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The Effectiveness of Native-Coded Interactive Worksheets Integrated with Virtual Laboratories to Enhance Computational Thinking in Thermal Concepts

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Computational thinking; Interactive electronic worksheet; Native coding; Thermal concepts; Virtual laboratory

Abstract

This study aims to examine the effectiveness of a native-coded interactive electronic worksheet integrated with a three-dimensional virtual laboratory in enhancing junior high school students' computational thinking in thermal physics. The innovation of this study lies in the coherent integration of native web programming and a 3D virtual laboratory within a single learning environment, enabling structured interactivity, dynamic visualization, and embedded computational tasks. The findings indicate that the developed media achieved high feasibility, practicality, and readability, and significantly improved students' computational thinking, with moderate learning gains and a significant difference between the experimental and control groups. These results suggest that the integration of interactive worksheets and virtual laboratories supports key computational thinking processes, including decomposition, abstraction, and algorithmic reasoning. This study contributes to physics education by demonstrating how computational thinking can be systematically embedded through the alignment of interactive media and virtual experimentation. In conclusion, this integrated approach provides a scalable and pedagogically grounded model for advancing higher-order thinking skills in digital physics learning.

How to Cite

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INTRODUCTION

The digital transformation of science education has increased the demand for higher-order thinking skills, particularly computational thinking, as a key competency in 21st-century learning (Buitrago-Flórez et al., 2021). Interactive digital worksheets support engagement and conceptual understanding through structured activities (Wintribrata et al., 2025) and can enhance analytical and problem-solving skills (Taranto et al., 2024). However, most studies emphasize outcomes rather than how worksheet design facilitates computational thinking processes (Lee & Malyn, 2020). This indicates a weak alignment between instructional design and computational thinking development. This gap highlights the need for more conceptually grounded design approaches.

In physics education, especially thermal concepts, virtual laboratories support visualization and inquiry-based learning (Gerhátová et al., 2021) and enable simulation-based experimentation beyond classroom limitations (Falloon, 2019). Although some studies combine digital worksheets with virtual laboratories (Putri et al., 2021), the integration remains superficial and functionally separated. Virtual laboratories are often used only as supplementary tools rather than core components (Elmoazen et al., 2023). Consequently, computational thinking is not systematically developed. This reflects a lack of coherent instructional integration.

A key limitation is the dominance of platform-based development, which restricts flexibility and pedagogical alignment (Choi, 2022). While platforms simplify development, they limit interactive features and complex simulations (Asare et al., 2023). In contrast, native coding enables full control over system design and integration (Seitnazarov & Mambetkarimov, 2024). This allows tighter alignment between content, interaction, and computational thinking processes (Hutchins et al., 2020). Therefore, native coding provides a more coherent and pedagogically robust approach.

A clear research gap emerges from these limitations. Existing studies treat digital worksheets, virtual laboratories, and computational thinking as separate components. This fragmentation reduces coherence and limits learning effectiveness. Platform dependence further constrains integration. Consequently, no unified system integrates native coding, virtual laboratories, and computational thinking within single framework.

To address this gap, this study proposes a native-coded interactive electronic worksheet integrated with a three-dimensional virtual laboratory for thermal physics learning. This study is novel as it is among the first to integrate native coding, virtual laboratories, and computational thinking into a single coherent system. It embeds computational thinking directly within virtual experiments for more meaningful learning. Accordingly, this study aims to: (1) develop the system, (2) evaluate its feasibility and practicality, and (3) examine its effectiveness in enhancing computational thinking in thermal concepts. This study contributes a concise, integrated, and flexible digital learning environment for physics education.

METHOD

Research Design

This study employed a quasi-experimental method using a non-equivalent control group pretest-posttest design, while the development of the learning media followed the ADDIE model consisting of analysis, design, development, implementation, and evaluation stages. In the analysis stage, students' initial computational thinking skills, learning needs, and laboratory limitations were identified through interviews with teachers and students. The design stage involved structuring learning activities, defining computational thinking indicators, and developing assessment instruments. The development stage produced a native-coded interactive E-Worksheet integrated with a 3D virtual laboratory (ThermoLab) using HTML, CSS, and JavaScript. Furthermore, the implementation stage compared an experimental group using the developed media with a control group receiving conventional instruction, while the evaluation stage assessed feasibility, practicality, readability, and effectiveness to determine the overall quality of the product. The comprehensive framework of the research procedure is illustrated in Table 1.

Participants

The study involved 63 seventh-grade students from SMP Negeri 10 Semarang, consisting of 32 students in the experimental group and 31 students in the control group, with students aged approximately 12–13 years. Sampling was conducted using cluster sampling, where intact classes were selected based on existing school groupings without random assignment, and both groups were considered to have relatively similar academic characteristics based on prior achievement records.

Operational Definition of Computational Thinking

Computational Thinking Skills (CTS) in this study were operationalized into five measurable indicators, namely decomposition, abstraction, pattern recognition, algorithmic thinking, and generalization. Decomposition refers to the ability to break down complex problems into smaller, manageable parts, while abstraction is defined as the ability to identify relevant information and ignore irrelevant details. Pattern recognition involves the ability to identify similarities or relationships across different cases, and algorithmic thinking refers to the ability to construct logical and sequential steps to solve problems. Generalization, on the other hand, is the ability to apply solutions or patterns to new problems. Each of these indicators was assessed through structured multiple-choice items aligned with thermal physics contexts.

Data Analysis

Feasibility Analysis of Interactive E-Worksheet

Expert validators assessed five aspects of the E-Worksheet using a descriptive percentage formula:

$$P = \frac{f}{N} \times 100\%$$

The resulting percentage provides a clear indicator of level of feasibility, which is then matched with predetermined criteria to categorize the media's quality. The criteria used in this study follow Arifin (2015), as presented in Table 2.

Table 2. Feasibility Criteria for the Interactive E-Worksheet

Percentage	Criteria	Description
76% – 100%	Very Good	Highly Feasible, No Revision Required
51% – 75%	Good	Feasible, Revision Required
36% – 50%	Poor	Not Feasible, Revision Required
≤ 35%	Very Poor	Highly Not Feasible, Revision Required

Instruments

The CTS instrument consisted of multiple-choice items validated for content validity using Aiken's V, with items accepted at $V \geq 0.70$ (Aiken, 1985). Reliability was assessed using the KR-20 formula, with a minimum acceptable coefficient of 0.70 (Sugiyono, 2022). The CTS instrument used in pretest and posttest covered five indicators: decomposition, abstraction, pattern recognition, algorithmic thinking, and generalization.

Practicality Analysis of the Interactive E-Worksheet

Practicality was evaluated by both expert validators and students using:

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

This percentage outcome was then interpreted based on predetermined practicality criteria to classify the E-Worksheet's usability level. The criteria used in this study refer to Sudjana (2001) as cited in Murni (2022), and are presented in Table 3.

Table 3. Practicality Criteria for the Interactive E-Worksheet

Percentage Range	Classification
79% < score ≤ 100%	Very Practical
64% < score ≤ 79%	Practical
54% < score ≤ 64%	Not Practical
0% < score ≤ 54%	Very Not Practical

Analysis of Media Readability by Students

Student readability was assessed across seven dimensions using the formula:

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

This percentage value reflects the overall level of clarity, accessibility, and user-friendliness of the E-Worksheet. Subsequently, the resulting scores were compared against established readability criteria to classify the media into appropriate categories. The classification scheme used in this study follows Utami et al. (2022), as outlined in Table 4.

Table 4. Readability Criteria for the Interactive E-Worksheet

Percentage Range	Classification
75% < score ≤ 100%	Very Good
50% < score ≤ 75%	Good
25% < score ≤ 50%	Poor
0% < score ≤ 25%	Very Poor

Analysis of the Characteristics of a ThermoLab

Characteristics were assessed using:

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

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

The resulting percentage was then interpreted using predetermined criteria to classify the quality level of the ThermoLab characteristics. These classification criteria, adapted from Arikunto (2021), are presented in Table 5.

Table 5. Characteristics Criteria for the Interactive E-Worksheet

Percentage (%) Range	Classification
81.25% < score ≤ 100%	Very Good
62.50% < score ≤ 81.25%	Good
43.75% < score ≤ 62.50%	Poor
25.00% < score ≤ 43.75%	Very Poor

Validation of Multiple Choice Computational Thinking Skills Test Instrument

Content validity was measured using Aiken's V formula:

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

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

Reliability

Instrument reliability was analyzed using the KR-20 formula because the test items were dichotomous (correct/incorrect). The CTS instrument was considered reliable if the coefficient was ≥ 0.70 (Sugiyono, 2022).

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

Note : R11 : Overall test reliability; p_i : Proportion of items answered correctly; q_i : Proportion of items answered incorrectly; n : Number of items (questions); St^2 : Question variance

Media Effectiveness Analysis

Independent Sample T-Test

In this study, the effectiveness of the native-coded interactive E-Worksheet integrated with a 3D virtual laboratory was examined using an independent sample t-test to compare learning outcomes between the experimental and control groups. The analysis relied on students' posttest Computational Thinking Skills (CTS) scores as a direct indicator of the media's impact. The hypotheses tested whether there was no significant difference between the two groups (H_0) or whether a significant difference existed (H_1). A significant result favoring the experimental group would demonstrate the superior effectiveness of the interactive E-Worksheet in enhancing students' computational thinking. Thus, the independent sample t-test provides essential evidence of the developed media's comparative advantage over conventional instruction.

N-Gain Test

The effectiveness of the native-coded interactive E-Worksheet was also examined using the N-Gain test to measure improvements in students' Computational Thinking Skills (CTS) from pretest to posttest. The N-Gain score provides a standardized measure of learning progress by comparing the actual gain with the maximum possible gain. The normalized gain was calculated using the following formula:

$$g=\frac{S_{post}-S_{pre}}{S_{max}-S_{pre}}$$

Ethical Considerations

This study was conducted with permission from the school. Students participated voluntarily, and all data were collected anonymously. Participants were informed about the purpose of the study, and their responses were used solely for research purposes.

RESULT AND DISCUSSION

The feasibility assessment of the native-coded interactive E-Worksheet integrated with a 3D virtual laboratory was conducted to ensure that the developed media met the required quality standards prior to classroom implementation. The evaluation covered several aspects, including visual design, presentation, content accuracy, deep learning support, and alignment with computational thinking skills. Expert validators reviewed each component to ensure its pedagogical relevance and technical quality. The results of the feasibility assessment are presented in Table 6.

Table 6. Feasibility Assessment of the Interactive E-Worksheet

Assessment Aspect	Score (%)	Category
General Appearance	91%	Very Good
Presentation	93.67%	Very Good
Material / Content	98.88%	Very Good
Deep Learning	100%	Very Good
Computational Thinking	100%	Very Good
Total Feasibility Score	95.94%	Very Good

The feasibility assessment of the developed interactive E-Worksheet indicates that the media achieved a Very Good category across all evaluated aspects, with an overall score of 95.94%. Beyond confirming its technical adequacy, these findings suggest that the media is pedagogically aligned with higher-order learning processes. The high score in content accuracy (98.88%) implies that the conceptual representations embedded within the virtual environment are reliable, which is essential for supporting students' understanding of abstract thermal concepts and preventing misconceptions (Darman et al., 2024). In virtual laboratory contexts, conceptual accuracy not only reflects content validity but also serves as a cognitive foundation that guides students in constructing meaningful scientific understanding. Moreover, the perfect scores in deep learning and computational thinking aspects (100%) indicate that the media is not merely informative but facilitates cognitively generative learning processes. The integration of structured inquiry tasks and computational thinking activities likely promotes decomposition, abstraction, and algorithmic reasoning, which are fundamental mechanisms underlying higher-order thinking (Herlina et al., 2025; Wang et al., 2022). From a constructivist perspective, this suggests that students actively construct knowledge through interaction with simulations and problem-solving tasks (Mayer, 2021), explaining not only that the media is feasible but also why it has the potential to support meaningful learning. These findings are consistent with previous studies reporting high validation scores in digital learning media design and presentation (Nenggala & Razi, 2024; Dewi et al., 2023). Nevertheless, the uniformly high validation scores may indicate a potential ceiling effect in expert judgment, suggesting the need for broader validation in diverse contexts.

Practicality of Interactive E-Worksheet with 3D Virtual Laboratory Integration

The practicality of the Interactive E-Worksheet integrated with a 3D Virtual Laboratory was evaluated to determine its usability and feasibility in supporting the learning process. This assessment considered several aspects, including content quality, accuracy, presentation format, usefulness, ease of use, timeliness, and user satisfaction. Practicality evaluation is an essential component in educational media development because it reflects the extent to which a learning tool can be effectively implemented in real classroom settings. Previous studies emphasize that the successful implementation of digital learning media depends not only on content quality but also on usability and adaptability within instructional contexts (Toma et al., 2023; Limbu & Pham, 2023). The results of the practicality assessment are presented in Table 7.

The practicality results, with an overall score of 81.9% categorized as Very Practical, indicate that the media is usable within real classroom settings; however, a deeper analysis reveals that practicality plays a critical role in bridging design quality and learning effectiveness. The relatively high scores in ease of use (80.9%) and presentation format (82.7%) suggest that the interface design successfully reduces extraneous cognitive load, allowing students to allocate more cognitive resources to processing core learning content (Toma et al., 2023; Sweller et al., 2019).

Table 7. Results of the Practicality Analysis of the Learning Media

Assessment Aspect	Score (%)	Category	Interpretation
Content	84.2%	Very Practical	Content is appropriate and supports learning objectives well
Accuracy	83.4%	Very Practical	Information is accurate and reliable with no major revisions required
Format	82.7%	Very Practical	Presentation format is clear and systematically organized
Usefulness	81.6%	Very Practical	Media is useful and supports learning activities effectively
Ease of Use	80.9%	Very Practical	Media is easy to use and user-friendly
Timeliness	80.5%	Very Practical	Media is appropriate for use within the allocated learning time
User Satisfaction	80.6%	Very Practical	Users show a high level of satisfaction in using the media
Overall Average Score	81.9%	Very Practical	Media is feasible to use and does not require revision

In addition, the usefulness score (81.6%) reflects students' perception that the media meaningfully supports their learning activities, which aligns with the Technology Acceptance Model, where perceived usefulness is a key determinant of user engagement (Limbu & Pham, 2023). The integration of interactive simulations and inquiry-based tasks likely enhances this perception by enabling experiential and active learning (Ouyang et al., 2025). When interpreted alongside feasibility results, an important pattern emerges in which well-structured content supports usability, and usability in turn enhances engagement, ultimately contributing to learning effectiveness. This cross-analysis indicates that effectiveness is not solely determined by content quality but by the interaction between pedagogical design, usability, and cognitive engagement (Antonio, 2023; Song et al., 2025). However, the slightly lower practicality scores compared to feasibility suggest that high technical validity does not automatically translate into optimal user experience, highlighting an area for further refinement.

Readability of Interactive E-Worksheet with 3D Virtual Laboratory Integration by Students

The readability of the developed learning media was evaluated to ensure that the content can be clearly understood and effectively accessed by students during the learning process. Readability plays an important role in digital instructional media because it influences learners' comprehension, engagement, and overall learning experience. Well-structured and clearly presented digital materials support students in processing and retaining information during self-directed learning activities (Lim et al., 2024; Cho et al., 2023). The readability assessment covered several aspects, including comprehensibility, ease of reading, language and style, visual readability, organization and structure, interactivity and responsiveness, and user satisfaction. The results are presented in Table 8.

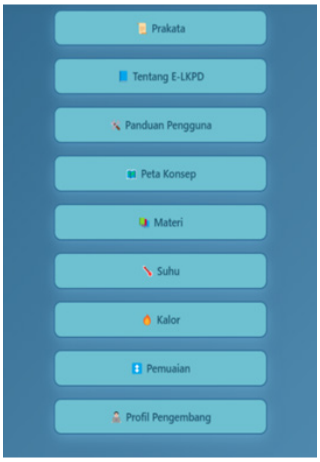
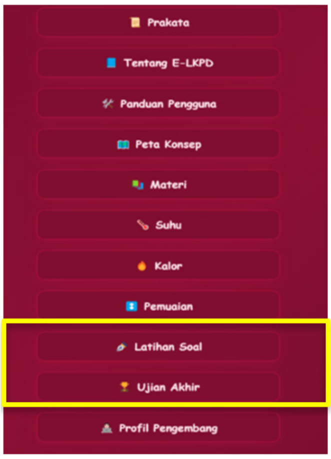
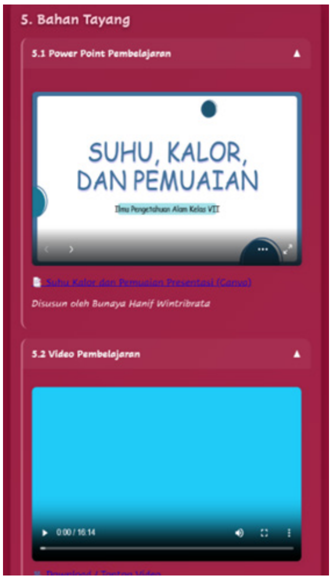
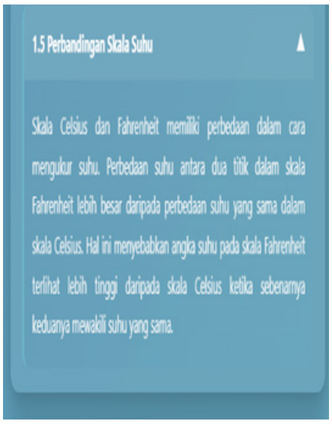
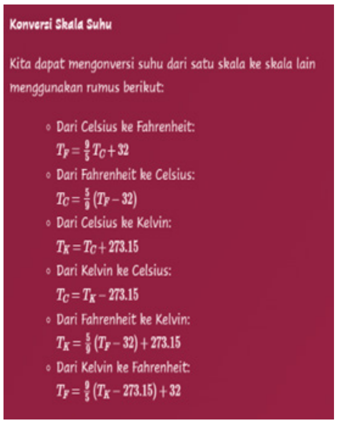
The readability results, with an overall score of 94.33% in the Very Good category, reinforce the accessibility and pedagogical quality of the developed media. High scores in comprehensibility, organization, and interactivity indicate that the material is presented in a clear, structured, and engaging manner, which supports students' ability to process and retain information effectively (Lim et al., 2024; Cho et al., 2023). From a theoretical standpoint, readability functions not only as a measure of clarity but also as a mechanism that reduces cognitive barriers during learning. Well-organized content and clear language facilitate guided cognitive processing, enabling students to focus on higher-order thinking tasks rather than struggling with understanding instructions or representations (Mayer, 2021). Furthermore, readability appears to act as a mediating variable between usability and learning outcomes, as clear and structured presentation reduces cognitive load and enhances engagement, which in turn supports improved learning performance (Kefalis et al., 2025; Lin et al., 2024). Visual elements such as animations and simulations also contribute to conceptual understanding, particularly for abstract scientific phenomena (Kefalis et al., 2025; Banda & Nzabahimana, 2021). Thus, the effectiveness of the interactive E-Worksheet cannot be attributed solely to virtual simulations but also to how information is structured and communicated to learners (Alam, 2023; Kiegaldie & Shaw, 2023).

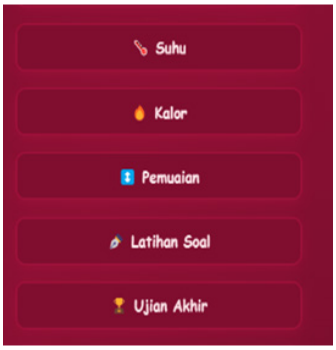
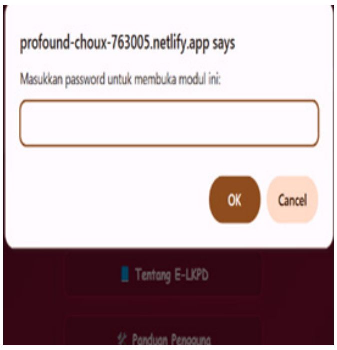
Table 8. Results of the Readability Analysis of the Learning Media

Assessment Aspect	Score (%)	Category	Interpretation
Comprehensibility	94.4%	Very Good	The content is easy to understand and clearly conveys learning messages
Ease of Reading	92.3%	Very Good	Text is easy to read and supports smooth learning activities
Language and Style	93.1%	Very Good	Language use is appropriate, clear, and consistent
Visual Readability	93.6%	Very Good	Visual elements enhance readability learning engagement
Organization and Structure	96.6%	Very Good	Content is well-organized and systematically structured
Interactivity and Responsiveness	97.0%	Very Good	Media shows high interactivity and responds well to user input
User Satisfaction	93.3%	Very Good	Users are highly satisfied with the readability of the media
Overall Average Readability Score	94.33%	Very Good	The learning media demonstrates excellent readability and requires no revision

Table 9. 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>1</td><td>The font type should be replaced with a more appealing option, and the background color should be adjusted to ensure better contrast with the text.</td><td>
</td><td>
</td></tr>
<tr><td></td><td></td><td colspan="2">Improvement Effort: A modern and readable font was selected, and the background color was changed to a contrasting tone to enhance overall visual clarity and aesthetics.</td></tr>
<tr><td>2</td><td>The “Student Identity” menu layout needs refinement by including the E-Worksheet logo and organizing the text neatly.</td><td>
</td><td>
</td></tr>
<tr><td></td><td></td><td colspan="2">Improvement Effort: The Student Identity section was redesigned to include the E-Worksheet logo and improved text alignment for a cleaner, more professional interface.</td></tr>
<tr><td>3</td><td>The QR Code linking to the 3D Virtual Laboratory should be enlarged for better visibility.</td><td>
</td><td>
</td></tr>
<tr><td></td><td></td><td colspan="2">Improvement Effort: The QR Code size was increased to ensure clearer scanning and easier access to the virtual laboratory.</td></tr>
</table>

<table>
<tr><th>No.</th><th>Suggestion</th><th>Before Revision</th><th>After Revision</th></tr>
<tr><td>4</td><td>Additional features such as "Practice Questions" and "Final Exam" should be included.</td><td>
</td><td>
</td></tr>
<tr><td></td><td></td><td colspan="2">Improvement Effort: New interactive menus titled "Practice Questions" and "Final Exam" were added to support assessment and skill mastery.</td></tr>
<tr><td>5</td><td>A learning video should be added to the "Material" section under the Presentation submenu.</td><td>
</td><td>
</td></tr>
<tr><td></td><td></td><td colspan="2">Improvement Effort: A concise instructional video was embedded within Material section to enrich multimedia learning.</td></tr>
<tr><td>6</td><td>Important formulas should be added to the material to aid conceptual understanding.</td><td>
</td><td>
</td></tr>
<tr><td></td><td></td><td colspan="2">Improvement Effort: Key formulas were inserted into lesson content, accompanied by brief explanations to reinforce students' comprehension.</td></tr>
</table>

<table>
<tr><th>No.</th><th>Suggestion</th><th>Before Revision</th><th>After Revision</th></tr>
<tr><td>7</td><td>A password feature should be added to menus (“Temperature”, “Heat”, “Expansion”, “Practice Questions”, “Final Exam”) so students can only access them when permitted by the teacher.</td><td>
</td><td>
</td></tr>
<tr><td></td><td></td><td colspan="2">Improvement Effort: A password-locked access system was implemented, ensuring each menu becomes available only when activated by the instructor.</td></tr>
<tr><td>8</td><td>A download-certificate feature should be added based on mastery level (>75), requiring students with lower scores to repeat the activity.</td><td>
</td><td>
</td></tr>
<tr><td></td><td></td><td colspan="2">Improvement Effort: A performance-based download system was added; certificates become available only for scores above 75, while students scoring below must redo activities before progressing.</td></tr>
</table>

Interactive E-Worksheet with 3D Virtual Laboratory Integration Characteristics

The characteristics of the E-Worksheet were evaluated across six aspects: accessibility, multimedia integration, design interactivity, automatic evaluation, computational thinking support, and virtual laboratory integration. Overall, the results indicate that the E-Worksheet demonstrates high accessibility, interactive design, and strong integration of multimedia and virtual simulation features, supporting flexible and engaging learning experiences.

Assessment Results of Media Characteristics by Experts

Table 10. Assessment Results of Media Characteristics by Experts for Interactive E-Worksheet with 3D Virtual Laboratory Integration

Media Characteristics	Score
E-Worksheet, accessible on laptop/smartphone	100%
Equipped with video, sound, images, QR code, animations	100%
Interactive and practical design	95%
Automatic evaluation after completing the exercises	100%
Supports computational thinking	95%
Integrated with 3D virtual lab for simulation	95%

The results presented in Table 10 confirm that all assessed aspects achieved high scores (95%–100%), indicating strong performance across key characteristics. The high accessibility score reflects the ability of the E-Worksheet to support flexible learning across devices (Prahani et al., 2022; Rahmat et al., 2023). The integration of multimedia elements enhances conceptual visualization and student engagement (Tsoukala et al., 2024; Anggraeni et al., 2022), while the interactive and user-friendly design helps reduce cognitive barriers during learning (Shatri & Shala, 2022; Rizal et al., 2024). The automatic evaluation feature provides immediate feedback, which is essential for improving learning performance (Andriamiseza et al., 2023; Atwa et al., 2024). Furthermore, the support for computational thinking and the integration of a 3D virtual laboratory enable students to engage in interactive simulations and inquiry-based problem solving, contributing to deeper conceptual understanding (Kiegaldie & Shaw, 2023; Gebreheat et al., 2022; Reyes et al., 2024). Overall, these findings indicate that the E-Worksheet offers a comprehensive and effective digital learning environment.

Results of the Normality Test

The normality test was conducted to examine whether the pretest and posttest scores of both control and experimental groups met the assumptions required for parametric analysis. In this study, the Kolmogorov–Smirnov test was applied due to the sample size, which is more appropriate for larger datasets (Nahm, 2022; Uyanto, 2022). The results are presented in Table 11.

Table 11. Normality Test Results of Pretest and Posttest Data

Class	Test	Kolmogorov–Smirnov Statistic	df	Sig.	Shapiro–Wilk Statistic	df	Sig.
Control Class	Pretest	0.151	31	0.069	0.957	31	0.236
Control Class	Posttest	0.153	31	0.062	0.942	31	0.095
Experiment Class	Pretest	0.152	32	0.060	0.953	32	0.180
Experiment Class	Posttest	0.142	32	0.099	0.927	32	0.033

As shown in Table 11, all Kolmogorov–Smirnov significance values exceed 0.05, indicating that data are normally distributed. This result confirms that the dataset meets the assumptions required for parametric statistical testing, allowing further analysis such as independent samples t-test to be conducted reliably. The normal distribution of both pretest and posttest scores also suggests that there is no substantial deviation or extreme bias in data, supporting the validity of comparisons between the control and experimental groups (Mishra et al., 2021; Ozdemir, 2021).

Results of the Homogeneity Test

The homogeneity test was conducted to determine whether variance structures of control and experimental groups were equivalent prior to hypothesis testing. In this study, Box's M test was applied to assess the equality of covariance matrices, which is a key assumption for conducting parametric analysis (Hahs-Vaughn & Lomax, 2020). The results are presented in Table 12.

As shown in Table 12, the significance value of Box's M (0.945) is greater than 0.05, indicating that the covariance matrices between groups are homogeneous. This result confirms that the variance structures of the control and experimental groups are comparable, ensuring that subsequent statistical analyses can be conducted without bias due to unequal variance (Ojeda, 2024). Therefore, the homogeneity assumption is satisfied, supporting the validity of further hypothesis testing.

Table 12. Box's M Test Results for Equality of Covariance Matrices

Statistic	Value
Box's M	0.382
Approx. F	0.126
df1	3
df2	26.775.842
Sig.	0.945

Results of the Independent Samples t-Test

The independent samples t-test was conducted to examine differences in learning outcomes between the experimental and control groups. Prior to analysis, Levene's test was used to assess the equality of variances to ensure the appropriateness of the parametric test (Uyanto, 2022). The results are presented in Table 13.

Table 13. Results of the Independent Samples t-Test

Varians	Levene's Test (F)	Sig.	T	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% CI Lower	95% CI Upper
Equal variances assumed	0.106	0.745	-3.436	61	0.001	-16.623	4.838	-26.297	-6.949
Equal variances not assumed			-3.431	60.084	0.001	-16.623	4.845	-26.314	-6.932

As shown in Table 13, the significance value of Levene's test (0.745) exceeds 0.05, indicating that the assumption of equal variances is satisfied. The t-test results reveal a significant difference between the experimental and control groups (p = 0.001), suggesting that the implemented intervention had a meaningful impact on student learning outcomes. The negative mean difference indicates that the experimental group outperformed the control group, reflecting the effectiveness of the interactive E-Worksheet integrated with a 3D virtual laboratory. This result implies that the combination of interactive simulations and computational thinking tasks supports deeper understanding and problem-solving processes rather than surface-level learning. These findings are consistent with previous studies demonstrating that technology-integrated and virtual laboratory-based learning environments can enhance student achievement compared to conventional instruction (Banda & Nzabahimana, 2023; Al-Nakhle, 2022), as well as meta-analytic evidence highlighting their effectiveness across STEM contexts (Wang et al., 2024).

Results of the N-Gain Test

The N-Gain test was used to evaluate effectiveness of learning media by measuring improvement in students' learning outcomes from pretest to posttest. This analysis provides an indication of how far intervention contributes to learning gains. The results are presented in Table 14.

Table 14. Descriptive Statistics of N-Gain Test Results

Variabel	N	Minimum	Maximum	Mean	Std. Deviation
N-Gain Score	32	0.17	1.00	0.6635	0.23572
N-Gain Persen (%)	32	16.67	100.00	66.3517	23.57205
Valid N (listwise)	32				

As shown in Table 14, the mean N-Gain score of 0.6635 falls within the moderate category, indicating a meaningful improvement in students' learning outcomes. Although not reaching a high category, this result suggests that the intervention effectively supports learning progression, particularly in developing computational thinking skills. The moderate gain implies that the impact of the media is substantial but still influenced by factors such as learning duration, prior knowledge, and the level of instructional support. This finding indicates that technology-enhanced learning does not produce instant maximal outcomes but facilitates gradual cognitive development through repeated engagement and problem-solving processes. Similar patterns have been reported in studies on virtual laboratory-based learning, which typically yield moderate yet significant improvements in conceptual understanding (Banda & Nzabahimana, 2023; Al-Nakhle, 2022).

The evaluation stage further confirms the overall quality of the developed media. Through the ADDIE framework, evaluation was conducted both formatively and summatively to ensure continuous refinement of the product (Spatioti & Kazanidis, 2022; Senadheera et al., 2024). Feedback from experts and users indicates that the E-Worksheet demonstrates strong feasibility, practicality, readability, and instructional effectiveness. This multi-source evaluation strengthens the validity of the findings, as it integrates both empirical data and user experience perspectives (Timotheou et al., 2023; Deriba, 2024). Overall, the results indicate that the interactive E-Worksheet integrated with a 3D virtual laboratory provides a meaningful and effective learning environment that supports computational thinking and inquiry-based learning (Wang et al., 2024; Wörner et al., 2022).

Critical Insights and Cross-Findings Analysis

Despite the overall positive findings, several critical insights emerge from the analysis. The gap between feasibility and practicality scores suggests that expert validation may not fully reflect actual user experience, emphasizing the importance of incorporating user-centered evaluation in future development. In addition, the moderate level of learning gain, despite high readability and usability, indicates that clarity and accessibility alone are insufficient to guarantee high-level cognitive outcomes without sustained practice and deeper instructional support. This indicates that high design quality alone is insufficient without sustained pedagogical support and repeated learning exposure. These findings highlight that the effectiveness of digital learning media is multifactorial, involving the interaction between content quality, usability, readability, and pedagogical implementation (Hattie, 2023). Therefore, effectiveness should be understood as an emergent result of multiple interconnected factors rather than a direct outcome of a single variable.

This study has several limitations that should be considered when interpreting the findings. First, the duration of the intervention was relatively short, which may limit the development of higher-order thinking skills such as computational thinking. Second, the study was conducted within a single school context, which may restrict the generalizability of the findings. Third, the reliance on quantitative data limits the ability to capture in-depth cognitive processes experienced by students during learning. Additionally, the uniformly high expert validation scores may indicate limited variability in evaluation, suggesting the need for more diverse assessment perspectives (Timotheou et al., 2023; Deriba, 2024). Future research is therefore recommended to employ longitudinal designs, larger samples, and mixed-method approaches to provide a more comprehensive understanding of the mechanisms underlying the effectiveness of digital learning media.

Overall, the findings demonstrate that the effectiveness of the interactive E-Worksheet integrated with a 3D virtual laboratory is not determined by a single factor but by the interaction between feasibility, practicality, and readability. These elements collectively support cognitive processes that lead to improved learning outcomes, highlighting the importance of integrating pedagogical design, usability, and content clarity in the development of digital learning media (Wörner et al., 2022; Wang et al., 2024).

CONCLUSION

This study demonstrates that the effectiveness of the native-coded interactive electronic worksheet integrated with a three-dimensional virtual laboratory is determined by the alignment of feasibility, practicality, and readability with learning processes that support students' computational thinking in thermal physics. The findings indicate that the observed moderate improvement and significant group differences reflect not merely the use of technology, but the role of structured interactivity, virtual experimentation, and guided tasks in facilitating decomposition, abstraction, and algorithmic reasoning. Theoretically, this study contributes to physics education by conceptualizing computational thinking as an embedded cognitive process developed through the integration of interactive media and virtual laboratory environments. Practically, the developed media provides a feasible and effective alternative to support active and flexible learning, particularly in contexts with limited access to physical laboratories. However, this study is limited by its small sample size, restricted scope to thermal concepts, and dependence on technology, which may limit generalizability. Future research should examine its application across broader physics topics, involve larger and more diverse samples, and investigate long-term impacts using longitudinal and mixed-method approaches. In conclusion, the integration of native-coded interactivity and virtual laboratories offers a coherent approach to embedding computational thinking in physics learning, with implications for advancing higher-order thinking skills in digital education contexts.

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