Enhancing Critical Thinking in Optics through Project-Based STEAM Learning with Visual Simulations

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Abstract - *Optical material is widely applied in everyday technology but remains difficult for students to grasp due to its abstract nature. This challenge is linked to students' low critical thinking skills—an essential 21st-century competence. This study aims to enhance students' critical thinking on optical topics through the integration of project-based learning with a STEAM approach and visual simulation media (PjBL-STEAM-MSV). A mixed-method design with an untreated control group and pretest-posttest was employed. The participants were 54 students from SMAN 1 Woha, NTB, Indonesia, divided into an experimental group (PjBL-STEAM-MSV) and a control group (conventional instruction). Data collection used a critical thinking essay test (5 items, reliability = 0.636) and interview guidelines. Quantitative data were analyzed using t-tests, N-gain, and effect size; qualitative data through reduction, coding, and interpretation. Results indicated that PjBL-STEAM-MSV significantly improved students' critical thinking in optics (α = 0.01). The experimental group's N-gain score was 0.48 (moderate), higher than the control group's 0.20 (low). The most notable improvements in the experimental group were in evaluation and explanation, while in the control group, gains were limited to analysis and explanation. Experimental group students struggled with explanation during presentations due to time constraints, whereas the control group showed difficulty across most indicators due to a focus on rote learning. Interviews revealed that experimental group students experienced more active, interactive, and structured learning. This aligns with the high effect size of 1.7. Further research should explore media development and sustained student mentoring to maximize outcomes.*

Keywords: *PjBL, STEAM, Visual Simulation Media, critical thinking skills, optics*

INTRODUCTION

In the era of rapid technological advancement, understanding optics is essential as it underlies innovations like cameras, sensors, and imaging tools (Zhu et al., 2022). At the high school level, optics not only deepens scientific knowledge but also builds relevant skills to face future challenges. However, many students struggle with this material due to its abstract nature and their limited critical thinking abilities (Sebald et al., 2022; Wahyudi et al., 2022; Uwamahoro et al., 2021; Mešić et al., 2019).

Critical thinking, comprising interpretation, analysis, inference, evaluation, and explanation, is a core 21st-century skill (Facione, 2000; Rahmawati et al., 2021). Although vital for mastering complex concepts like optics, students often lack these skills in practice (Fauziyah et al., 2021; Rapi et al., 2022). Field observations show students struggle to interpret problems, analyze causes, draw logical conclusions, and evaluate results.

Initial assessments confirm this issue, with average critical thinking scores on optics material still moderate (55.28) and low-skilled students dominating each subtopic (Anshori et al., 2024). These outcomes stem from teacher-centered, memorization-based instruction, minimal student engagement, and lack of practical experience (Rosdiana & Parno, 2023; Betari et al., 2021). Hence, an innovative learning model that encourages active participation and higher-order thinking is needed.

Several models have been applied to improve critical thinking in optics, including augmented reality, STEAM-based PjBL, and digital PBL resources (Faridi et al., 2021; Zayyinah et al., 2022; Paramitha et al., 2023; Mabrurah et al., 2023). While beneficial, these approaches often lack integration between hands-on experience and tools to visualize abstract concepts. A gap remains in approaches that fully support both engagement and conceptual clarity.

The PjBL-STEAM model addresses this gap by combining interdisciplinary problem-solving with active, project-based learning (Sinta et al., 2022; Prahani et al., 2023). It promotes creativity, collaboration, and practical application, key to improving critical thinking (Indahwati et al., 2023; Sari et al., 2024). Meanwhile, visual simulation media supports conceptual understanding by making abstract optics content more tangible (Anggraini et al., 2021; Sarwinda et al., 2020). Despite the potential, the combined use of PjBL-STEAM and visual simulations in optics learning remains underexplored.

This study aims to implement the PjBL-STEAM model integrated with visual simulation media to enhance students' critical thinking in optics. This combination is expected to foster meaningful, conceptually rich learning and improve performance across all critical thinking indicators. The results will offer insights into more effective physics instruction strategies, particularly in addressing the challenges of abstract material.

RESEARCH METHODS

This study was conducted on Grade XI students at a senior high school in Bima Regency. The participants were selected using purposive sampling (Campbell et al., 2020), with XI IPA 6 (27 students) as the control class and XI IPA 2 (27 students) as the experimental class. The control class received conventional instruction, while the experimental class was taught using the PjBL-STEAM model supported by visual simulation media. The learning process in the experimental group was implemented over two meetings. In the first meeting, students worked on a pinhole camera project, and in the second, they constructed a simple telescope. Each activity followed the PjBL-STEAM stages: posing essential questions, designing and scheduling the project, monitoring progress, assessing outcomes, and evaluating the learning experience (Permana et al., 2023; Rohman et al., 2023).

This research used a mixed-methods approach with an embedded experimental design (Creswell, 2021). The quantitative phase followed a pre-test–post-test control group design to measure the improvement in students' critical thinking skills. The test instrument consisted of five essay questions, each targeting one of the five critical thinking indicators: interpretation, analysis, inference, evaluation, and explanation (Facione, 2000; Rahmawati et al., 2021). The instrument was validated by two subject matter experts for content and construct validity and was revised accordingly. A small-scale field trial was also conducted to ensure clarity and functionality before use.

Quantitative data were analyzed using an independent samples t-test to determine differences between the two groups (Fiandini et al., 2024), supported by N-gain analysis to assess improvement levels (Triyono et al., 2024), and effect size calculation to evaluate the strength of the intervention (Thompson et al., 2022). Students' critical thinking scores are categorized based on the criteria in Table 1.

Table 1. Critical Thinking Skills Category (Arikunto, 2013)

Score	Category
81-100	Very High
61-80	High
41-60	Medium
21-40	Low
0-20	Very Low

Meanwhile, qualitative data were collected through interviews conducted before, during, and after the intervention. The qualitative analysis included data description, reduction, and conclusion drawing (Khoa et al., 2023), aiming to explore students' responses, engagement, and learning experiences during the implementation of the PjBL-STEAM model. The integration of both quantitative and qualitative data provided a more comprehensive understanding of the model's impact on students' critical thinking development.

RESULTS AND DISCUSSION

Pre- and post-test data on critical thinking skills were obtained from assessments conducted before and after the intervention, as summarized in Table 2

Table 2. Results of Pre- and Post-test of Critical Thinking Skills

Test	Class	N	Max	Min	SD	Average	Description
Pre	Experiment	27	60	15	10,5	37,0	Low
	Control	27	55	10	10,3	33,1	Low
Post	Experiment	27	90	45	12,4	68,0	High
	Control	27	65	15	12,6	46,3	Medium

The average pre-test results in both classes indicated that students' critical thinking skills were relatively low and comparable. However, a substantial difference appeared in the post-test scores, with the experimental class showing a significantly greater improvement. This suggests that the implementation of the PjBL-STEAM model with visual simulation media (MSV) contributed to the enhancement of students' critical thinking skills. The statistical effect of PjBL-STEAM and MSV was further examined using an independent t-test in SPSS. A prerequisite test confirmed that the data were homogeneous, normally distributed, and showed no significant difference in students' initial critical thinking skills, as presented in Table 3.

Table 3. Results of Independent t-Test of Initial Critical Thinking Skills

t-test for Equality of Mean		t	df	Significance	
				One-Sided	Two-Sided
Critical Thinking	Equal variances assumed	-1.374	52	0.088	0.175
	Equal variances not assumed	-1.374	51.982	0.088	0.175

As shown in Table 3, the sig values for the t-test results of both critical and creative thinking skills exceeded 0.05, confirming no significant differences in the baseline skills of students in both classes. The low initial scores can be attributed to a lack of engagement and limited conceptual understanding of optics—issues noted in prior research (Agustini et al., 2022; Yusuf & Asrifan, 2020). Interviews revealed that before treatment, students associated optics only with familiar objects such as mirrors and glasses, without comprehending underlying scientific principles.

Post-intervention analysis revealed that students in the experimental group demonstrated significantly improved critical thinking skills compared to those in the control group, as evidenced by the independent t-test results on post-test data (Table 4).

Table 4. Results of Independent t-Test of Final Critical Thinking Skills

t-test for Equality of Mean		T	df	Significance One-Sided	Significance Two-Sided
Critical Thinking	Equal variances assumed	-6.362	52	<.001	<.001
	Equal variances not assumed	-6.362	51.989	<.001	<.001

Table 4 shows a sig value of less than 0.05, indicating that the PjBL-STEAM model supported by MSV was more effective than conventional teaching approaches. The effectiveness of PjBL-STEAM stems from its interdisciplinary nature, which encourages students to apply scientific concepts through real-world projects, thus promoting deep and meaningful learning (Rizki et al., 2022). The integration of STEAM elements fosters systematic inquiry and problem-solving, which are core components of critical thinking. MSV further enhances this process by allowing abstract and complex optical phenomena to be visualized and explored interactively, leading to deeper understanding (Parno et al., 2021b).

These findings are in line with previous studies. For instance, Anggraini et al. (2021) found that the application of PjBL-STEAM in physics significantly improved students' higher-order thinking skills. Similarly, Supriyatno et al. (2020) reported that the use of interactive simulation media contributed positively to students' conceptual understanding and analytical thinking. In contrast, conventional methods that rely on passive learning and repetitive exercises, such as those used in the control group, have been shown to have limited impact on developing critical thinking (Alsaleh, 2020).

Through PjBL-STEAM, students actively engaged in problem-solving and project completion, with the teacher acting as a facilitator (Mariani et al., 2024; Syamsuriwal et al., 2024). This approach contrasts with traditional methods where students typically absorb information passively. MSV played a critical role by enabling students to simulate and manipulate optical phenomena, which helped them develop reasoning and hypothesis-testing skills (Ndihokubwayo et al., 2020).

Table 5. Results of N-gain Analysis of the Average Critical Thinking Skills.

Class	N-Gain	Category
Experiment	0.48	Medium
Control	0.20	Low

The effectiveness of the experimental approach was further confirmed by the N-gain analysis shown in Table 5. Students in the experimental class achieved moderate improvement, while those in the control class exhibited only a low level of gain. This suggests that hands-on, contextualized learning—core to the PjBL-STEAM model—significantly enhanced students' understanding (Wahyudi et al., 2022), whereas the control group, which focused on rote learning and solving textbook problems, struggled to build transferable thinking skills (Parno et al., 2019). These findings are consistent with Mabrurah et al. (2023), who emphasized the importance of observation and application in strengthening critical thinking.

Table 6. Results of N-gain Analysis of Critical Thinking Skills Per-Indicator

Class	Critical Thinking Skills Indicators (BK)				
	CT-1	CT-2	CT-3	CT-4	CT-5
Experiment	0.57 (M)	0.49 (M)	0.43 (M)	0.59 (M)	0.39 (M)
Control	0.28 (L)	0.29 (L)	0.19 (L)	0.16 (L)	0.12 (L)

Ket: L: low, M: medium, and H: high.

Table 6 further details the N-gain scores per critical thinking indicator, with the experimental class outperforming the control class across all categories. Student interviews also highlighted that PjBL-STEAM activities facilitated critical thinking practice in real-life contexts, consistent with the findings of Zayyinah et al. (2022), Permana et al. (2023), and Hasani et al. (2024).

Indicator-wise analysis reveals that students in the experimental class showed notable improvements across all critical thinking aspects. In interpretation, they could relate shadow formation to reflective surfaces, aided by guiding questions and problem identification, consistent with Sutiani et al. (2021), who highlight the role of active processing. The analysis phase benefited from the project design stage, where students applied reflection principles in constructing pinhole cameras, aligning with Ndihokubwayo et al. (2020) on the value of project-based inquiry. For inference, students drew conclusions based on data from simulations, supporting Shaw et al. (2020)'s findings on the role of simulations in inference development. In terms of evaluation, students more effectively assessed data from telescope construction due to continuous monitoring and reflection, as emphasized by Sarwanto et al. (2021). Lastly, explanation improved through structured presentations and peer feedback, though it had the lowest N-gain (0.39), likely due to time limitations and suboptimal MSV use during final presentations, echoing insights from Mulders et al. (2020).

The Cohen's d value of 1.70 suggests a very large effect size, showing that the intervention had a strong impact on students' critical thinking development. Further analysis revealed that 95.5% of students in the experimental class scored above the control class average, reaffirming the robustness of the learning model. This aligns with Zayyinah et al. (2022) and Sarwanto et al. (2021), who also reported high impact from PjBL-STEAM and MSV, respectively.

The PjBL-STEAM model and MSV media provided a cohesive learning environment where students explored content deeply and applied it contextually. MSV served as both a visualization and independent learning tool (Parno et al., 2021a), fostering self-paced exploration and concept mastery. Student feedback indicated that these experiences were not only educational but also meaningful and applicable to everyday life.

Despite the overall success, challenges remain—particularly regarding explanation skills, which showed the lowest gain. This may be improved in future research by allocating more time for group presentations and enhancing MSV integration in the final stages of project reporting.

In conclusion, the combination of PjBL-STEAM and MSV proved to be significantly more effective in enhancing critical thinking skills in optics compared to conventional methods, as supported by statistical evidence, comparative findings, and alignment with prior research.

CONCLUSION

This study shows that the implementation of the Project-Based Learning Model (PjBL) with the STEAM approach and Visual Simulation Media (MSV) significantly improves students' critical thinking skills in optics material compared to the conventional model, with a significance value of 0.001. The N-gain results in the experimental class reached 0.48 (medium category), better than the control class, which was only 0.20 (low category). All indicators of critical thinking—interpretation, analysis, inference, evaluation, and explanation—showed an increase in the experimental class higher than in the control class. The effect of implementing PjBL-STEAM and MSV on improving critical thinking was high (1.7) based on Cohen's d-effect size analysis. Interviews with students in the experimental class indicated that they had a more active and structured learning experience in understanding optics concepts. The practical implications of this study indicate that PjBL-STEAM and MSV can be used as effective methods to improve students' critical thinking skills. Therefore, for further research, it is recommended that existing projects be maximized by paying attention to the availability of tools and materials and better media access.

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