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ThermoLab for STEM: An Interactive 3D Virtual Lab to Strengthen Students' Computational Thinking in Heat, Temperature, and Expansion

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ABSTRACT

Computational Thinking Skills are among the essential competencies students must master to face the challenges of the digital era. Unfortunately, digital learning media that can effectively enhance students' Computational Thinking Skills, especially through the visualization of abstract science concepts, are still limited. ***Objectives:*** *This study aims to analyze the feasibility, characteristics, and impact of a STEM-based 3D virtual laboratory on students' computational thinking skills in the topic of temperature, heat, and expansion.* ***Methods:*** *The 3D virtual laboratory was developed using Unity and guided by the ADDIE development model.* ***Results:*** *The media feasibility score was very feasible, and the readability score was well understood. The 3D laboratory had excellent characteristics across five key features: accessibility, observability, realistic scenario simulation, realism, and isolation. In general, computational thinking skills improved, where male students (84.38%) outperformed female students (80.67%), in terms of abstraction, pattern recognition, algorithmic thinking, and generalization, while females were more dominant in decomposition.* ***Novelty:*** *The resulting STEM-based 3D virtual laboratory offers an immersive approach to strengthen Computational Thinking Skills and differs from previous studies that generally only focus on interactive simulations.*

INTRODUCTION

Computational thinking is categorized as Higher Order Thinking (HOT) at levels 4 to 6 (Dinni, 2018), with indicators such as identifying, reflecting, formulating, interpreting, evaluating, generalizing, and optimizing available information (Safitri et al., 2024). In Indonesia, Computational Thinking Skills (CTS) still require serious attention. This is evident from the 2022 PISA scores, which show that Indonesian students' CTS are still not optimal (Hafild & Yulianti, 2025; PISA, 2022) because students' abilities at levels 4, 5, and 6 remain relatively low (OECD, 2023). This finding confirms that Indonesian students' CT must be improved so they can formulate problems and develop effective problem-solving strategies in the future (Supiarmo et al., 2021). In line with this, interviews conducted at SMP Negeri 26 Semarang also revealed that the learning practices have not fully developed students' CTS. Several challenges were identified, including limited laboratory facilities, especially for subjects requiring experimental observation, such as physics, which results in learning that is overly theoretical and lacking in concrete concept understanding. Additionally, the lack of technology integration poses a barrier to creating interactive and relevant learning experiences. Therefore, technology-based learning innovations are essential to overcome these limitations while strengthening students' CTS.

The suboptimal mastery of CTS by students in Indonesia is one of the main reasons for the need to improve the quality of education (Sutaryo & Hasan, 2024). To overcome this problem, the Ministry of Education, Culture, Research and Technology continues to make various improvement efforts, one of which is through the implementation of an independent curriculum that emphasises a competency-based approach and flexibility in learning (Barus et al., 2024). This curriculum is designed to make students more active in critical thinking and able to solve problems with a systematic approach (Ivantri, 2024). In addition, regulations regarding the assessment of learning outcomes are continuously updated to ensure that the assessment process covers aspects of higher-order thinking, including analysis and synthesis skills (Ali et al., 2024). Through a more open and innovative learning system, students are expected to develop creativity and logical thinking skills more optimally (Husamah, 2024). This approach also guides educators in adapting instructional methods to better meet students' needs, including in the development of computational thinking skills (Susanto et al., 2023). Therefore, these initiatives are expected to contribute significantly to the overall improvement of education quality in Indonesia.

Several previous studies are relevant to this research, but they differ in their approaches and focus. Najah & Indriyanti (2024) developed a STEM-based virtual laboratory with an articulate storyline, however, their work only reached the needs analysis stage. Mashami et al. (2024) investigated the effectiveness of virtual laboratories on the concept of half-life, while this study focuses on the topics of temperature, heat, and expansion. Atalay & Mutlu (2023) used interactive simulations but did not develop a 3D STEM-based virtual laboratory using the ADDIE model. Kusmiati (2022) discussed environmental change learning, while Ngandoh (2022) used PhET simulations that were not fully based on 3D virtual laboratories. This study develops a 3D virtual laboratory based on STEM using the ADDIE model to strengthen students' computational thinking skills. Its main innovation is the use of interactive and systematic 3D technology to enhance the quality of science education.

Strengthening CTS can be achieved through the use of virtual laboratories as interactive learning media (Ngandoh, 2022). A virtual laboratory is a multimedia-based software that can simulate experimental activities interactively and realistically (Swandi et al., 2021). The learning experience provided by 3D virtual laboratories has proven effective in strengthening the understanding of abstract scientific concepts, such as temperature, heat, and expansion, which are often difficult to understand through conventional learning (Syarifuddin & Utari, 2022). In addition, virtual laboratories offer a more flexible learning experience as they can be accessed anytime and anywhere, without the limitations of physical laboratory facilities (Ibda et al., 2023). Their development is commonly guided by a STEM (Science, Technology, Engineering, and Maths) approach, which integrates various disciplines to create a comprehensive learning experience (Sari et al., 2022). This approach also facilitates the development of students' problem-solving abilities, algorithmic thinking, and programming skills (Juldial & Haryadi, 2024). Therefore, STEM-based virtual laboratories have the potential to serve as effective tools for enhancing students' CTS. Based on the described background, this study aims to: (1) Analyse the feasibility of STEM-based 3D virtual laboratories developed to strengthen CTS in temperature, heat, and expansion materials, (2) Analyse the characteristics of STEM-based 3D virtual laboratories developed to strengthen CTS in temperature, heat, and expansion materials, and (3) Analyse the profile of computational thinking skills after the application of STEM-based 3D virtual laboratories in temperature, heat, and expansion materials, in terms of gender perspective.

RESEARCH METHOD

Research Design

ThermoLab is the name of the STEM-based 3D virtual laboratory developed to strengthen Computational Thinking Skills (CTS). It was created using the Research and Development (R&D) method and followed the ADDIE model (Analyze, Design, Develop, Implement, Evaluate). The ADDIE development process is sequential yet interactive, where evaluation results from each stage inform improvements in the subsequent stage. Thus, the final output of one phase serves as the foundational input for the next. The detailed design of the research procedure is illustrated in Figure 1.

Sample / Participants / Group

During the implementation phase, to evaluate the effectiveness of *ThermoLab* in enhancing students' CTS, a one-group pretest-posttest design was used. Through cluster random sampling, class VII A (30 students) was selected as the product trial class (to assess readability), while class VII B (31 students) was designated as the experimental research class.

Instrument and Prosedur

There are three instruments used to answer the proposed problem formulation. First, the feasibility instrument to measure aspects of general appearance, virtual laboratory presentation, material, STEM, and Computational Thinking. Second, the characteristics instrument to measure the aspects of accessibility, observability, ability to simulate realistic scenarios, realism, and insulation. Finally, the CTS test instrument in the form of multiple choice and consisting of 10 items was content valid ($\bar{V}$-Aiken = 1.00), had a good level of difficulty (.37-.87), good item differentiation (.30 < DP ≤ 1.00), and was reliable (KR-20 = .71). The questions contained five CTS indicators, namely Algorithmic Thinking, Decomposition, Pattern Recognition, Abstraction, and Generalization. The questions were given at the beginning and end of learning to determine whether there was a difference in the average score of students' CTS after the application of a STEM-based 3D virtual laboratory.

Data Analysis

Feasibility Analysis of ThermoLab

The feasibility of *ThermoLab* was evaluated by two expert lecturers and three science teachers based on five assessment aspects. This feasibility test aimed to ensure that the developed product could effectively address existing problems and be user-friendly. Its success was determined by its alignment with the established feasibility criteria, namely 76% – 100% (Excellent), 51% – 75% (Good), 36% – 50% (Poor), and < 35% (Very Poor) (Arikunto, 2010). Following the expert evaluation, the next step was to conduct calculations (Sugiyono, 2022).

$$Feasibility\ (\%) = \frac{The\ total\ score\ obtained\ by\ the\ researcher}{The\ maximum\ possible\ score} \times 100\%$$

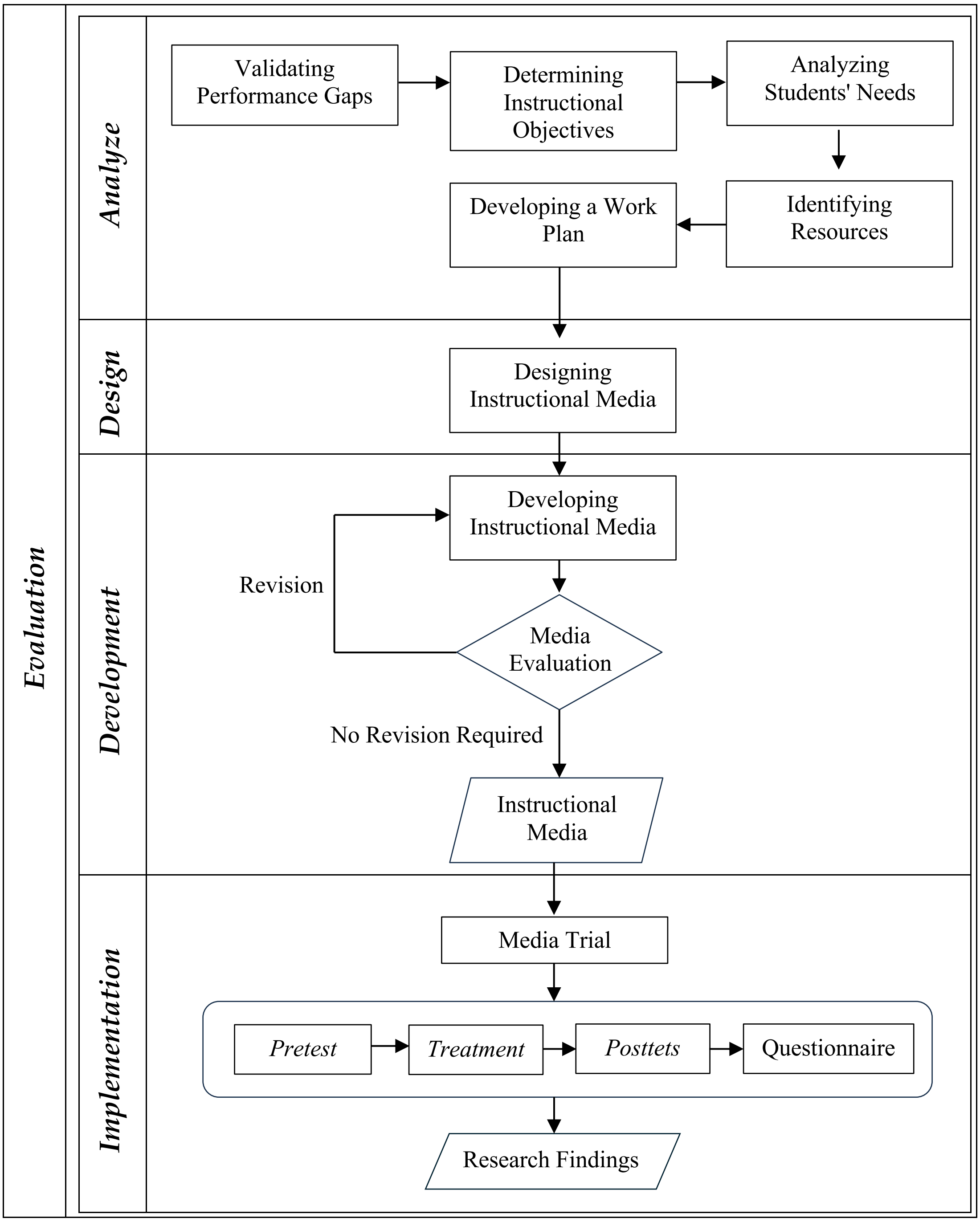


Figure 1. Research procedure

Analysis of Media Readability by Students

The readability analysis of the *ThermoLab* was conducted using a Likert scale questionnaire with four categories: Excellent (score = 4), Good (score = 3), Poor (score = 2), and Very Poor (score = 1). The obtained scores were analyzed using a descriptive percentage test with the following formula dan readability level criteria for *ThermoLab* as follows: 81.26-100% (Excellent), 62.51-81.25% (Good), 43.76-62.50% (Poor), dan 25.00-43.75% (Very Poor) (Arikunto, 2010).

$$Readability\ (\%) = \frac{Obtained\ Score}{Maximum\ Score} \times 100\%$$

Analysis of the Characteristics of a ThermoLab

The characteristics of the *ThermoLab* were analyzed descriptively based on expert assessment questionnaires and student readability evaluations. The data were analyzed by calculating the average score for each evaluated item to gain insights into the laboratory's characteristics (Arikunto, 2010). The characteristic criteria for *ThermoLab* are as follows: 81.26-100% (Excellent), 62.51-81.25% (Good), 43.76-62.50% (Poor), dan 25.00-43.75% (Very Poor) (Arikunto, 2010).

$$Characteristic\ (\%) = \frac{\sum X}{N} \times 100\%$$

Note: P: Average scoring; $\sum X$: Total responses from each respondent for each evaluated item; N: Total ideal score

Validation of Multiple-Choice Computational Thinking Skills Test Instrument

Content validity was demonstrated using Aiken's V index, assessed by five experts based on four assessment criteria. The CTS instrument was concluded valid if V≥0.87 (p<.05). The V Aiken formula is as follows (Aiken, 1985).

$$V = \frac{\sum s}{[n(c-1)]}$$

Note: V = Aiken's index; s = r-lo; l_o = the lowest validity rating score; c = the highest validity rating score; r = the score given by an expert; n = the number of raters.

Reliability

Reliability shows the extent to which the research instrument can be trusted to measure in accordance with its intended purpose. The calculation is done with KR-20 because the answer response is dichotomous data. The KR-20 formula is as follows (Sugiyono, 2022).

$$R_{11} = \frac{n}{(n-1)} \times \frac{({S_t}^2 - \sum p_i q_i)}{{S_t}^2}$$

Note : R_{11} : Overall test reliability; p_i : Proportion of items answered correctly; q_i : Proportion of items answered incorrectly; n : Number of items (questions); S_t^2 : Question variance

Paired Sample T-Test

Paired Sample t-Test is an analytical method used to examine differences between two paired samples, specifically the same subjects under different treatments. This test is commonly applied to compare conditions before and after treatment to evaluate its effectiveness (Wati et al., 2024). In this study, a significance level of 0.05 (α = 5%) was used, with the test criteria Ho is rejected if the significance value is <0.05, where Ho = there is no significant difference in mean CTS scores before and after the application of *ThermoLab*, and Ha = there is a significant difference in mean CTS scores before and after the application of *ThermoLab*.

RESULTS AND DISCUSSION

Analysis

Interviews with school officials revealed that existing laboratory facilities are inadequate to support practical activities, particularly in physics. These limitations result in learning that is predominantly theoretical, hindering students' ability to concretely grasp abstract concepts. Furthermore, the instructional methods currently employed do not effectively cultivate students' computational thinking skills. These skills, which encompass decomposition, abstraction, pattern recognition, algorithmic thinking, and generalization, are essential for preparing students to meet future challenges. The limited integration of technology in the teaching process further impedes the creation of interactive and contextually relevant learning experiences that align with current scientific and technological developments. Therefore, innovative, technology-based learning solutions are needed, not only to overcome the constraints of physical laboratory infrastructure but also to systematically strengthen students' computational thinking skills.

Design

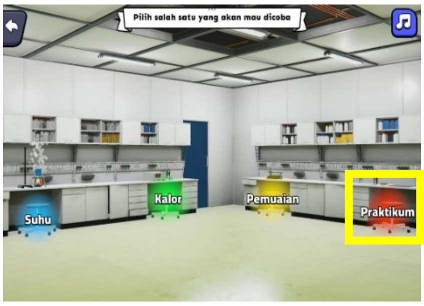
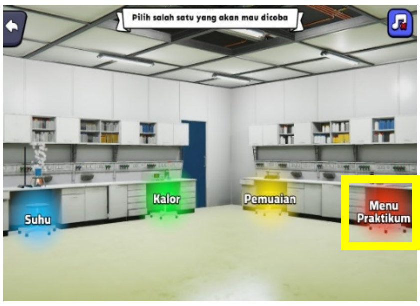
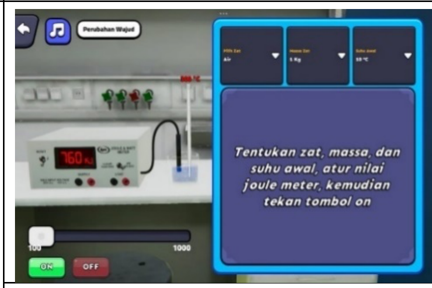
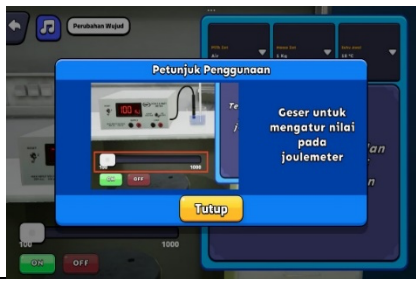
This STEM-based 3D Virtual Laboratory is designed to facilitate interactive and contextual science learning, particularly on the topics of temperature, heat, and changes in the state of matter. The initial interface of the application presents main menus such as profile, application information, and a start experiment button. The profile and about menus provide information about the developers and explanations regarding the objectives, STEM components, and computational thinking indicators. The learning outcomes and learning objectives page displays the competencies and learning objectives to be achieved. Users can select various experiments, such as temperature, heat, and changes in the state of matter, which are presented through interactive simulations and animations. There is also a project for making a simple thermometer and experiments on heat transfer through conduction, convection, and radiation. This media was developed as a solution to the limitations of physical laboratories and as a tool to train students' computational thinking skills.

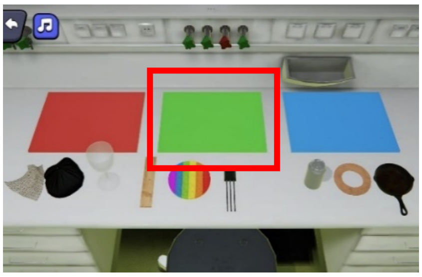
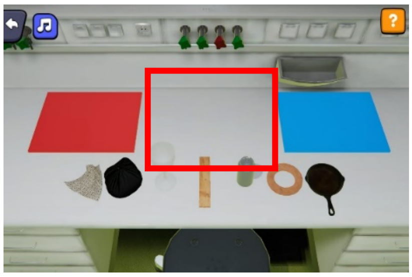
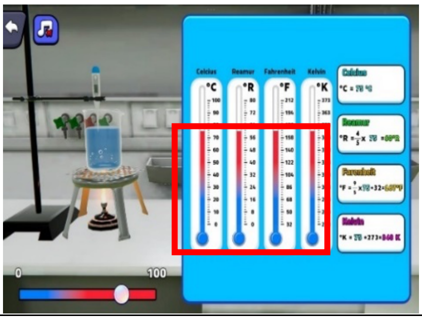
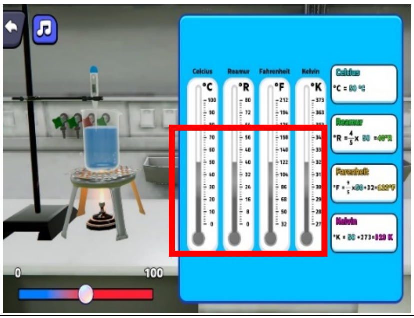
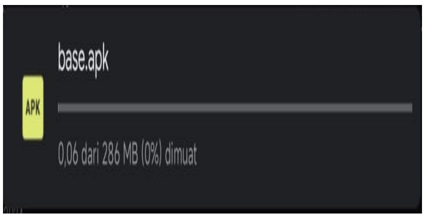
Development

Feasibility of ThermoLab

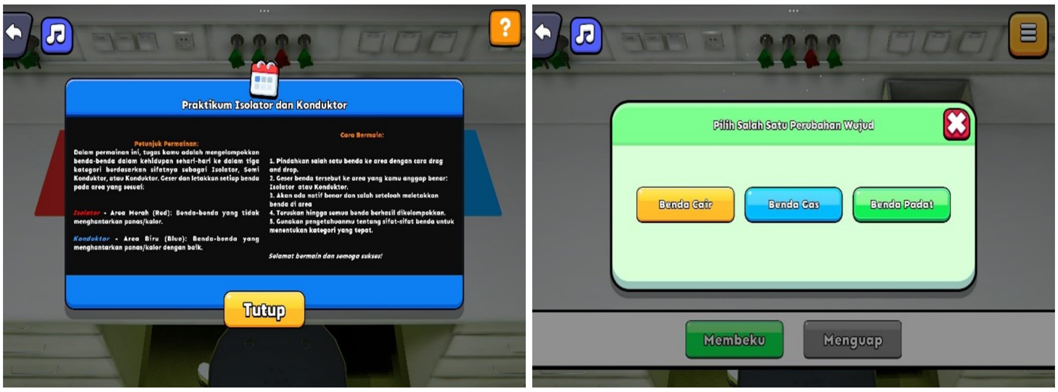
The feasibility of *ThermoLab* was evaluated by a panel of experts, consisting of two lecturers and three science teachers, across five aspects: appearance (96%), presentation (95%), content/material (98%), STEM integration (98%), and computational thinking (100%). The overall average feasibility score was 96.7%, indicating that *ThermoLab* is highly feasible. However, several suggestions were provided for improvement, particularly regarding the media aspects—such as the color scheme, element sizing, and layout within the virtual laboratory—as well as refinements to the instructional content (see Table 1).

Table 1. Suggestions and revisions by experts in the media feasibility test

<table>
<tr><th>No.</th><th>Suggestion</th><th>Before Revision</th><th>After Revision</th></tr>
<tr><td rowspan="2">1</td><td rowspan="2">The color contrast between the pipette and the liquid needs to be enhanced so that the difference between them is clearer and easier to observe.</td><td>
</td><td>
</td></tr>
<tr><td colspan="2">Improvement: The pipette color was changed to a darker shade, while the liquid was adjusted to a lighter tone to create a sharper contrast and facilitate easier identification by users.</td></tr>
<tr><td rowspan="2">2</td><td rowspan="2">The text color and background should be adjusted to avoid clashing or blending, ensuring better readability.</td><td>
</td><td>
</td></tr>
<tr><td colspan="2">Improvement: The previous color combination of red and orange was replaced with black text on a white background to enhance legibility.</td></tr>
<tr><td rowspan="2">3</td><td rowspan="2">The addition of a "Practicum Menu" label in the practicum section is necessary to help users easily identify the feature.</td><td>
</td><td>
</td></tr>
<tr><td colspan="2">Improvement: In the practicum section, a "Practicum Menu" label was added at the top using a larger font size to make it more prominent and easier to locate.</td></tr>
<tr><td rowspan="2">4</td><td rowspan="2">User instructions should be included to facilitate a better understanding of the available features.</td><td>
</td><td>
</td></tr>
<tr><td colspan="2">Improvement: Instructions were added at each step in the form of pop-up messages containing brief guidance on how to carry out the practicum activities.</td></tr>
</table>

No.	Suggestion	Before Revision	After Revision
5	The practicum content on insulators, conductors, and semiconductors needs to be revised by removing the material on semiconductors, as it only addresses the thermal properties of insulators and conductors.		
		Improvement: The semiconductors section was removed from the practicum guide and gameplay instructions. Descriptions of the thermal properties of insulators and conductors were clarified to align with the correct concepts.	
6	The liquid color in the thermometer should be standardized to a single color for better recognition.		
		Improvement: The previously multi-colored liquid in the thermometer was standardized to a single color—silver—to improve consistency in appearance and readability of measurement results.	
7	The application size should be optimized to be lighter without compromising feature quality and functionality.		
		Improvement: The application size was reduced from 286 MB to 198 MB by optimizing graphic elements and data usage for greater efficiency.	

The integration of STEM in the developed 3D virtual laboratory is designed to foster students' scientific thinking through observation, experimentation, and analysis of natural phenomena (Baptista, 2023). The science component is reflected in thermodynamic concepts, particularly temperature, heat, and expansion. Temperature experiments enable students to measure in various scales (Celsius, Reamur, Fahrenheit, and Kelvin) and perform mathematical conversions between them. Heat experiments demonstrate energy transfer that influences substance temperature, including conduction, convection, and radiation, as well as phase changes such as melting and evaporation. Thermal property experiments distinguish conductors from insulators by analyzing material responses to heat. The expansion experiment visualizes the varying expansion of metals based on their coefficients, incorporating scientific calculations involving initial length, temperature change, and expansion coefficient. Overall, this virtual laboratory offers a comprehensive and interactive learning experience that deepens students' understanding of thermal phenomena.



(a) (b)

Figure 2. (a) Science element in isolators and conductors practicum; (b) Science element in shape change practicum

Secondly, the Technology element in this virtual lab includes interactive simulations of temperature, heat, and expansion experiments. The technology component of STEM focuses on the creative use and development of technology to solve real-world problems (Ochkov et al., 2020). The digital thermometer features automatic conversion between temperature scales, while the Joule & Watt Meter measures heat energy in real-time to improve the accuracy of observations. The 3D animations show the expansion of metals with different expansion coefficients, providing a visualization of dimensional changes due to temperature. Interactive technology allows the setting of experimental variables, such as initial temperature, substance mass, and specific heat, as well as the automatic calculation of physical quantities, reducing manual errors. This approach makes lab work more effective, safe, and efficient in understanding thermodynamic concepts.

(a) (b)

Figure 3. (a) Aspects of technology in the expansion practicum (musschenbroek) (b) Aspects of technology in the temperature practicum (digital thermometer)

Thirdly, the Engineering element in this virtual lab includes designing and testing a simple thermometer based on liquid expansion. A water bottle is used as the main container, with plasticine as a sealer to keep the pressure stable. Pipettes and food coloring make it easy to visualize changes in liquid volume due to thermal expansion. The design considers temperature-responsive materials, such as colored water as the thermometric fluid and fabric as a shield. Tests were conducted by dipping the base of the bottle into hot water to observe the rise of liquid in the pipette. Engineering teaches students the process of designing technical solutions based on a project approach that integrates science and mathematics concepts (Setyowati & Litasari, 2024). This experiment reflects the engineering principle in STEM, which is designing and optimizing simple tools based on scientific concepts.

Figure 4. Engineering element in the practicum of simple thermometer making

Finally, the Mathematics element in this virtual lab includes calculations and data analysis related to temperature change, heat, and expansion. In this experiment, temperature conversion between units, such as Celsius, Fahrenheit, Reamur, and Kelvin, is done using the standard transformation formula to understand the relationship between temperature scales. Calculation of heat using the formula $Q = m \times c \times \Delta T$ is applied to determine the amount of energy required in the heating process of a substance. In addition, the concept of linear expansion was analyzed through the formula $\Delta L = L_0 \times \alpha \times \Delta T$ to observe the change in metal length due to temperature increase. The results of these calculations are validated by comparing the experimental results and theory, ensuring compatibility between predictions and observations. The utilization of algebraic concepts, number operations, and graph analysis in this experiment strengthens students' understanding of mathematical relationships in physical phenomena. Meanwhile, Mathematics strengthens students' logical thinking, problem-solving, and quantitative skills (Ayu & Rahayu, 2022). Thus, this practicum process emphasizes the importance of mathematics in STEM as a tool to model, calculate, and analyze data systematically and accurately. This is supported by the statement of Damayanti et al. (2020), who stated that easy-to-use virtual-based learning media can increase learner engagement and interactive learning effectiveness. With this convenience, STEM-based 3D virtual laboratories can be an innovative alternative in supporting experiment-based learning without space and time limitations.

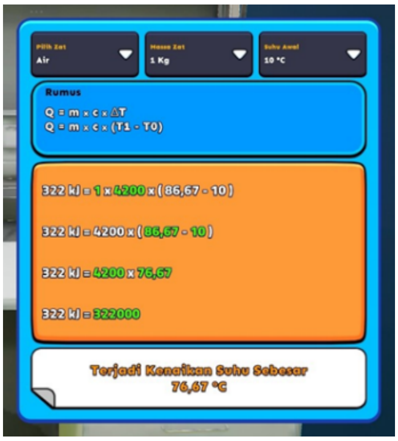
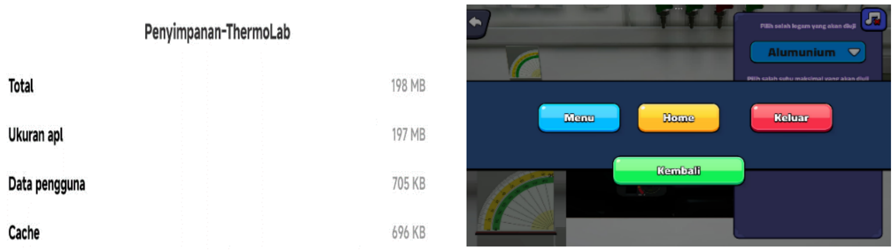


Figure 5. Mathematical element in the calor practicum

The *ThermoLab*, which has been revised based on experts and declared feasible, is then tested for readability using a questionnaire. The readability test was conducted on 30 students of class VII A SMP Negeri 26 Semarang who had previously studied the material on temperature, heat, and expansion. This readability test aims to obtain input, criticism, and suggestions from students. The readability questionnaire includes aspects of media and material. The average result of the readability test showed a value of 93.7% with very good criteria, with details of material aspects (93%) and media (94%). Learning media that has clear text and easy navigation can increase student engagement in the learning process (Pantow & Korompis, 2024). In addition, the experimental activities also have the potential to increase students' motivation in solving science problems in a coherent manner. In terms of media, visual appearance, animation layout, colour selection, and attractive fonts also increase learners' interest. Clear navigation, instructions for use, and communicative language also facilitate understanding and implementation of the practicum.

ThermoLab Characteristics

By involving the same expert, the characteristics of *ThermoLab* were assessed in five aspects, namely: accessibility, observability, ability to simulate realistic scenarios, realism, and insulation. Firstly, *ThermoLab* shows a very good level of accessibility in terms of application size and navigation (see Figure 6). At 198 MB, *ThermoLab* remains lightweight for modern devices and is easily accessible. Navigation is intuitively designed with large, clear, and contrasting buttons, such as 'Menu', 'Home', 'Back', and 'Exit', making it easy for users with different levels of digital skills. Thus, the app is not only interactive but also user-friendly. This is supported by research by Rahmi et al. (2022), who stated that STEM-based virtual laboratories can improve the understanding of scientific concepts as well as learner engagement through an interactive and responsive simulation environment. Additional features, such as audio and supporting text, also play a role in improving accessibility, providing alternatives for learners with different learning preferences.



(a) (b)

Figure 6. (a) Size of the application (b) Ease of navigation

(a) (b)

Figure 7. (a) Observability character in conduction practicum, (b) Observability character in convection practicum

Secondly, the observability character of *ThermoLab* indicates that this media allows learners to observe objects or simulation processes clearly and is able to visualize science concepts interactively. Based on the expert assessment, this virtual laboratory obtained a score of 95% with excellent criteria, confirming its effectiveness in assisting scientific understanding through realistic simulations. The interactive 3D visualization allows for clearer observation of experimental process details compared to conventional methods. The observability character is presented in Figures 7(a) and 7(b). Figure 7(a) shows the practice of conduction through heat transfer differences in metal and plastic spoons, indicated by the discoloration and melting of cheese. Meanwhile, Figure 7(b) shows the convection lab with the spread of food coloring in hot water, illustrating the pattern of fluid movement due to temperature change. These interactive visualizations enhance understanding of physics concepts and student engagement, making *ThermoLab* more effective than conventional methods. STEM-based virtual laboratories equipped with realistic simulations can improve students' understanding and engagement in science learning (Aspariga et al., 2024).

Third, the characteristic of the ability to simulate a realistic scenario shows the ability of *ThermoLab* to simulate the same scenario as the original. This character serves to ensure that the virtual environment developed can accurately represent real experimental conditions, so that students can gain practical experience that is close to direct experiments. Based on the expert assessment, *ThermoLab* obtained a score of 100% (excellent), which indicates that this media has been able to simulate experimental scenarios with a high level of realism. The characteristics of the ability to simulate realistic scenarios appear in: (1) temperature practicum, where students can observe changes in the temperature of heated water and its conversion to various units, (2) heat practicum that allows the determination of the mass of the substance, the initial temperature, and the energy given to understand the change of form and heat concretely, and (3) expansion practicum that allows exploration of the expansion characteristics of various metals with adjustable temperatures. This feature supports the understanding of physics concepts through an in-depth, experiment-based learning experience.

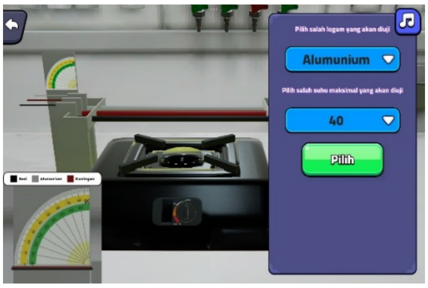
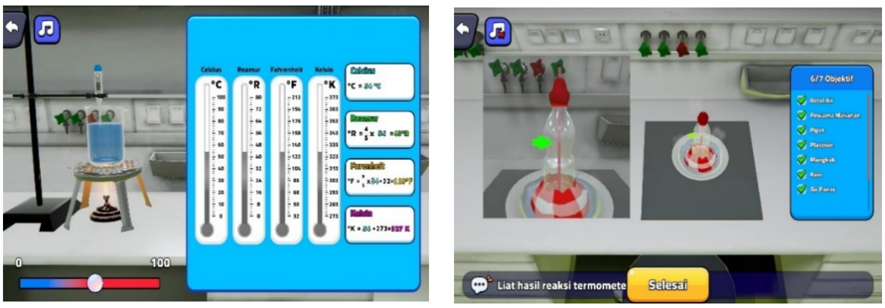


Figure 8. Ability to simulate a realistic scenario character in the expansion practicum

Fourth, the realistic characteristic of *ThermoLab* shows the visual appearance and representation of objects that closely resemble the real world (i.e., graphic details, texture, colour, and shape of objects). Based on the expert assessment, *ThermoLab* obtained a score of 100% (excellent), which indicates high quality in representing the laboratory environment because the higher the realistic level of a learning media, the more immersive the learning experience of students. In Figure 9(a), realism is shown through the colour of the liquid in the thermometer that resembles mercury, while in Figure 9(b), accuracy is shown in the simple thermometer components, such as bottles, pipettes, and plasticine. This accuracy creates a practical experience that is close to real experiments, visually enhances concept understanding, and effectively supports experiment-based learning. STEM-based virtual labs increase learner engagement and learning effectiveness through more immersive exploratory experiences (Makransky et al., 2019). Therefore, this realistic simulation feature plays an important role in effectively improving the quality of science and engineering learning.



(a) (b)

Figure 9. (a) Realistic character in temperature practicum, (b) Realistic character in simple thermometer making practicum

Finally, the insulated characteristic of *ThermoLab* shows that this media can operate independently without relying on external factors (i.e., internet connection or additional devices). The expert assessment showed a score of 100% (excellent), confirming that this media is optimal for independent learning without distractions. This isolated learning environment also helps improve learning efficiency by minimizing distractions that often occur in internet-based systems. These results are in line with research by Fatuzzahra et al. (2024), who stated that an insulated virtual learning environment can improve learning effectiveness by reducing external distractions and allowing learners to focus more. With these advantages, *ThermoLab* becomes an innovative solution that supports self-directed learning flexibly, efficiently, and without technical barriers.

Figure 10. An insulated character can run without the need for internet access

Implementation

Students' Computational Thinking Skills Profile After Using the STEM-Based 3D Virtual Laboratory: A Gender Perspective

The implementation of *ThermoLab* involved two groups: class VII A (pilot group) and class VII B (experimental group), utilizing a one-group pretest–posttest design. The sample was selected using a cluster random sampling technique after confirming the homogeneity of variance in students' final science scores from the odd semester. During the learning process, students in the experimental class accessed *ThermoLab* individually via smartphones, then collaborated in groups to complete worksheets (LKPD) designed according to computational thinking steps. The results of the paired t-test revealed a statistically significant difference in students' CTS scores before and after the use of *ThermoLab* ($p < .05$; t-value = -38.930). Specifically, the posttest score (Mean = 82.58; SD = 10.63) was significantly higher than the pretest score (Mean = 49.35; SD = 12.89), indicating that *ThermoLab* effectively enhanced students' computational thinking skills. The high average posttest score was then further analyzed descriptively to explore potential differences in CTS based on gender.

Numerically, it was found that male students (84.38%) slightly outperformed female students (80.67%), with a relatively small margin of 3.71%, suggesting that the level of computational thinking skills between genders is generally comparable. Hence, skill development is necessary for all students regardless of gender. A detailed profile of students' CTS by gender (see Figure 11) shows that female students (87.78%) had a higher level of mastery in the decomposition indicator compared to males (81.25%). In contrast, male students demonstrated stronger performance in abstraction (87.5%) and pattern recognition (92.71%) compared to females (80% and 78.89%, respectively). Similarly, in algorithmic thinking, males (78.13%) also outperformed females (75.56%). For the generalization indicator, males again scored higher at 84.38%, while females achieved 80.67%.

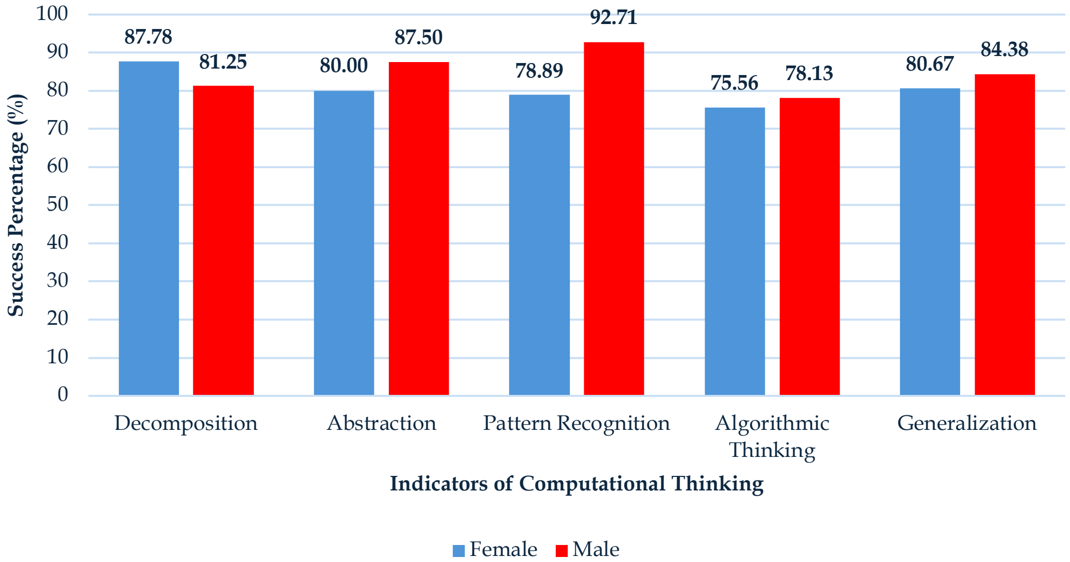


Figure 11. Computational thinking skills profile by gender

Overall, male students demonstrated higher proficiency in most CTS indicators, except for decomposition, in which female students performed better. This finding aligns with Grover & Pea (2013), who noted that males tend to exhibit stronger rule-based and pattern-oriented thinking in computational problem solving. Conversely, the superiority of female students in decomposition suggests that they tend to be more meticulous and analytical, breaking down complex problems into simpler parts to ensure deeper understanding before identifying solutions (Werner et al., 2013). Thus, although both genders demonstrated a high level of computational thinking skills, male students excelled in pattern recognition, while female students showed greater strength in problem decomposition.

Evaluation

This final stage aims to evaluate the entire process that has been carried out and use the evaluation results as a basis for revising the development of the STEM-based 3D virtual laboratory. Evaluations are conducted at each stage of development to improve the overall quality of the product. The process of improving the 3D virtual laboratory is based on input obtained from various parties, including media experts, material experts, supervising lecturers, and students. All feedback and responses are carefully analyzed to develop an appropriate revision plan aimed at improving the quality of the 3D virtual laboratory.

CONCLUSION

Fundamental Findings: STEM-based 3D virtual laboratories have been proven highly feasible for strengthening students' computational thinking skills, with a feasibility score of 96.6% from experts and a readability score of 93.7% from students. Their characteristics were rated as very good, with an average score of 98%. Male students demonstrated computational thinking skills 3.71% higher than female students, particularly in pattern recognition, while female students outperformed males in decomposition. **Implications:** These findings highlight the importance of developing STEM-based 3D virtual laboratories as alternative learning media to enhance students' computational thinking skills. **Limitations:** This study is limited to the topic of Temperature, Heat, and Expansion and involved a specific group of participants. **Future Research:** Future studies should focus on improving the quality of STEM-based 3D virtual laboratories, integrating more interactive features, and expanding their application to various science subjects to further optimize students' computational thinking skills.

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