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An Experimental Trial of an Infrared Sensor-Based Simple Pendulum Apparatus to Foster Senior High School Students' Critical Thinking Skills on Simple Harmonic Motion

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Abstract
Critical thinking is a fundamental 21st-century skill, yet its development in physics education remains challenging, especially in abstract topics such as Simple Harmonic Motion (SHM). Traditional pendulum experiments often rely on manual procedures, limiting students' engagement in higher-order thinking. Objective: This study investigates the effectiveness of a low-cost infrared sensor-based simple pendulum apparatus in fostering senior high school students' critical thinking skills on SHM. Methods: A pre-experimental one-group pretest–posttest design was implemented involving 97 eleventh-grade science students. The intervention consisted of guided-inquiry learning sessions using the custom-built apparatus integrating an infrared sensor and an Arduino microcontroller. Critical thinking skills were measured using a validated Likert-scale questionnaire encompassing four dimensions: Conceptual Understanding, Data Analysis & Interpretation, Reflection & Evaluation, and Collaboration & Interest. Descriptive statistics and normalized gain values were employed to assess improvement. Results: Findings revealed consistent improvement across all dimensions, with the highest gains observed in Collaboration & Interest (+2.07) and Conceptual Understanding (+2.01), followed by Data Analysis & Interpretation (+2.00) and Reflection & Evaluation (+1.79). Conclusion: The integration of the infrared sensor-based pendulum apparatus effectively enhanced students' critical thinking skills. Automating data collection reduced cognitive load associated with procedural tasks, enabling students to focus on analysis, evaluation, and collaborative inquiry. This study concludes that the apparatus is a viable pedagogical innovation capable of transforming traditional physics laboratories into inquiry-oriented learning environments that support the development of essential higher-order thinking skills.

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INTRODUCTION

Laboratory activities are an essential component of physics learning, particularly for topics that involve reasoning about relationships among physical variables, such as Simple Harmonic Motion (SHM). In simple pendulum experiments, students are expected not only to apply formulas but also to analyze experimental data, interpret graphical relationships, evaluate discrepancies between theory and observation, and draw justified conclusions. These cognitive demands place **Critical Thinking Skills (CTS)**—defined as reasonable and reflective thinking focused on deciding what to believe or do (Ennis, 2004)—at the core of meaningful physics laboratory learning. Numerous studies have shown that inquiry-oriented physics laboratory activities play a crucial role in developing students' CTS, particularly when learners are required to reason with experimental data rather than merely apply formulas (Putra & Sugiyanto, 2020; Zhang & Li, 2023).

However, pendulum practicums in many senior high schools still rely on manual stopwatches and verification-oriented procedures. Manual measurement of oscillation periods often produces inconsistent and inaccurate data due to human reaction-time error, especially when the oscillation period is short (Setya et al., 2021; Sukmak & Musik, 2021). As a result, students frequently obtain data that do not clearly reflect the theoretical relationships being investigated, and under such conditions they tend to focus on completing procedures or manipulating calculations to match expected results rather than engaging in reflective reasoning about the quality and meaning of their data.

This situation has important implications for the development of CTS because when experimental data are unreliable, opportunities for students to critically examine evidence become limited. Instead of analyzing patterns, evaluating sources of error, or making inferences based on empirical results, students are more likely to treat laboratory work as a routine task. Consequently, key CTS processes—such as interpreting evidence, evaluating the credibility of results, and justifying conclusions—are insufficiently supported during traditional pendulum experiments (Distrik et al., 2024). In this study, CTS are operationalized using **Ennis's framework**, which emphasizes students' abilities to analyze data, interpret representations such as tables and graphs, evaluate the reliability and validity of evidence, make inferences from observations, and provide conclusions that are logically justified by data (Ennis, 2004).

Advances in educational technology offer opportunities to redesign pendulum experiments in ways that better support these CTS dimensions. Sensor-assisted laboratory tools based on Arduino microcontrollers and infrared sensors enable automatic, precise, and continuous measurement of oscillation periods, thereby reducing human error and procedural burden (Sukmak & Musik, 2021; Setya et al., 2021; Saputri et al., 2025). Importantly, the pedagogical value of such tools lies not merely in their technical accuracy but in how they reshape students' cognitive engagement. Reliable and consistent data allow students to focus on analyzing trends, interpreting graphs, evaluating discrepancies between experimental results and theoretical predictions, and constructing evidence-based explanations—activities that align closely with Ennis's CTS indicators. Previous studies suggest that sensor-based laboratory environments can support scientific reasoning by providing structured and interpretable data, although their cognitive impact depends strongly on instructional design and learner characteristics (Chen et al., 2024; Altmeyer et al., 2024).

Several studies have reported the development of pendulum experiment tools using infrared and optical sensors to improve measurement accuracy and efficiency in physics laboratories (Riza & Anderegg, 2019; Novitasari et al., 2018; Bachtiar & Ermawati, 2025). More recent developments have integrated Arduino-based systems with real-time data acquisition and visualization to support pendulum experiments (Chiriacescu et al., 2020; Fauzi et al., 2024). However, most of these studies primarily emphasize technical performance and instrumentation aspects—such as precision, automation, and real-time display—while giving limited attention to how such tools are pedagogically integrated to support students' reasoning processes. In many cases, sensor-based pendulum experiments are still implemented in verification-oriented laboratory activities that focus on confirming theoretical formulas rather than engaging students in critical examination of experimental evidence (Novitasari et al., 2018; Dewi et al., 2022).

Previous research has reported that Arduino-based and sensor-assisted pendulum experiments improve measurement accuracy and support data analysis and graph interpretation (Sukmak & Musik, 2021; Setya et al., 2021). Other technology-enhanced approaches, such as smartphone-sensor experiments and electronic student worksheets (e-LKPD), have also been shown to facilitate students' reasoning with data in SHM contexts (Ariyansah et al., 2021; Distrik et al., 2024; Raharja et al., 2025). Nevertheless, most existing studies focus on technical performance or general learning outcomes, while empirical investigations that explicitly examine how **low-cost infrared sensor-based pendulum apparatuses** foster students' CTS—particularly the Ennis-aligned indicators of **analysis, interpretation, evaluation, inference, and justification**—remain limited at the senior high school level.

To address this gap, the present study conducts an experimental trial of a low-cost infrared sensor-based simple pendulum apparatus controlled by an Arduino microcontroller for SHM learning in senior high school. The apparatus is designed to automatically measure oscillation periods with high precision, providing students with reliable data as a foundation for inquiry-based investigation. Within this learning framework, students are guided to formulate investigable questions, analyze and interpret experimental data, evaluate the credibility of results, and draw justified conclusions. Accordingly, this study examines the extent to which the use of an infrared sensor-based simple pendulum apparatus enhances students' **Critical Thinking Skills** in SHM learning and identifies which CTS indicators—**analysis, interpretation, evaluation, inference, and justification**—are most strongly developed through sensor-assisted, inquiry-oriented pendulum experiments.

METHOD

Research Design

This study employed a **pre-experimental one-group pretest–posttest design** to conduct an initial empirical evaluation of a newly developed instructional intervention, namely an **infrared sensor-based simple pendulum apparatus integrated into guided inquiry learning**. This design was selected to examine the **preliminary effectiveness and feasibility** of the intervention in an authentic classroom context prior to large-scale implementation. In educational research, the one-group pretest–posttest design is commonly used in early-stage trials of instructional innovations when random assignment or the use of a comparison group is not feasible due to structural constraints in school settings (Shadish et al., 2002; Creswell & Creswell, 2018).

The research design is represented as **O_1 X O_2**, where O_1 denotes the pretest measurement of students' Critical Thinking Skills (CTS), X represents the instructional treatment, and O_2 denotes the posttest measurement. To reduce common threats to internal validity in pre-experimental studies, the intervention was conducted within a relatively short timeframe, implemented using standardized instructional procedures, and monitored through treatment fidelity checks.

Research Subjects

The participants were **97 eleventh-grade science-track (MIPA) students** from SMA Negeri 7 Bandar Lampung during the 2025/2026 academic year. Participants were selected using **purposive sampling** based on the following criteria: (1) students had completed basic mechanics topics but had not yet received formal instruction on Simple Harmonic Motion (SHM); (2) classes had access to laboratory facilities and supporting technology; and (3) the school supported technology-integrated learning. All participants were assigned to a single experimental group. Ethical considerations were addressed through informed consent, voluntary participation, and confidentiality of student data.

The Treatment: Learning Product, Guided Inquiry Protocol, and Data Collection Procedure

Learning Product

The instructional intervention utilized a **custom-developed infrared (IR) sensor-based simple pendulum apparatus**. An IR break-beam sensor was positioned at the equilibrium point of the pendulum to detect each pass of the bob and transmit signals to an **Arduino Uno microcontroller**. The use of Arduino-based experimental tools has been increasingly adopted to support hands-on learning activities in physics and electronics education, demonstrating their practicality and suitability for classroom laboratory settings (Riskawati et al., 2025). Similar infrared-sensor pendulum systems have been implemented using alternative microcontroller platforms such as NodeMCU ESP8266 (Yani Rizka Andri et al., 2022). In the present study, Arduino Uno was selected due to its stability, ease of programming, and suitability for classroom laboratory settings.

After a specified number of detections, the Arduino application displayed oscillation waveform graphs and numerical frequency values on a laptop screen.

Pedagogically, the apparatus was designed to reduce human reaction-time error and procedural burden, enabling students to work with more reliable experimental data as a basis for analysis, evaluation, and evidence-based reasoning.

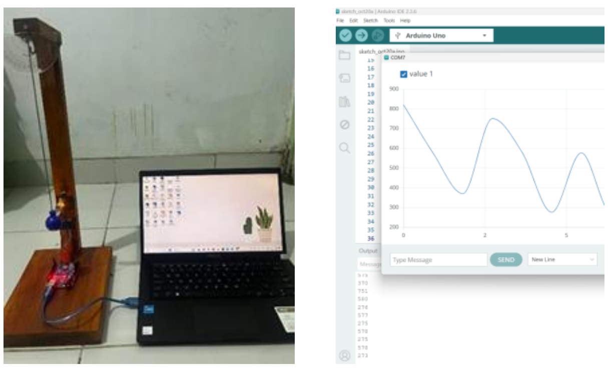

Figure 1. The Infrared Sensor-Based Pendulum Apparatus and Example Data Output

Guided Inquiry Learning Protocol

The intervention was implemented over **two guided inquiry sessions (2 × 90 minutes)** using **structured student worksheets (LKS)**. All student groups received **identical treatment**, including the same experimental procedures, worksheets, guiding questions, and teacher scaffolding.

- **Session 1: Orientation and Hypothesis Development (90 minutes)** Students were introduced to a contextual problem related to pendulum precision (e.g., designing an accurate pendulum-based timekeeping device). Guided questions prompted students to identify variables, formulate investigable questions, and propose hypotheses. The teacher demonstrated the IR-based apparatus and discussed the limitations of manual stopwatch measurements.
- **Session 2: Investigation, Analysis, and Reflection (90 minutes)** Students conducted experiments, analyzed measurement results, and completed reflection and evaluation prompts in the worksheets. These prompts required students to assess data consistency, identify sources of error, compare experimental results with theoretical predictions, and construct conclusions using a **claim–evidence–reasoning (CER)** framework.

Experimental Conditions and Measurement Procedures

The pendulum experiment involved **two variations of string length** and **two initial angular displacements**, resulting in four experimental conditions:

- **String length (L):** 20 cm and 30 cm
- **Initial angle (θ):** 15° and 30°

For **manual measurement**, students recorded the total time required for **10 complete oscillations** using a stopwatch and calculated the period using:

$$T = \frac{t_{10}}{10}$$

For **sensor-based measurement**, the experiment was repeated using the IR sensor system. After **10 pendulum passes** were detected, the Arduino application displayed waveform graphs and frequency values. Students calculated the **average frequency** and determined the period using:

$$f_{avg} = \frac{\sum f_i}{n}, \quad T = \frac{1}{f_{avg}}$$

All data were recorded in analysis tables provided in the worksheets, including string length, initial angle, time for 10 oscillations (stopwatch), period, average frequency (sensor), and measurement method.

Treatment Fidelity

Treatment fidelity was ensured through standardized lesson plans, identical worksheets, consistent time allocation, and uniform teacher guidance. An independent observer used a structured checklist to monitor adherence to the protocol, including variable settings, number of oscillations or detections, completion of analysis and reflection tasks, and correct use of the apparatus. The treatment was considered to have adequate fidelity when at least **80% of the planned instructional components** were implemented as intended.

Research Instruments, Variables, and Indicators

1. Critical Thinking Questionnaire (Primary Instrument)

Students' Critical Thinking Skills (CTS) were assessed using a 15-item Likert-scale questionnaire (1 = Strongly Disagree to 5 = Strongly Agree) administered via Google Forms after the completion of the learning intervention. The instrument was developed based on Ennis's (2004) critical thinking framework. Content validity was established through expert judgment by three specialists in physics education and educational measurement, yielding an Aiken's V index of 0.87. Instrument reliability was confirmed through a pilot test involving 30 students, resulting in a Cronbach's Alpha coefficient of 0.89, indicating high internal consistency.

Only items representing the core dimensions of Critical Thinking Skills were included in the CTS score, while items related to engagement and learning interest were analyzed descriptively as supporting data.

2.Variable Operationalization

The dependent variable—Critical Thinking Skills—was operationalized into four dimensions as detailed in Table 1.

Table 1. Operationalization of Critical Thinking Skills

Dimension	Operational Indicator	Sample Questionnaire Item
Analysis	Identifying variables and experimental goals	*"I can identify which variables affect the pendulum's period based on the experiment."*
Interpretation	Interpreting tables and graphs	*"I can interpret the graph of T versus √L to explain the relationship between variables."*
Evaluation (Reflection)	Evaluating data reliability and procedures	*"I evaluated possible sources of error and their effect on the results."*
Inference	Drawing conclusions from experimental data	*"I can draw conclusions about SHM based on the collected data."*
Justification	Providing evidence-based explanations	*"I can justify my conclusions using experimental data."*

3. Observation Sheet (Secondary Instrument)

An observation sheet was used to document qualitative aspects of student engagement, collaboration, and inquiry behaviors during the learning sessions. These data served as supporting evidence for interpreting the quantitative results.

Data Analysis Technique

Data analysis was conducted in four stages. First, descriptive statistics (mean and standard deviation) were calculated for pretest and posttest CTS scores. Second, a **paired samples t-test** was used to determine the statistical significance of pre–post differences ($p < 0.05$). Third, learning improvement was quantified using the **Normalized Gain (N-gain)**. Fourth, **effect size was calculated using Cohen's d for paired samples** to estimate the magnitude of the intervention's impact.

Research Achievement Indicators

Considering CTS as a multidimensional construct, the intervention was regarded as effective only when it met all of the following criteria: (1) a statistically significant pre–post improvement in CTS scores ($p < 0.05$), (2) an overall N-gain and dimensional N-gain of at least 0.30 (medium category), (3) a paired-samples Cohen's d of

≥ 0.50 (medium effect or higher), (4) improvement across multiple CTS dimensions rather than being confined to a single aspect, and (5) adequate treatment fidelity of at least 80% to ensure the intervention was implemented as planned.

RESULTS AND DISCUSSION

Results

During the learning intervention, students conducted Simple Harmonic Motion (SHM) experiments using an **infrared sensor-based pendulum apparatus integrated with an Arduino microcontroller**. The apparatus automatically recorded oscillation data and displayed waveform visualizations in real time, allowing students to work with continuous and consistent datasets during experimental activities. Students operated the apparatus in small groups, recorded measurement outputs, and analyzed the displayed data using the provided worksheets.

Figure 1. Implementation of the infrared sensor-based pendulum apparatus during guided inquiry learning on SHM.

Figure 1 presents the classroom implementation of the experimental setup, showing students conducting the pendulum experiment using the infrared sensor-based apparatus. The infrared sensor detected periodic pendulum motion and transmitted signals to the Arduino interface. The recorded signals were visualized on a laptop screen as a periodic waveform (**Figure 2**), which served as a representation for students to examine regularity in oscillatory motion and to support subsequent data analysis and reasoning tasks.

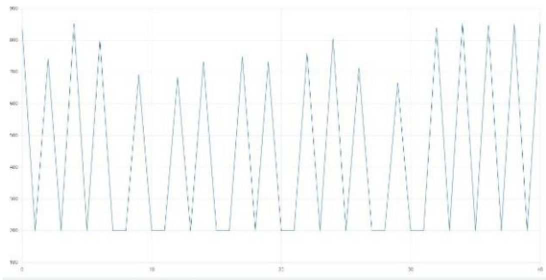

Figure 2. shows an example of the waveform output generated by the Arduino interface from infrared sensor detections of pendulum motion.

The waveform visualization provided students with a continuous representation of oscillatory motion, which served as a basis for identifying periodicity and supporting subsequent data analysis activities.

The relationship between pendulum length and oscillation period follows the standard theoretical model for a simple pendulum. Students used this relationship as a reference framework to compare experimental measurements with theoretical expectations. The sensor-based apparatus produced data that were sufficiently consistent with the expected trend, allowing the experimental results to be used as a valid basis for analysis and reasoning tasks rather than as a metrological validation of the instrument.

Students' Critical Thinking Skills (CTS) were assessed using a Likert-scale questionnaire. Mean pretest and posttest scores for each measured dimension are presented in Table 2. Descriptive analysis indicated increases in mean scores across all dimensions following the intervention.

Table 2. Comparison of Critical Thinking Dimensions in Pretest and Posttest

Dimension	Pretest Mean (SD)	Posttest Mean (SD)	Mean Difference	N-Gain	Effectiveness Category
Conceptual Understanding	2.24 (0.51)	4.24 (0.43)	+2.00	0.65	Medium
Data Analysis & Interpretation	2.54 (0.49)	4.53 (0.38)	+1.99	0.81	High
Reflection & Evaluation	2.49 (0.53)	4.28 (0.46)	+1.79	0.71	High
Collaboration & Interest	2.58 (0.48)	4.65 (0.34)	+2.07	0.85	High
OVERALL	**2.46 (0.39)**	**4.43 (0.30)**	**+1.97**	**0.78**	**High**

Normalized Gain (N-gain) analysis showed high gains in dimensions closely related to data-based reasoning, particularly Data Analysis & Interpretation (N-gain = 0.81) and Reflection & Evaluation (N-gain = 0.71). Conceptual Understanding showed a moderate gain (N-gain = 0.65). The Collaboration & Interest dimension exhibited the highest N-gain value (0.85); however, consistent with the research design, this dimension was treated as a supporting affective outcome rather than a core component of CTS.

A paired-samples t-test confirmed that the overall improvement in CTS scores was statistically significant *(t(96) = [value], p < .001)*.

Figure 3 illustrates the comparison of mean pretest and posttest scores across the measured dimensions. An increase in mean scores is observed for all dimensions, indicating consistent improvement following the intervention.

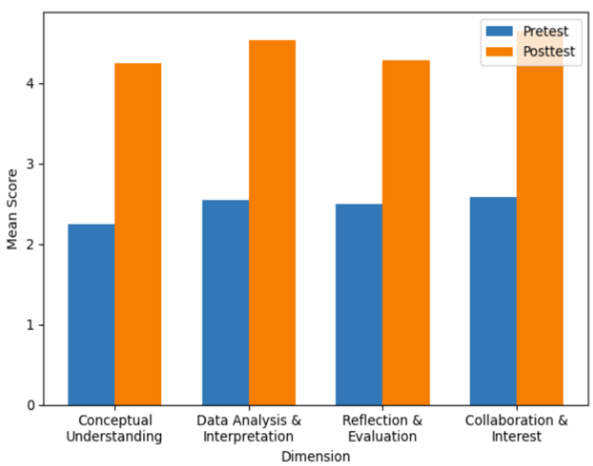

Figure 3. Shows an increase in mean scores from pretest to posttest across all dimensions.

Discussion

Development of Core Critical Thinking Skills

The results indicate that the infrared sensor-based pendulum apparatus, when integrated into a guided inquiry learning framework, supported the development of students' core Critical Thinking Skills. The strongest gains were observed in **analysis and interpretation**, suggesting that access to consistent and readable experimental data enabled students to more effectively identify patterns, examine functional relationships between variables, and interpret graphical representations. This finding is consistent with previous studies reporting that inquiry-oriented and technology-enhanced physics learning environments can foster students' critical thinking, particularly when learners actively engage in data-based reasoning (Putra & Sugiyanto, 2020; Lestari et al., 2023; Zhang & Li, 2023)..

The strong improvement in **Data Analysis & Interpretation** aligns with prior research indicating that sensor-based laboratories support scientific reasoning by providing reliable, interpretable, and repeatable datasets (Sukmak & Musik, 2021; Wijaya et al., 2022; Chen et al., 2024). In this study, the automated data acquisition reduced procedural demands related to manual timing and allowed students to focus more on examining data patterns and drawing evidence-based conclusions.

Improvements in **Reflection & Evaluation** further indicate that students engaged in higher-level metacognitive processes, such as assessing measurement reliability and comparing empirical results with theoretical predictions. Importantly, these gains cannot be attributed to the technological tool alone. Rather, they appear to result from the interaction between the sensor-based apparatus and **explicit pedagogical scaffolding**, particularly worksheet prompts that required students to identify sources of error, evaluate data consistency, and justify conclusions using evidence. This finding supports guided inquiry theory, which emphasizes that reflection and evaluation must be intentionally structured rather than assumed to emerge automatically from experimentation (Kuhlthau et al., 2004; Putra & Sugiyanto, 2020). This interpretation is consistent with prior research showing that improvements in students' Critical Thinking Skills depend not merely on the presence of technology, but on instructional designs that explicitly structure reasoning, reflection, and evidence-based justification (Saputra et al., 2023).

The moderate gain in **Conceptual Understanding** suggests that while students increasingly used empirical data to support explanations of SHM phenomena, conceptual change was less pronounced than gains in analytical and evaluative reasoning. This pattern is consistent with previous research indicating that conceptual understanding often develops more gradually and may require repeated exposure across multiple learning contexts (Chen et al., 2021; Zhang & Li, 2023). In this study, conceptual understanding is therefore interpreted as a **supporting cognitive outcome** that reinforces, rather than defines, critical thinking development.

Reconsidering Collaboration and Learning Interest

The highest N-gain was observed in the **Collaboration & Interest** dimension. While this result indicates increased engagement during the learning activities, it should not be interpreted as direct evidence of enhanced Critical Thinking Skills. Collaboration and interest are **affective and social variables** that may facilitate critical thinking but do not, in themselves, constitute it.

Similar increases in student engagement have been reported in previous technology-enhanced physics learning studies, including those using smartphone sensors and digital experiment tools (Imtinan & Kuswanto, 2023; Wijayanti et al., 2022). However, the substantial increase in engagement observed in this study may partially reflect a **novelty or Hawthorne effect**, whereby students respond positively to the introduction of new technology rather than to sustained cognitive demands. Because this study did not include a comparison group or longitudinal follow-up, it is not possible to determine whether the observed gains in interest and collaboration would persist once the novelty of the apparatus diminished. Consequently, these outcomes are more appropriately interpreted as **supporting conditions** that may indirectly contribute to CTS development by increasing participation and motivation, rather than as primary indicators of instructional effectiveness.

Clarifying Claims Related to Cognitive Load

Previous studies frequently argue that sensor-based tools can reduce extraneous cognitive load by automating procedural tasks (Sweller, 1988; Chen et al., 2024; Altmeyer et al., 2024). However, in the present study, cognitive load was not directly measured using established instruments such as NASA-TLX or open-ended workload probes. Therefore, claims regarding cognitive load reduction should be interpreted cautiously.

Rather than asserting cognitive load reduction as an empirical finding, a more defensible interpretation is that the apparatus **restructured the learning activity** by shifting students' attention from manual timing procedures to data interpretation and reasoning tasks. This interpretation is conceptually consistent with cognitive load theory (Sweller, 1988) but does not constitute direct evidence of reduced cognitive load. Future research incorporating explicit cognitive load measures is required to substantiate this mechanism.

Educational Implications

The findings suggest that technology-enhanced physics laboratories can support Critical Thinking Skills when technological affordances are deliberately aligned with pedagogical design. Teachers should avoid equating increased engagement with improved critical thinking and ensure that collaborative activities are accompanied by structured analytical and reflective tasks. Low-cost sensor-based apparatuses, such as the one developed in this study, offer practical opportunities for implementing inquiry-oriented laboratory learning, provided that pedagogical scaffolding remains the primary driver of cognitive engagement.

Limitations and Future Research

This study employed a one-group pretest–posttest design, which limits causal interpretation. Additionally, the absence of direct cognitive load measurement restricts conclusions regarding underlying cognitive mechanisms. Future studies should employ controlled or quasi-experimental designs, incorporate explicit cognitive load instruments, and examine the long-term stability of both cognitive and affective outcomes to distinguish enduring instructional effects from short-term novelty effects.

CONCLUSION

This study demonstrates that the infrared sensor-based simple pendulum apparatus is an effective pedagogical innovation for enhancing senior high school students' critical thinking skills in learning Simple Harmonic Motion (SHM). Integrating the automated measurement tool within a guided-inquiry learning framework resulted in significant improvements across all four dimensions of critical thinking. The highest gains were observed in Collaboration & Interest (N-gain = 0.85) and Data Analysis & Interpretation (N-gain = 0.81), highlighting the dual function of the apparatus as both a catalyst for learner engagement and a cognitive tool that reduces extraneous cognitive load (Sweller, 1988), enabling students to focus on analytical reasoning and evidence-based interpretation. The substantial improvement in Reflection & Evaluation (N-gain = 0.71) further indicates the development of scientific metacognition and students' emerging ability to critically assess experimental procedures and outcomes.

The real-time visualization of oscillation data played a central role in supporting students' analytical and reflective thinking. By observing waveform patterns, validating empirical evidence, identifying inconsistencies, and analyzing sources of measurement error, students developed stronger argumentation skills and a deeper awareness of data reliability. These experiences not only strengthened their conceptual reasoning but also demonstrated the apparatus's value as a pedagogical tool capable of transforming traditional, verification-based physics laboratories into inquiry-oriented learning environments that promote essential 21st-century thinking skills.

Although the improvement in Conceptual Understanding (N-gain = 0.65) was slightly lower than the other dimensions, it remained substantial and meaningful. This outcome suggests that while the apparatus provides a strong empirical foundation for conceptual learning, deeper levels of conceptual mastery may require repeated exposure across multiple instructional contexts. Overall, the findings validate a low-cost, scalable model for modernizing physics laboratory practices by shifting toward technology-supported inquiry approaches that directly foster higher-order cognitive skills.

The main limitation of this study lies in its pre-experimental, one-group design, which restricts causal generalization. Therefore, future research should employ controlled experimental designs to strengthen causal claims, investigate long-term retention of critical thinking skills, and explore the transferability of this approach to other physics topics. Further research examining how specific technological features interact with varying levels of inquiry scaffolding would provide valuable insights into optimizing digital tools for cognitive development.

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