data collection was carried out using a test in the form of critical thinking skills questions. The critical thinking skills question is composed of six indicators adapted from Ennis' critical thinking criteria (Ennis, 2015), namely: 1) Formulating problems; 2) Doing deductions; 3) Perform induction; 4) Conduct an evaluation; 5) Provide arguments; and 6) Decide. Each indicator consists of 2 question items so that the total number of question items is 12. The question items are at the cognitive level C4-C6.

Analysis of the validity and reliability of critical thinking skills is carried out to ensure that the instrument used can measure according to the measurement objectives (valid) and can provide consistent results within a certain time limit (reliable). Validity analysis begins with applying content validity by experts (Yaghmaie, 2003). This expert assessment provides evidence for items built relevant to the concept (Carretero-dios et al., 2005). Furthermore, the validity of the instrument was statistically analyzed using the Confirmatory Factor Analysis technique and the reliability of the instrument was analyzed by the Reliability Analysis technique using the Jamovi 2.3.28 application involving 60 respondents.

Data Analysis

The influence of PhET simulations-assisted inquisition learning was assessed based on the differences in students' critical thinking skills in the experimental class and the control class. The data

collected were statistically analyzed using an independent sample t-test using the Jamovi 2.3.28 application.

The determination of the effectiveness of PhET simulations-assisted inquiry learning follows the following hypothesis:

H_0 : PhET simulations-assisted inquiry learning had no significant effect on students' critical thinking skills.
H_1 : PhET simulations-assisted inquiry learning has a significant effect on students' critical thinking skills.

The acceptance of such a hypothesis refers to the following test criteria:
H_0 is accepted if the p-value (sig) is > 0.05 or H_0 is rejected if the p-value (sig) < 0.05
H_1 is accepted if the p-value (sig) is < 0.05 or H_1 is rejected if the p-value (sig) > 0.05

The test criteria are accepted if the data meets the prerequisite tests of normality and homogeneity. The data is declared to be normally distributed if the p-value > 0.05 in the *Normality Test (Shapiro-Wilk) analysis*. Furthermore, the data is declared homogeneous if the p-value is > 0.05 in the analysis *of the Homogeneity of Variances Test (Levene's).*

RESULTS

This experimental research involved an experimental class and a control class where the experimental class was given PhET simulations-assisted inquiry learning and the control class was given video-assisted inquiry learning. Treatment was given during 3 meetings on gas kinetic theory material. In both classes, students worked on critical thinking skills before and after being treated. The data obtained in this study are data on the validity and reliability analysis of critical thinking skills, as well as data from hypothesis tests. In detail, the two main data are described as follows.

Validity of Critical Thinking Skills Questions

Based on the Confirmatory Factor Analysis test using Jamovi 2.3.28, Test for Exact Fit (Table 1) and Fit Measures (Table 2) data were obtained in the Fit Model, and Path Diagram (Figure 1).

Table 1. Test for Exact Fit in Fit Models

χ^2	df	p
19.2	15	0.205

Table 1 shows that the p-value < 0.205 (> 0.05), which means that the model is declared insignificant. Furthermore, with the value $\chi^2/_{df} = {}^{19,2}/_{15} = 1{,}28$ (< 3), then the model is declared fit.

Table 2. Fit Measures in Fit Models

				RMSEA 90% CI	
CFI	TLI	SRMR	RMSEA	Lower	Upper
0.995	0.988	0.0131	0.0683	0.00	0.148

Table 2 shows that the CFI value = 0.995 (> 0.9), which means the model is declared fit; the TLI value = 0.988 (> 0.9), which means the model is declared fit; SRMR = 0.0131 (< 0.8), which means the model is declared unfit; RMSEA = 0.0683 (< 0.07), which means the model is declared fit. Thus, the critical thinking skills measuring instrument used is only for CFI, TLI, and RMSEA tests.

Furthermore, the Path Diagram on this CFA test can be seen in Figure 4. The path diagram shows the path and categorization of instrument items has been confirmed according to a theoretical study consisting of six dimensions.

Thus, it is confirmed that the latent variable of critical thinking skills consists of 6 indicators which include: 1) Formulating Problems, with point 4 and point 8; 2) Doing Deduction, with point 2; 3) Provide Arguments, with point 6 and point 7; 4) Decide, with point 3; 5) Doing Induction, with point 9; and 6) Conducting Evaluation, with points 1 and 5, declared valid to measure students' critical thinking skills.

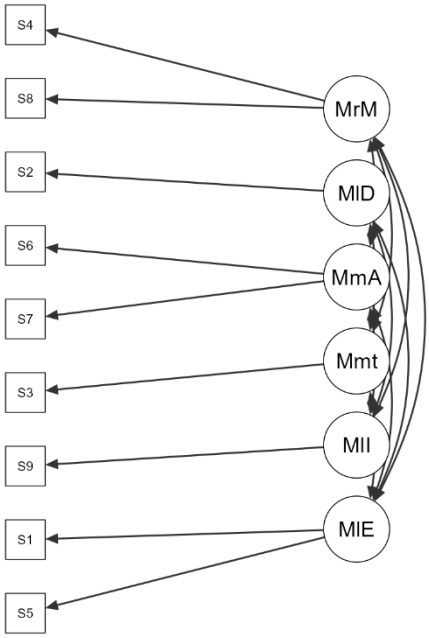

Figure 1. Path Diagram

Reliability of Critical Thinking Skills

Based on the results of the statistical test, it was obtained that Cronbach's α value was 0.925 (Table 3). This means that critical thinking skills are interpreted to be of high scale internal consistency (Sürücü & Maslakci, 2020). Furthermore, the value of the item-rest correlation for the item setial is positive in the range of 0.658 – 0.853. Thus, it can be stated that the 9 questions about critical thinking skills are declared reliable.

Table 3. Scale Reliability Statistics

	Cronbach's α
scale	0.925

Hypothesis Testing

Based on Table 4, the p-value is < 0.001 (< 0.05). This shows that differences in treatment in experimental and control classes exert a significant influence on the critical thinking skills of high school students. Thus, H1 is accepted. This means that PhET simulations-assisted inquiry learning has a significant effect on students' critical thinking skills.

Table 4. The Results of Independent Samples T-Test

		Statistic	*df*	*p*
Score	Student's t	-6.08	42.0	< .001

Note. H_a $\mu_1 \neq \mu_2$

Assumptions

The H_1 acceptance was strengthened by the fulfillment of the prerequisites for normality and homogeneity of data. The data is declared to be normally distributed with a p-value of 0.267 (> 0.05) in the Normality Test (Shapiro-Wilk) analysis (Table 5 and Figure 2).

Table 5. The Result of Normality Test (Shapiro-Wilk)

	W	*P*
Score	0.968	0.267

Note. A low p-value suggests a violation of the assumption of normality

Furthermore, the data is declared homogeneous with the p-value of 0.740 (> 0.05) in the analysis of the Homogeneity of Variances Test (Levene's) (Table 6).

Table 6. The Result of Homogeneity of Variances Test (Levene's)

	F	*df*	*df2*	*p*
Score	0.112	1	42	0.740

Note. A low p-value suggests a violation of the assumption of equal variances

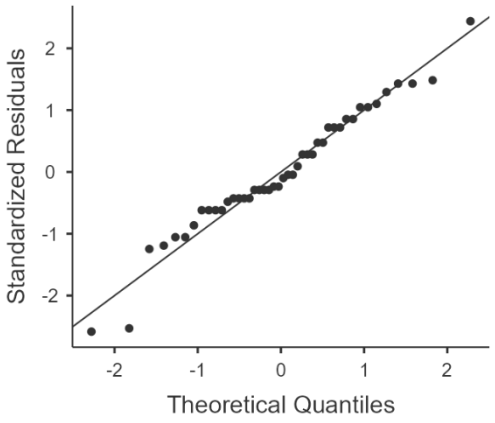

Figure 2. Q–Q plot (Quantile–Quantile plot) to Check the Assumption of Residual Normality

DISCUSSION

The effectiveness of inquisitive-based learning has been measured in various studies. For example, the application of the OE3R strategy in chemistry courses resulted in a significant improvement in students' critical thinking skills, with post-test scores significantly higher than pre-test scores (Rahmadhani et al., 2021). Similarly, the use of ICT-based guided inquiry models in junior high school settings showed high N-gain scores, suggesting a substantial improvement in critical thinking (Indana et al., 2020).

Inquiry-based learning is a pedagogical approach that emphasizes student-centered learning through exploration, questioning, and problem-solving. Inquisition-based learning typically involves five phases: Engagement, Exploration, Explaination, Elaboration, and Evaluation (Lam et al., 2024). These phases help students build knowledge on an iteration, improving their critical thinking skills. Inquisition-based learning allows students to act as scientists, using scientific methods to explore natural phenomena, which further develops their critical thinking and problem-solving skills (Shroat-Lewis & Hage, 2021).

Inquisition-based learning encourages students to actively participate in their learning process by proposing and testing hypotheses, conducting experiments, and collecting observational data. This active involvement helps students develop critical thinking and communication skills necessary for a variety of fields of study (Shroat-Lewis & Hage, 2021). The process of formulating meaningful questions and investigating them through different materials and theories is at the heart of inkuri-based learning. This approach helps students develop high-level thinking skills, including analysis, evaluation, and information synthesis (Kori, 2021). Inquisition-based learning involves solving problems and answering questions that have several possible resolutions. It stimulates critical thinking by requiring students to analyze situations, evaluate different solutions, and make informed decisions (Li & Huang, 2024).

A number of studies have shown the effectiveness of ink-based learning in improving critical thinking skills. For instance, a study on the Guided Inquiry-Blended Learning (GI-BL) strategy showed a significant improvement in students' ability to recognize assumptions, evaluate arguments, and interpret information (Suwono et al., 2019). Another study found that inkuri-based learning significantly improved students' critical thinking skills in open and distance learning environments, with more than 75% of students achieving high performance in key areas (Sapriati et al., 2024).

Inquiry-based learning often involves collaborative learning, where students work together to explore questions and solve problems. This collaboration fosters communication, teamwork, and the ability to consider multiple perspectives, all of which are critical to critical thinking (Santana-Vega et al., 2020). As a result, critical thinking skills allow individuals to analyze complex problems, investigate various techniques, and design effective solutions (Koçoğlu & Kanadlı, 2025). Further, critical thinking allows individuals to evaluate various solutions and choose the best methods, thereby improving the decision-making process (Gibson, 2016). In addition, critical thinking is related to better reading comprehension and mastery of concepts (Kuzina et al., 2022).

The use of technology in inkuri-based learning, such as mobile learning apps and online platforms, provides students with immediate feedback and access to a wealth of information. This integration enhances their ability to critically analyze and synthesize information from a variety of sources (Kousloglou et al., 2023). Thus, combining a PhD simulation with a real experiment can provide complementary advantages, improving students' conceptual understanding and critical thinking skills more effectively than using either method alone (Flegr et al., 2023). PhET simulations can be integrated into digital learning environments, such as Learning Management Systems (LMS), to support both distance and hybrid learning models. This integration has been shown to improve students' critical thinking and learning independence (Hasyim et al., 2020).

The use of PhET simulations in inquiry-based learning settings improves students' inquiry process skills, such as formulating questions, designing experiments, and interpreting data (Fan et al., 2018). PhET simulations can be used effectively in guided inquiry activities, where students are supported through structured tasks that promote independent learning and critical thinking (Gerhátová et al., 2021). PhET simulations help students develop a deeper understanding of scientific concepts by providing visual and interactive ways to explore and test hypotheses (Ramaila, 2024). Studies consistently show that students show significant improvements in critical thinking skills after using PhET simulations, as evidenced by higher scores in post-tests compared to pre-tests (Prayogi, 2023).

Despite its benefits, inquiry-based learning can be challenging to implement due to factors such as the need for proper guidance and feedback, the reluctance of some educators to adopt new methods, and difficulties in managing the diverse needs of students (Justice et al., 2009). To optimize the benefits of inquiry-based learning, it is recommended to provide continuous feedback, integrate technology effectively, and ensure that educators are well-trained in the inquiry-based learning methodology. Additionally, creating a supportive classroom culture that encourages inquiry and exploration is essential for fostering critical thinking (Mkimbili & Ødegaard, 2020).

Likewise, the use of PhET simulations, while beneficial, their open nature can sometimes be detrimental to students cognitively. Providing proper scaffolding and support is essential to help students navigate these simulations effectively (Cock et al., 2025). The effectiveness of PhET simulations in inquiry-based learning is highly dependent on the instructor's ability to integrate these tools into the curriculum. Professional development for teachers is essential to maximize the benefits of PhET simulations (Geelan & Fan, 2014). Ensuring equitable access to technology and resources is critical to the successful implementation of PhET simulations in diverse educational environments (Sayadi & Pangandaman, 2025).

CONCLUSION

Based on the results and discussion, it can be concluded that inquiry-based learning with PhET simulations can improve the critical thinking skills of high school students. Inquisition-based learning allows students to act as scientists, using scientific methods to explore natural phenomena, so as to develop students' critical thinking and problem-solving skills. Blending with PhET simulations helps students develop a deeper understanding of scientific concepts by providing visual and interactive ways to explore and test hypotheses. Nonetheless, its effectiveness depends on proper integration into the curriculum and adequate support for students and teachers.

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