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Validation of PBL-based Physics Virtual Laboratory on Heat and Temperature to Improve Critical Thinking and Mathematical Representation Skills of High School Students

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Abstract

This study aims to analyze the feasibility of PBL-based virtual laboratory for use in learning physics on heat and temperature to improve students' critical thinking and mathematical representation. This research is a R&D study using the ADDIE (Analysis, Design, Developed, Implementation and Evaluation) development research, which consists of five stages: (1) Analysis stage consists of needs analysis, students analysis, curriculum analysis, concept analysis, and analysis of learning objectives; (2) Design, related to designing initial products of PBL-based virtual laboratory learning media and critical thinking and mathematical representation test instruments; (3) Developed stage related to the stage of product preparation, editing, validation, revision, and fields trial; (4) Implement is the stage of implementing products with pretest-posttest control group design and using the quasi experiment method (5) Evaluate is the evaluation process starts from the analysis stage to the implementation stage. The subjects in this study were 108 students of SMA N 1 Kalasan as a field trial. The products developed include PBL-based virtual laboratory learning media, validation assessment sheets, student response questionnaires and test instruments. These products are reviewed by expert validators and practitioners using a 4-point rating scale before being used in trials. The data analysis techniques carried out are descriptive and inferential analysis. The analysis also uses the ideal standard deviation (SBi) to assess the feasibility of learning media and a questionnaire on the practicality of students. While the analysis using V Aiken is to assess the results of the analysis of critical thinking test instruments and mathematical representation. The result of this study showed that the PBL-based virtual laboratory is highly suitable for use in physics learning on heat and temperature to improve critical thinking and mathematical representation, as indicate by evaluations from expert validators, practitioners, and students’ response.

Keywords: *Learning Media; Problem based Learning (PBL); Virtual Laboratory; Critical Thinking; Mathematical Representation; Heat and Temperature*

Introduction

Critical thinking skills often present their own challenges, especially in the digital era that is flooded with diverse information (Gonzalez-Cacho & Abbas, 2022; Miranda et al., 2021). Critical thinking is a vital competency that students must possess in order to adapt and succeed when facing challenges, problems, life demands, and career requirements in the 21st century (Din, 2020; Tang et al., 2024). Din (2020) emphasizes that critical thinking refers to an individual's ability to gather, evaluate, and use information effectively. This process requires individuals to assess the validity, relevance, and implications of information so that decisions are made based on sound reasoning (Butler et al., 2017). This view is strengthened by Kleemola et al. (2022), who state that critical thinking not only helps solve complex problems but also supports students in making decisions based on logical analysis and in-depth evaluation. Similar opinions were expressed by Dinni (2018), stating that critical thinking is necessary for students to analyze and solve problems effectively. In the context of learning physics, this skill becomes crucial to develop because physics not only requires understanding concepts but also applying them in real life, which involves critical analysis, evaluation, and deep thinking (Holmes et al., 2019; Papadakis et al., 2020). By mastering these aspects, students not only gain a deep understanding of physics concepts but also develop the ability to solve complex problems and make rational decisions (Rosyida & Prahani, 2025).

Previous research conducted by Neswary et al. (2023) revealed a significant gap in critical thinking skills among high school students in the context of physics learning. This finding is supported by Yuanata et al. (2023), who reported that 62% of students fall into the low critical thinking ability category. Similar results were found by Marisda et al. (2024) in their descriptive study, showing that the average critical thinking score among high school students reached only 73.09 (medium category), with the achievement of inference, analysis, and interpretation indicators being 34.58%, 33.70%, and 31.71%, respectively. Furthermore, studies indicate that students' average critical thinking skills in the topic of temperature and heat are still low, as shown in the aspects of drawing conclusions and providing further explanations. Meanwhile, critical thinking in the aspects of providing simple explanations, building basic skills, and planning strategies in the topic of temperature and heat falls within the medium category (Sundari & Sarkity, 2021).

The topic of temperature and heat is one of the important subjects in high school physics because it is closely related to everyday phenomena. However, in reality, many students still face difficulties because it involves both microscopic and macroscopic phenomena that are not easily observed directly (Anisa et al., 2020). Various studies show that students struggle to explain these phenomena scientifically, which leads to overlapping conceptual understanding (Hung & Young, 2021). For example, when students are asked to explain that heat is a form of energy that transfers from one object to another due to temperature differences, they often become confused about connecting the concepts of energy and temperature correctly (Fernandez, 2017). Students also struggle to distinguish between temperature and heat, and some believe that there is "cold heat" and "hot heat" (Sundari & Sarkity, 2021). Additionally, students tend to think that an object's temperature is proportional to its size and that temperature can be transferred (Alwan, 2011; Chu et al., 2012).

The concepts of temperature and heat in physics have characteristics that support the enhancement of conceptual understanding and the development of critical thinking skills (Sundari & Sarkity, 2021). Fitriyani et al. (2022) found that students' critical thinking ability in the topic of temperature and heat generally falls into the low category, and the ongoing learning process has not been able to encourage students to think critically and solve problems independently. Similar findings were presented by Kamalia & Wasis (2021), who noted that students' critical thinking skills in learning temperature and heat vary across indicators. The analysis indicator is in the adequate category, while interpretation, evaluation, and conclusion indicators are still relatively low. In fact, the concepts of temperature and heat are highly relevant to students' everyday lives and form an essential foundation for mastery of scientific knowledge in general (Inaltekin & Akcay, 2021; Chen & Wu, 2018). Based on these conditions, a learning strategy is needed that can improve students' critical thinking skills, particularly in understanding and applying temperature and heat concepts within the physics learning context.

Physics learning is also inseparable from the need for representational ability, which plays an important role in supporting students' cognitive development. This ability enables students to build deeper conceptual understanding through presenting information in various forms (Widianingtiyas, Siswoyo, & Bakri, 2017). McPadden & Brewe (2017) emphasize that representation in learning functions as a means of practicing problem-solving and scientific communication skills, including in physics. Representation in physics acts as a cognitive bridge that helps students understand and solve problems through various forms (Alvarez et al., 2020).

In the context of physics learning, mathematical representation becomes a crucial aspect in solving physics problems. Mathematical representation in physics serves as a bridge linking abstract concepts to real-life situations (Samsudin & Retnawati, 2018). Students tend to perceive physics and mathematics as two separate ways of thinking, making it difficult for them to understand the physical meaning behind mathematical equations (Zulaikha et al., 2024) or to construct mathematical models of physical phenomena (Kind et al., 2017).

Students' mathematical representation abilities, as seen from various previous studies, are still relatively low (Selamet et al., 2018; Prahani et al., 2021). A study by Rahayu & Hakim (2021) found that students' average mathematical representation ability reached only a score of 55.1, with 27% in the low category, 60% in the medium category, and only 13% in the high category. Zulaikha et al. (2024) reported student scores on the subtopics of temperature, expansion, heat, and heat transfer as 67.66, 63.67, 58.86, and 60.43, respectively. These low achievements are largely due to students' tendency to rely on memorizing formulas without understanding the conceptual meaning behind them (Fatmawati, 2015; Theasy, 2018).

To address these challenges, an innovative and student-centered learning model is needed. The appropriate learning model is not only focused on delivering content but also on building students' thinking skills and conceptual understanding. The Problem-Based Learning (PBL) model aligns with these characteristics, as it focuses on using real-world problems as the starting point for learning (Astra et al., 2021). Problem-based learning uses authentic problems as learning stimuli that encourage students to develop problem-solving skills (Arends, 2007; Jacobsen et al., 2009), construct new knowledge before understanding formal concepts and engage in collaboration between students and teachers as well as among students themselves (Samadun & Dwikoranto, 2022). This approach can enhance students' problem-solving abilities as well as their capacity for critical and analytical thinking skills that are essential in the information-rich digital era (Ellianawati et al., 2025).

One learning strategy within the problem-based learning (PBL) model that effectively encourages active student engagement is experimental activities. In this context, experiments serve as authentic investigative tools that allow students to discover concrete solutions to the problems being studied (Yahya et al., 2023). Experimental activities can be optimized through the use of computer technology, enabling students not only to explore but also to explain and present their learning outcomes more interactively (Arends, 2012). Integrating technology into PBL is considered effective in improving learning outcomes, especially in helping students understand abstract physics concepts through digital visualization and manipulation of phenomena (Xudayberdiyevna, 2024). One prominent form of technological integration in problem-based physics learning is the use of virtual laboratories.

The use of virtual laboratories in learning has been proven to significantly contribute to improved conceptual understanding across various scientific topics (Sari & Hakim, 2021; Halkia et al., 2018; Keengwe et al., 2014). Research by Wijaya et al. (2020) shows that virtual laboratories can substantially enhance students' conceptual understanding. Other studies also report that virtual practicums based on multiple representations are effective in increasing students' interest in learning (Hasanudin et al., 2023). An experimental study by Maulani et al. (2020) demonstrated that implementing a problem-based learning model equipped with virtual PhET simulations can significantly improve students' learning outcomes, particularly in the concepts of temperature and heat.

In line with these findings, several other studies report that implementing virtual laboratories based on problem-based learning offers various benefits, such as encouraging conceptual understanding through practical experiences (Jiniarti et al., 2019; Yahya, 2019; Hermansyah, 2017), developing critical thinking and problem-solving skills (Herayanti & Habibi, 2015; Yulianti & Gunawan, 2019; Hastuti, 2016), and increasing interest in physics through engaging problem-solving activities (Gunawan, 2017). Additionally, this approach is considered effective in fostering collaborative and communication skills (Ramadani, 2020), preparing students for real-world problems involving physics concepts (Yahya & Fitriyanto, 2016), and supporting the development of 21st-century skills (Mayasari et al., 2016).

Based on the previous discussion, it is necessary to develop a physics learning medium that can enhance students' critical thinking and mathematical representation skills, particularly in the topic of temperature and heat. Therefore, the researcher considers it important to design and develop a learning medium that integrates virtual laboratories with the problem-based learning (PBL) model.

Method

This study uses the research and development (R&D) method developed by Borg and Gall (1983) and ADDIE learning design model (Branch, 2009). The ADDIE consist of several stages, namely the analysis stage (analyze), the design stage (design), the development stage (develop), the implementation stage (implementation), and the evaluation (Branch, 2009).

The content validity value of the instrument items according to Aiken (1985) in Azwar (2015: 112-113) is formulated in Aiken's V formula to calculate the content validity coefficient value based on the assessment results of expert validators or experts numbering n people. The scoring analysis is obtained by the following process:

a. Compiling a table containing data from the results of instrument assessments by expert validators.

b. Measuring the validity coefficient of the content using Aiken's V

$$V = \frac{\Sigma s}{n(c-1)}$$

V : Content validity coefficient
Σs : The sum of s of n rater, where $s = r - l_0$
r : Score given by validators
l_0 : The lowest validity assessment score (in this case =1)
c : The highest validity assessment score (in this case =4)
n : Number of validators

c. Comparing the scores obtained with the Aiken's V index range in the following table.

Table 1. Eligibility Assessment Category Criteria

Score Range	Category
$V \leq 0,4$	Low
$0,4 < V \leq 0.8$	Moderate
$0,8 < V$	High

(Arikunto, 2006)

The results of the validation analysis are also compared with the *right-Tail Probabilities* (P) *for selected Value of Validity Coefficient* (V) table that for a scale of 4 with 8 validators, the instrument is said to be valid if the coefficient = 0.83 (Aiken, 1985).

Analysis of the media students' response questionnaire results is based on the scores on the assessment sheet. Each statement is scored using a 4-point scale. The data is analyzed using the SBi average equation to determine the eligibility criteria. The scoring analysis is carried out using following process:

a. Calculate the average score ($\bar{X}$) for each component aspect of the statement

$$\bar{X} = \frac{\sum X}{n}$$

b. Compare the average score with the following quality categories

Table 2. Eligibility Assessment Category Criteria

Score Range	Category
$\bar{X} > (\bar{X}_i + 1{,}5\ SBi)$	Highly Worth It
$(\bar{X}_i + 1{,}5\ SBi) > \bar{X} \geq \bar{X}_i$	Worth It
$\bar{X}_i > \bar{X} \geq (\bar{X}_i - 1{,}5\ SBi)$	Less Worth It
$(\bar{X}_i - 1{,}5\ SBi) > \bar{X}$	Not Worth It

$\bar{X}_i$: average ideal score

$\bar{X}$: average score

SBi : ideal standard deviation

Where,

$\bar{X}_i = \frac{1}{2}$ (highest score – lowest score)

$SBi = \frac{1}{6}$(ideal highest score – ideal lowest score)

Results and Discussion

Feasibility of Measurement Instruments

The assessment of products feasibility, also referred to as the validation stage, is carried out to evaluate and refine the product that has been developed. This validation process involves two lecturers from the physics education study program as expert validators and six physics teachers as practitioner validators. The results of this assessment are used to determine the feasibility level of the product to be employed in the research. The following section presents the analysis of the product feasibility evaluation:

Results of the Critical Thinking and Mathematical Representation Test Instrument Feasibility

The results of the Aiken's V analysis based on the validators' assessments of the test instrument indicate that the Aiken coefficient ranges from 0,81 to 0,87. The results of the test instrument feasibility assessment are presented in the following table.

Table 3. Results of Critical Thinking and Mathematical Representation Test Instrument Feasibility

No	Aspects	Grain	Average	Category
1	Material	The test indicators are aligned with the curriculum, learning objectives, and criteria for achieving the learning goals	0,86	High
		The test instrument aligns with the indicators of critical thinking skills and mathematical representation		
		The questions are appropriate for the students' abilities at senior high school		
		The questions are appropriate for the abilities of Grade XI students in Phase F		
		The test instrument corresponds to the developmental level of critical thinking skills and mathematical representation		
2	Construction	The formulation of the test items is clear	0,87	High
		The instructions for completing the test items are clear		
3	Language	The use of standardized language is ensured	0,81	High
		The language used is communicative		
		The sentences used do not contain ambiguity		
Average amount			**0.85**	**High**

Based on the critical value of V Aiken in the table, the average score is 0,85. The results of the analysis of Aiken's V calculations show that all critical thinking and mathematical representation questions meet the criteria of V Aiken's critical value of 0.85 which falls into the highly feasible category so that all test questions are declared valid and can be used for research. Therefore, the test instrument is considered suitable for use in the research after revisions were made in accordance with the validators' suggestions.

Results of Student Response Questionnaire Feasibility

The validity analysis of the response questionnaires for students was conducted using a four-point scale analysis technique. The feasibility assessment results for the student response questionnaire are presented in table 4.

Table 4. Feasibility of The Student Response Questionnaire

No	Aspects	Total Average Score	Category
1	Constructions	0,91	Valid
2	Content	0,91	Valid
3	Language	0,83	Valid
Average Score		**0,88**	**Valid**

Based on Table 4, the response questionnaire, which had been validated by expert and practitioner validators, obtained an average score of 0,88 across all assessed aspects. These results indicate that all items in the questionnaire are valid dan therefore suitable for use in the research.

Results of PBL-based Virtual Laboratory Learning Media Feasibility

The feasibility assessment of virtual laboratory learning media is seen from the material aspect and the media aspect. Media aspect is seen from 5 sub-aspects, namely content quality, language, implementation, design, and visual appearance. Meanwhile, the material aspect is seen from 3 sub-aspects, namely learning, completeness of content, and physics material. Virtual laboratory media was assessed by 2 expert validators and 6 practitioners. The results of the assessment of the feasibility of virtual laboratory are presented in table 5.

Table 5. Results of Virtual Laboratory Feasibility

Aspects	**Sub-aspects**	**Value**	**Category**
Media	Content quality	0,96	Highly Worth It
	Language	0,88	Highly Worth It
	Implementation	0,85	Highly Worth It
	Design	0,88	Highly Worth It
	Visual appearance	0,77	Worth It
Average		**0,87**	**Highly Worth It**
Material	Learning	0,81	Highly Worth It
	Completeness of content	0,85	Highly Worth It
	Physics material	0,88	Highly Worth It
Average		**0,85**	**Highly Worth It**

Based on Table 5, the feasibility assessment of the PBL-based virtual laboratory media indicated that the material and media aspects obtained average scores of 0,85 and 0,87, respectively, both of which are categorized as highly feasible. The lowest score was found in the visual appearance aspect, attributed to the insufficient descriptions accompanying the images and the excessive variation in font types and sizes. Therefore, the media requires revisions concerning typographical consistency and the inclusion of captions for each image, in accordance with the validators' recommendations.

Limited Trial Results

Limited trial was conducted to determine the level of readability of the media before implemented in learning. A limited trial conducted with 108 Phase F students at SMAN 1 Kalasan yielded data on learners' responses to the developed virtual laboratory learning media. The students provided evaluations and suggestions regarding the use of virtual laboratory through a response questionnaire. A summary of the analysis of students' responses to the media is presented in table 6.

Table 6. Results of Students' Responses to Virtual Laboratory-based Learning Media in Limited Trial Class

Aspects	Score	Category
The attractiveness of virtual laboratory media	3,7	Highly Worth It
The ease of use of the virtual laboratory media	3,8	Highly Worth It
The effectiveness of the virtual laboratory media	3,5	Highly Worth It
Average	**3,7**	**Highly Worth It**

Based on Table 6, the analysis of the questionnaire results showed an average score of 3,7, which falls into highly worth it category. These findings indicate that the developed virtual laboratory media is feasible and suitable for use in the research.

Conclusion

The PBL-based physics virtual laboratory learning media in this study is feasible for use in physics learning on the topic of heat and temperature to improve critical thinking and mathematical representation based on expert and practitioner evaluations, with an average score of 0,87 (highly worth it) for the media aspect and 0,85 (highly worth it) for the material aspect. Meanwhile, based on students' responses this media get an average score of 3,7 (highly worth it). This practicality is reflected in the media's attractiveness, ease of access, ease of operation, and effectiveness in supporting teaching and learning activities.

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