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Enhancing Students' Mathematical Critical Thinking Skills through a GeoGebra Integrated Project-Based Learning Model

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Abstract

This study investigates the efficacy of the Project-Based Learning (PjBL) paradigm integrated with GeoGebra in fostering students' critical thinking skills in mathematics. Utilizing a quasi-experimental design, two groups were compared: the experimental group received instruction via the GeoGebra-integrated PjBL model, while the control group followed a traditional explanatory approach. Data were collected through pretest and posttest assessments of mathematical critical thinking skills. Statistical analyses, including an independent samples t-test, revealed a significant improvement in the experimental group compared to the control group ($p < 0.05$, significance value 0.000). The N-Gain test categorized the intervention as "quite effective." These findings demonstrate that the GeoGebra-integrated PjBL model substantially enhances students' mathematical critical thinking abilities compared to conventional teaching methods. This study highlights the pedagogical implications for mathematics education, advocating for broader implementation of innovative teaching strategies that integrate digital tools.

Keywords: *Project-Based Learning (PjBL), GeoGebra, Critical Thinking Skills (CTS), Learning Effectiveness.*

Introduction

Critical Thinking Skills (CTS), especially mathematics, have become crucial in education in the twenty-first century. In addition to teaching numerical concepts, mathematics improves students' capacity for logical and methodical thought (Basri et al., 2019; Szabo et al., 2020). CTS is essential in today's society, allowing pupils to understand mathematical ideas better, evaluate issues, and create workable solutions (Sutama et al., 2022). Gaining these abilities puts pupils in circumstances where precise solutions necessitate a deep comprehension of mathematics and logical thinking (Nikmah et al., 2021).

The specific use of CTS to solve mathematical issues is called mathematical CTS. With these abilities, students can assess mathematical arguments, spot trends, and spot presumptions or logical fallacies (Nardi et al., 2023; Minan et al., 2022). According to research, a supportive learning environment, student-centered teaching methods, and the successful integration of technology in mathematics education are all necessary for enhancing students' mathematical CTS (Liu et al., 2022; Kawuryan et al., 2022). Enhancing students' mathematical CTS at all educational levels requires incorporating cutting-edge teaching strategies and using technological resources like GeoGebra. Nevertheless, despite the importance of these abilities, teachers and students still face obstacles in their personal growth.

Improving pupils' critical mathematical CTS in conventional classroom settings might take time. According to research, traditional teaching approaches are less successful in developing these abilities because they frequently emphasize rote memorization and direct instruction more than encouraging CTS and problem-solving. Conventional teaching methods do not significantly increase CTS, according to studies comparing them to approaches like problem-based learning or mathematical problem-solving (Darhim et al., 2020; Suresman et al., 2023). Additionally, traditional instruction usually overlooks the value of developing problem-solving abilities, which can impair students' capacity to use mathematical ideas in real-world contexts (Szabo et al., 2020).

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One successful strategy for improving students' CTS is PjBL. Using real-world projects, PjBL fosters student discovery, teamwork, problem-solving, and reflective thinking (Wei et al., 2023; Cortázar et al., 2021). Under this strategy, students take on difficult yet pertinent assignments that promote a deeper comprehension and the growth of abilities necessary for success outside the classroom. This method encourages research, goal-setting, and introspection based on practical applications (Kokotsaki et al., 2016).

Regarding improving CTS, the PjBL approach offers clear benefits over more conventional teaching strategies like expository instruction. According to research, PjBL actively involves students in the learning process by assigning them projects that require investigation, analysis, and problem-solving, which greatly improve their CTS (Sasson et al., 2018). When PjBL is paired with digital tools like GeoGebra software, which has been shown to improve math instruction, its efficacy is further increased. With the help of GeoGebra, students may more accurately represent geometric and analytical concepts, which helps them comprehend the connections between ideas. Teachers can greatly enhance students' CTS by combining PjBL with digital technologies to create a more dynamic and interactive learning environment (Kholid et al., 2022; Ahmad et al., 2023; Al_Zainab., 2024).

In various subjects, including mathematics, prior research has consistently demonstrated that PjBL improves students' CTS (Jatmiko et al., 2018; Saputra et al., 2019; Evendi et al., 2022). Additional research shows substantial advantages to combining technology with PjBL, such as using GeoGebra. The GeoGebra-enhanced PjBL model (Geo-PjBL) is especially useful for teaching analytical geometry, which necessitates accurate and understandable representations, according to recent studies by Kholid et al. (2022). Because GeoGebra uses dynamic and interactive images to help students grasp difficult mathematical topics, the model is equally helpful for algebraic operations (Mansoor et al., 2024).

Even though the PjBL model has been shown in multiple studies to enhance CTS effectively, more study is necessary to fill in the gaps. Notably, more studies need to be done on combining PjBL with digital tools like GeoGebra to improve classroom math instruction. This study aims to determine the difficulties and barriers associated with applying the GeoGebra-integrated PjBL model and to investigate potential ways to improve its efficacy.

Based on the description, this study aims to address the following research questions:

1. Is there a significant difference in students' mathematical CTS between the PjBL and expository teaching models?
2. How effectively is the PjBL model enhancing students' mathematical CTS?

Methods

This study examines the GeoGebra integrated PjBL model compared to the traditional expository teaching method in improving students' mathematical CTS, through a quasi-experimental approach. The research took place at SMAS Hang Tuah Makassar during the 2024–2025 academic year, concentrating on the topic of transformation geometry. The participants included two classes: XI Martadinata which had 30 students (experiment), and XI Malahayati which had 29 students (control). Both groups underwent a pretest to assess their initial CTS level, followed by a posttest to evaluate their progress after the instructional intervention.

A pretest was conducted during the first session of the study's five-session intervention. Three instructional sessions were then held to present the learning materials, and the fifth session ended with a posttest. While the posttest examined the students' learning results following the intervention, the pretest evaluated the students' starting ability. One of the research tools was a mathematical CTS essay test with five validated questions that assessed abilities like evaluation, analysis, and problem-solving. An observation sheet was also used to track student participation during the classes.

An N-Gain test was used to evaluate how well the PjBL model improved students' CTS, and an independent t-test was used to find differences between the two groups.

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Results

A variety of features offered by GeoGebra, a technology-driven mathematics learning tool, can be easily incorporated into the PjBL paradigm. Through direct and interactive investigation, this integration helps students to comprehend mathematical ideas more deeply. Integrating GeoGebra into the PjBL framework makes the learning process more dynamic, and it actively engages students in tasks including project presentation, modeling, and research. The syntax or procedural steps of the PjBL paradigm combined with GeoGebra, intended to encourage active and collaborative learning, are described in the following table.

Table 1. GeoGebra integrated PjBL model syntax

Step 1: Determining the Fundamental Question	
Teacher Activity	**Students Activity**
The teacher compiles and delivers a theme or topic of questions about a problem and invites participants to discuss and find a solution.	Students ask basic questions about what to do to solve existing problems.
Step 2: Designing the Project Plan	
The teacher ensures that each participant is divided into groups and knows the project creation procedure.	Students discuss and start to plan the project. Divide roles/tasks into groups and note things that must be prepared for the project.
Step 3: Create a Build Schedule	
The teacher prepares a project schedule and divides it into stages to facilitate implementation.	Students agree on a schedule and begin to pay attention to project deadlines.
Step 4: Monitor Project Activity and Progress	
The teacher monitors the participation and involvement of participants; the teacher also observes the development of the designed project.	Students create projects using GeoGebra and ensure that their implementation is in accordance with the schedule. Students write down the stages and record the progress that will be included in the report later.
Step 5: Testing the Results	
The teacher discusses the projects the students are working on and then assesses them. The assessment is made measurably based on predetermined standards.	Students discuss the results of the projects they have carried out and submit a final report to the teacher.
Step 6: Evaluate the Learning Experience	
The teacher conducts evaluations and provides input or follow-up directions regarding the projects carried out by the participants.	Students present the results of the project and receive feedback and direction from the teacher. Students also note things that should be done to improve the project results.

A statistical evaluation was carried out to compare the learning outcomes of students taught through the PjBL model with conventional expositories, which aimed to determine the effectiveness of the teaching method for grade XI students at SMA Hang Tuah Makassar. This analysis uses SPSS 25 to calculate a variety of statistical metrics, including variance, mean, and median, to evaluate the significance of the observed differences:

Table 2. Descriptive Statistics of Critical Thinking Ability in Mathematics for Students in the Experimental Group

	N	**R**	**Min**	**Max**	**Mean**	**Std. Deviation**	**Variance**
Pre-Test	30	56	20	76	47.00	16.572	274.621
Post Test	30	22	68	90	78.70	6.655	44.286

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Table 3. Descriptive Statistics of Critical Thinking Ability in Mathematics for Students in the Control Group

	N	R	Min	Max	Mean	Std. Deviation	Variance
Pre-Test	29	57	17	74	43.72	15.252	232.635
Post Test	29	46	41	87	67.21	11.941	142.599

Students' mathematical CTS significantly improved in the experimental class, which used the PjBL approach, according to the descriptive analysis in Tables 2 and 3. The average score significantly increased from 47.00 on the pretest (classified as deficient) to 78.70 on the posttest (classified as moderate). The average scores of the control group, which followed the expository learning paradigm, increased less, from 43.72 (poor category) to 67.21 (low category). While there were advances in both groups, the experimental class's progress was noticeably greater.

Table 4. Frequency Distribution and Percentage of Critical Thinking Ability in Mathematics for Students in Experimental and Control Groups

Intervals in the score	Category	Percentage (%) (Control)		Percentage (%) (Experiment)	
		Pretest	*Posttest*	*Pretest*	*Posttest*
0-54	Very Low	83	17	63	0
55-69	Low	7	28	30	7
70-79	Medium	10	41	7	46
80-89	High	0	14	0	40
90-100	Very High	0	0	0	7
Total		100	100	100	100

The gains seen in both classes are further supported by Table 4's frequency distribution and percentage of students' scores on mathematical CTS. From 63% on the pretest to 0% on the posttest, the proportion of pupils in the experimental class who fell into the "very low" group dropped significantly. At the same time, the proportion of pupils in the "medium" group rose sharply from 7% to 46%. Conversely, the control group had a less noticeable improvement, with the proportion of pupils falling into the "very low" category from 83% to 17% and the "medium" category rising slightly from 10% to 41%.

Several statistical tests were carried out to understand better how the expository model and the PjBL model compare in terms of improving students' mathematical CTS. Among these were tests of homogeneity and normality to ensure the data satisfied the presumptions required for additional analysis. The normality test using the Shapiro-Wilk and Kolmogorov-Smirnov methods showed that the data were distributed normally (sig> 0.05). However, the homogeneity test revealed that the variances between the groups were not equal (significance value < 0.05).

The impact of the two learning methods on students' critical mathematical CTS in the transformation geometry course at SMAS Hang Tuah during the 2024–2025 academic year was then assessed using hypothesis testing. The following were the requirements for hypothesis testing:

1. The average critical mathematical thinking abilities of the PjBL and expository models differ significantly if sig < 0.05, which rejects H0 and accepts Ha.

2. There is no discernible difference between the two models' average critical mathematical thinking abilities if sig > 0.05, which means that Ha is rejected and H0 is approved.

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Table 5. Independent Samples Test Results

		Levene's Test for Equality of Variances		t-test for Equality of Means						
		F	Sig.	T	df	Sig. (2-tailed)	Mean	Std. Error	95% Confidence Interval	
									Lower	Upper
Kemampuan Berpikir Kritis	Equal variances assumed	11.360	.001	4.587	57	.000	11.493	2.506	6.476	16.511
	Equal variances are not assumed.			4.545	43.546	.000	11.493	2.529	6.396	16.590

The results of the t-test showed a significant difference in the students' mathematical CTS in the experimental and control groups during the learning of transformational geometry because the significance value was below 0.05. This conclusion is further supported by additional inferential analyses, which consistently demonstrate significant differences in student learning outcomes between the two groups. The rejection of H0 and acceptance of Ha at a significance value below 0.05 provide robust evidence that the PjBL model positively impacts students' mathematical CTS. Notably, this impact is considerably greater compared to the expository teaching approach. In addition, the results of the N-gain test highlighted the effectiveness of the PjBL model. The experimental group obtained an average of 59.8%, categorized as "moderately effective", while the control group obtained an average of 42.37%, belonging to the category of "less effective". These findings underscore the advantages of the PjBL model compared to conventional expository methods in improving students' mathematical CTS.

Discussion

The GeoGebra-integrated PjBL model is noticeably more successful at improving students' mathematical CTS. The findings of the hypothesis test obtained showed significant differences between the control group and the experiment. Research by Kholid et al. (2022) confirms these results, demonstrating that incorporating Geo-PjBL is especially successful for teaching mathematics. By offering exact and accurate visual representations, GeoGebra improves learning outcomes. This is particularly useful for subjects like transformation geometry, which require unambiguous visualizations. Furthermore, Drovosekov et al. (2019) showed that PjBL greatly enhances students' critical and analytical CTS in secondary schools by empowering them to organize and complete assignments independently, increasing their desire for mathematics.

PjBL encourages student engagement through collaborative and real-world learning settings, according to additional research from Almulla (2020). This is consistent with research demonstrating how PjBL increases student involvement and fosters deeper comprehension (e.g., Setemen et al., 2023; Juuti et al., 2021). Students develop CTS and analytics while tackling real-world challenges through PjBL (Sasson et al., 2018; Chaipichit et al., 2015; Awi et al., 2024).

The outcomes of the N-gain test provide additional evidence of the GeoGebra-integrated PjBL model's efficacy. With an average N-gain of 59.8%, the experimental class was classified as "quite effective," whereas the control class only managed 42.37%, classified as "less effective." This striking disparity highlights how much more effective the PjBL model and GeoGebra are than conventional techniques in fostering mathematical CTS.

Further research supports the advantages of GeoGebra, emphasizing its capacity to convert abstract ideas like geometry and mathematical functions into engaging and concrete learning experiences (Alabdulaziz et al., 2020; Mykoliuk et al., 2024). Other studies have also shown that GeoGebra improves overall results, speeds up

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learning, and strengthens mathematical skills, especially in structured learning situations (Juandi et al., 2021; Dahal et al., 2022; Yohannes & Chen, 2021; Zetriuslita et al., 2021).

The results of this study support the claim that the GeoGebra-integrated PjBL model not only enhances CTS but also offers a more dynamic and engaging teaching approach catered to students' learning needs. This is especially true given the experimental class's "quite effective" classification of N-gain results. However, carefully considering teacher preparedness and the availability of sufficient infrastructure, including required tools and resources, are essential for successfully implementing this paradigm.

As demonstrated by the notable improvements in the experimental group, this study concludes that the PjBL paradigm is effective in greatly enhancing students' mathematical CTS. These findings imply that PjBL, as opposed to conventional expository instruction, can more effectively foster the growth of analytical abilities. As a result, PjBL should be used more frequently in math classes, particularly for subjects like transformation geometry that call for deeper comprehension.

PjBL's interactive and participatory elements, which actively involve students in relevant, real-life situations, are the key to its success. On the other hand, the teacher-centered expository paradigm frequently leaves students passive in the learning process, which hinders its ability to foster CTS.

This study significantly advances mathematics education by offering a novel strategy that combines GeoGebra with PjBL to promote CTS. The interactive elements of GeoGebra combined with the inquiry-based, student-centered tenets of PjBL provide a strong teaching approach that improves conceptual knowledge and CTS. These results open the door for more creative teaching strategies in math classes by giving educators practical advice on implementing this approach in various educational environments.stic.

Conclusion

Teaching students utilizing the GeoGebra-integrated PjBL model significantly improves their mathematical CTS. Those taught utilizing the PjBL technique, students' CTS in mathematics improved more than those taught using the conventional expository model. The PjBL paradigm is exceptionally effective at improving CTS. The data shows that the PjBL model greatly outperforms the expository technique regarding the average gain in students' mathematical CTS. The model's capacity to actively involve students in developing analytical, evaluative, and problem-solving abilities within a significant mathematical context accounts for its efficacy. Given its advantages, the PjBL model is strongly advised for use in mathematics education as a successful tactic to encourage students' improved CTS.

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