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Enhancing Senior High School Students' Critical Thinking and Graphical Representation Skills through an AR-Integrated Guided Inquiry E-Book in Thermodynamics

B. A. Wicaksono[1*], H. Kuswanto[2]
Department of Physics Education, Faculty of Mathematics and Natural Sciences, Universitas Negeri Yogyakarta
[*]Corresponding Author. Email: bayu228fmipa.2023@student.uny.ac.id

Abstract

This study addresses the persistent challenge of improving students' higher-order thinking skills in physics, particularly critical thinking skills (CTS) and graphical representation abilities (GRA), which remain relatively low in Indonesian high schools. To overcome this issue, a guided inquiry-based e-book integrated with Augmented Reality (AR) was developed and tested within the domain of thermodynamics. The research employed the ADDIE model, encompassing analysis, design, development, implementation, and evaluation stages, to ensure the systematic construction of the product. A quasi-experimental pretest–posttest control group design was applied with three groups: (1) guided inquiry-based e-book assisted by AR, (2) guided inquiry-based e-book without AR, and (3) conventional PowerPoint-based instruction. The product was validated by subject matter experts and practitioners, who confirmed its feasibility across material, media, and design aspects. Student responses indicated that the developed e-book was practical and engaging for classroom use. Effectiveness testing was conducted with 90 students using MANOVA, supported by prerequisite tests for normality, homogeneity, and multicollinearity. The results revealed significant improvements in both CTS and GRA, with the AR-assisted e-book outperforming the other instructional methods and achieving a moderate effect size. These findings highlight the pedagogical potential of integrating AR into guided inquiry-based e-books to foster interactive, student-centered learning environments. Furthermore, the study suggests that such innovations may serve as an effective alternative to traditional physics teaching methods and could be adapted for other physics topics beyond thermodynamics.

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1. INTRODUCTION

Critical thinking skills (CTS) are one of the skills that students need to be able to adapt to technological developments. CTS is one of the essential skills required to navigate the challenges of the Industrial Revolution 4.0 era (Trilling & Fadel, 2009; Wardani et al., 2017). Individuals who possess strong CTS tend to be more adaptive to rapid technological advancements (Maskur et al., 2020) and are better equipped to make informed decisions in everyday life (Susilawati et al., 2015). This skill is also recognized as a core component of 21st-century learning competencies, alongside problem-solving, communication, and collaboration abilities (González & Ramírez, 2022). Keterampilan berpikir kritis menjadi salah satu hal yang penting bagi peserta didik untuk menghadapi persoalan di kehidupan sehari-hari dan menjadi hal primer dalam ilmu disiplin seperti fisika dan matematika (Lumbu et al., 2025). However, current physics learning outcomes in Indonesia indicate that students' CTS remain at a relatively low level (Rizki et al., 2024). Furthermore, literature in the field of physics education highlights CTS as one of the primary areas of concern (Al-Kamzari & Alias, 2025). CTS are skills that need to be honed through physics learning as part of higher-order thinking skills.

Graphical representation skills (GRA) are quite important in physics learning. In addition to CTS, GRA is a vital skill in physics education, as physics concepts are frequently conveyed through graphs, tables, and other visual formats (Kind et al., 2017). Mastery of GRA requires students to deeply comprehend the relationships between variables and underlying scientific concepts (Mayer, 2019; Coştu, 2023). The low scores on the Computer-Based National Examination (UNBK), particularly in the thermodynamics domain, reflect students' limited ability to interpret physics-related graphs. Performance indicators such as determining the efficiency of a Carnot engine or identifying physical quantities from a graph demonstrated absorption rates of less than 40% (Kemendikbud, 2025)], underscoring the urgent need to improve students' GRA in physics learning. One of the reasons students have difficulty understanding physics material is because their representational skills are still low (Pradana & Supahar, 2025). Representational ability is the ability to understand and process conceptual understanding (Volkwyn et al., 2020; Daniel et al., 2018). Several studies also state that representation skills are useful for improving understanding of physics concepts (Daniel et al., 2018; Küchemann, 2021). High GRA will have an impact on students' physics learning outcomes.

To enhance students' CTS and GRA, a student-centered learning approach is essential. One such approach is the guided inquiry model, which has been shown to promote active student engagement, strengthen conceptual understanding, and foster higher-order thinking skills (Li & Singh, 2018; Husnaini & Chen, 2019; Safarati, 2017; Sitindaon, 2017). Inquiry-based learning is considered to improve students' GRA (Fatmaryanti, 2017). Unfortunately, physics education in schools is still centered on educators (Verawati et al., 2021). Guided inquiry learning can be one of the relevant learning models used in physics education to improve students' skills and abilities.

With the advancement of technology, the integration of digital-based learning media such as Augmented Reality (AR) is regarded as a promising way to enhance the quality of learning experiences. AR allows the visualization of three-dimensional virtual objects within the real environment, making the learning process more contextual and interactive (Chen et al., 2019). Studies have shown that AR can significantly boost students' learning interest, conceptual understanding, and CTS (Simaremare et al., 2022; Socrates & Mufit, 2022). In addition, AR facilitates the development of communication and collaboration skills (Akçayır & Akçayır, 2017) and encourages more active student participation in the classroom (Mustaqim, 2017). AR assistance can be adapted to problem-based inquiry learning in the students' environment.

Another potential learning medium that supports interactive learning is the electronic book (e-book). Compared to conventional textbooks, interactive e-books offer various advantages due to their ability to incorporate multimedia elements such as videos, animations, simulations, and AR technology (Salamiyah & Kholiq, 2020) [28]. The use of e-books in physics instruction has been shown to increase students' engagement, deepen conceptual understanding, and foster scientific thinking skills (Apsari et al., 2017; Wulandari et al., 2022). However, the implementation of e-books in physics classrooms remains limited and has not yet been fully optimized (Setyawan et al., 2023). Therefore, integrating e-books with appropriate pedagogical models and advanced technologies such as AR presents a valuable opportunity to improve the effectiveness of science education.

In light of the aforementioned issues, the low level of students' CTS and GRA in physics learning—particularly in the domain of thermodynamics—necessitates the development of innovative and interactive instructional media. The combination of a guided inquiry-based learning model and an AR-integrated e-book is seen as a promising solution to address these challenges. Accordingly, this study aims to develop a guided inquiry-based e-book integrated with Augmented Reality, specifically designed for thermodynamics, as a means to improve high school students' CTS and GRA.

2. RESEARCH METHOD

This research includes research and development (R&D) using the Analysis, Design, Development, Implementation, and Evaluation (ADDIE) model. ADDIE was developed by Branch (2009) (Branch, 2009). The ADDIE model was chosen because it is effective and efficient for developing products in the field of education. The ADDIE model includes preliminary research to formulate problems, plan solutions, develop products and research instruments, validate and assess the eligibility of research products, and test and evaluate products (Maison, 2019). The ADDIE model can determine the eligibility, practicality, and effectiveness of development products as has been done (Sebastian & Kuswanto, 2025). The ADDIE model consists of 5 main stages (Simanjuntak, 2025), namely:

- Analysis, this stage involves problem formulation, task analysis, and development plans for the objects to be developed.
- Design, this stage involves the creation of learning instruments and data collection instruments, as well as the selection of instrument formats.
- Development, this stage involves the preparation of instructional designs, the development of materials, and the implementation of design plans.
- Implementation, this stage involves training instructors and implementing research products in the field.
- Evaluation, this stage involves evaluating research instruments as material for refinement for future research.

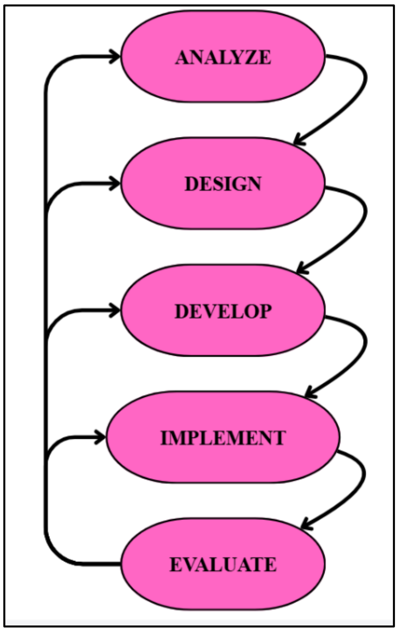

Figure 1. ADDIE Models Flowchart

1. **Research Design**

This study is a quasi-experimental study in the form of a pretest-posttest control group design. There are three groups, namely the experimental group, contrast group 1, and contrast group 2. The experimental group is the group that was given treatment using learning media in the form of AR-assisted guided inquiry-based e-books. Control group 1 is the group that was given treatment using guided inquiry-based e-books without AR assistance. Control group 2 is the group that was given treatment using PowerPoint presentations commonly used by teachers. The research design can be seen in Table 1.

Table 1. Research Design

Group	Pretest	Treatment	Posstest
Experiment	O_1	X_1	O_2
Contrast 1	O_1	X_2	O_2
Contrast 2	O_1	X_3	O_2

Description, O1: Pretest; O2: Posttest; X1: Physics learning based on guided inquiry learning assisted by AR; X2: Physics learning based on guided inquiry learning (without AR assistance); X3: Physics learning assisted by PowerPoint presentations.

The pretest–posttest control group design was employed to measure students' learning gains in CTS and GRA across different instructional treatments. Pretest scores were used to examine the initial equivalence of the groups before the intervention and to ensure that any observed differences in posttest scores could be attributed to the applied treatments rather than pre-existing ability differences.

2. **Research Sample**

Eligibility of Development Books

The eligibility of the developed e-book was obtained from an eligibility questionnaire. The eligibility questionnaire was given to two theoretical experts (lecturers) and one practitioner expert (teacher). The eligibility of the developed e-book was used to determine the assessment of the e-book on students' CTS and GRA. In addition, this eligibility was used to obtain suggestions and input for product revision. The eligibility of the developed product was assessed in terms of material, media, and construction.

Empirical Tests

Empirical tests were conducted to determine the validity and reliability of the pretest and posttest questions on CTS and GRA. The empirical tests were conducted at SMA N 1 Sewon with 120 grade XII students who had studied thermodynamics in physics class as respondents. The empirical tests consisted of 18 essay questions for CTS and 12 multiple-choice questions for GRA. Invalid and unreliable questions were removed. The empirical test used purposive sampling technique. This technique was used to determine the sample without probability by deliberately selecting samples with characteristics relevant to conducting certain tests.

Effectiveness Tests

Effectiveness testing is used to determine the effectiveness of the e-book product that has been developed in improving students' CTS and GRA. Effectiveness testing was conducted on grade XI students at SMA N 1 Sewon using cluster random sampling. This sampling technique divides a homogeneous population into several random sample groups. The number of students used to determine the effectiveness of the product was 90, with one group consisting of 30 students and each group receiving different treatments as discussed in Table 1.

3. Research Instrument

The research instruments consisted of learning instruments in the form of teaching modules and learning media that had been developed, and data collection instruments in the form of pretest-posttest questions for CTS and GRA, as well as student response questionnaires. The student response questionnaire is used to determine student responses to the developed products and to determine the practicality of the products. The CTS and GRA questions consist of indicators that have been synthesized from several experts. Table 2 shows the question indicators and variable indicators.

The indicators of CTS in this study were adapted from Ennis (2011), Facione (2011), and Changwong et al. (2019). According to Ennis (2011), CTS indicators include formulating problems, uncovering relevant facts, selecting logical arguments, examining problems, and drawing conclusions. Facione (2011) identifies CTS indicators as problem interpretation, problem analysis, solution formulation, argument evaluation, re-explanation, and reflection. Based on the synthesis of these frameworks, the CTS indicators employed in this research are understanding the problem, analyzing the problem, planning a solution, evaluating the solution, drawing conclusions, and re-interpretation.

The indicators of GRA were adapted from Sezen et al. (2012), Nguyen et al. (2010), and Larasati (2020). According to Sezen et al. (2010), GRA indicators include interpreting graphs, modeling, and transforming. Nguyen et al. (2010) identifies GRA indicators as finding presented values, interpreting physical concepts, and processing information. Meanwhile, Larasati et al. (2020) propose GRA indicators consisting of identify variables, describe data, relate data to concepts, and draw conclusions. Based on the synthesis of these frameworks, the GRA indicators employed in this research are identify the variables presented, describe the data, use the data with concepts, and draw conclusions from the information obtained.

Table 2. Pretest-Posttest Instrument Indicators

Variables	Variable indicators	Item Numbers	Question Indicators
CTS	Understanding the problem	1; 2	Presented with a picture of a closed pot and a thermos, students are expected to be able to analyze the picture using a closed system and provide valid reasoning.
	Analyzing the problem	4	An ideal gas with an unknown number of moles is presented. Students are expected to be able to analyze the number of moles of the ideal gas that has been decomposed.

Variables	Variable indicators	Item Numbers	Question Indicators
	Planning a solution	7; 9	The Carnot engine is presented with a specific efficiency and reservoir. Students are expected to be able to maximize the efficiency of the engine in the right way.
	Evaluating the solution	11; 12	An employee is shown repairing a machine. The employee must replace the machine's reservoir to ensure good machine efficiency. Students are expected to evaluate the employee's decision and provide appropriate reasons.
	Drawing conclusions	13; 14	Several examples of thermodynamic processes are presented. Students are expected to be able to decide which processes correspond to thermodynamic processes.
	Reinterpre-tation	17; 18	An image of a monatomic gas in an isolated system is presented. Students are expected to be able to regulate the temperature of the gas so that it has a certain energy value.
GRA	Identify variables	1; 2; 3	A graph showing the relationship between pressure and volume is presented. Students are expected to be able to calculate the pressure value at a given volume.
	Describe data	4; 5; 6	A graph showing the relationship between pressure and volume at a certain temperature is presented, along with several statements. Students are expected to be able to classify statements that do not match the graph.
	Relate data to concepts	7; 8; 9	A graph and explanation of Boyle's Law are presented. Students are expected to be able to accurately relate Boyle's Law to thermodynamic cases in everyday life.
	Draw conclusions	10; 11; 12	A graph of a Carnot engine with a certain level of efficiency is presented. Students are expected to be able to critique the graph with valid reasons.

Each CTS and GRA indicator was operationalized into specific test items in the pretest–posttest instruments. Students' responses were scored using predefined scoring rubrics, and the total scores represented students' CTS and GRA levels. These scores were then used as dependent variables in the effectiveness analysis.

4. Data Analysis

Analysis of e-book validation result

The eligibility analysis of the e-book development, teaching modules, and student responses was analyzed using the ideal standard deviation (Sbi). The analysis was conducted by calculating the average score and then converting it into specific categories. The average value was calculated by (Sugiyono, 2013):

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

Description:
$\bar{X}$: average score
x_i : total score obtained
n : number of respondents

The conversion of average values in certain categories can be seen in Table 3 with a Likert scale of 1 - 4 (Lukman & Ishartiwi, 2023).

Table 3. Average Values Category with Sbi

Score Range	Category
$X > 3.4$	Very good
$2.8 < X \leq 3.4$	Good
$2.2 < X \leq 2.8$	Fair
$1.6 < X \leq 2.2$	Poor
$X \leq 1.6$	Very poor

Analysis of research instrument tests

The theoretical validity test of the pretest-posttest questions on CTS and GRA of students was conducted using Aiken's V. The theoretical validity test was used to show the suitability between the instrument and the variables using a specific formula. The formula used was the one discovered by Aiken in 1985 (Istiyono et al., 2014). Aiken's V formula is:

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

Description:
s : $r - l_O$
V : expert agreement index on item validity
r : number given by the validator
l_0 : lowest validity rating number (1)
n : number of experts
c : highest validity rating number (4)

The validity assessment categories based on Aiken's V can be seen in Table 4.

Table 4. Aiken's V Value Category

Score Range	Category
$V \leq 0.6$	Bad
$0.6 < V \leq 0.8$	Fair
$V > 0.8$	Good

If the validity result is bad, the item will be deleted; if the validity result is fair, the item will be revised; and if the validity result is good, it can be used immediately.

Analysis of empirical tests result

Empirical testing analysis was conducted on the pretest-posttest questions for both variables. The analysis was performed using the QUEST program, which can analyze test items using classical analysis. Classical analysis uses the INFIT MNSQ value for each item. Valid items have an INFIT MNSQ value between 0.77 and 1.33. Meanwhile, the reliability analysis of the test instrument was conducted using Cronbach's Alpha. The categories of validity analysis results using the classical model and reliability using Cronbach's Alpha can be seen in Table 5 and Table 6.

Table 5. INFIT MNSQ Value Validity Categories

INFIT MNSQs Values	Description
> 1.30	Not Valid
0.77 – 1.30	Valid
< 0.77	Not Valid

Table 6. Reliability Category with Cronbach's Alpha

Score Range	Category
$0.00 \leq r < 0.20$	Very low
$0.20 \leq r < 0.40$	Low
$0.40 \leq r < 0.60$	Moderate
$0.60 \leq r < 0.80$	High
$0.80 \leq r < 1.00$	Very high

Questions can be used to measure student ability at least if the reliability analysis results are in the adequate category.

Analysis of effectiveness tests result

Product effectiveness analysis was conducted using Partial Eta Squared (η^2) values. Product effectiveness levels are shown in Table 7. Product effectiveness analysis also involved MANOVA testing using SPSS 25 software. MANOVA testing is a parametric test, so prerequisite tests are necessary before MANOVA testing can be performed. The prerequisite tests include a normality test using Shapiro-Wilk, a covariance homogeneity test using Bonferroni, and a multicollinearity test using Pearson Correlation.

In addition to statistical significance, effect size was calculated using Partial Eta Squared (η^2) to estimate the magnitude of the treatment effect. This measure provides practical significance by indicating the proportion of variance in CTS and GRA explained by the instructional treatments.

MANOVA was employed because this study involved two related dependent variables, namely CTS and GRA, which were expected to be correlated. Using MANOVA allowed simultaneous examination of treatment effects on both variables while controlling for Type I error inflation.

Table 7. Effectiveness Levels Category with Cohen's F

Cohen's f values	Interpretation
0.00 – 0.10	Small effect
0.11 – 0.25	Medium effect
0.26 – 0.40	Large effect

3. RESULT AND DISCUSSION

Product and Instrument Eligibility Validation Test

E-book product eligibility test

The developed product underwent eligibility testing prior to its broader implementation for effectiveness evaluation. Eligibility was assessed using a structured eligibility questionnaire administered to both expert validators (subject matter experts) and practitioner validators (teachers). The eligibility evaluation covered three key aspects: content/material quality, design quality, and media functionality. In addition, the questionnaire also examined the alignment of the developed product with the dependent variables of the study, namely CTS GRA, which were central to the research focus. The responses were analyzed using the SBI (Simpangan Baku Ideal) scoring method. The results of the product eligibility assessment are presented in Table 8.

Table 8. E-books Product Development Eligibility

Rated Aspect	Average Score
Material	3.83
Design	4.00
Media	3.67

The eligibility of the developed e-book learning media was rated in the "very good" category across all assessed aspects, including content, design, and media functionality

E-book product practicality test

The practicality of the product was tested to determine student response to the development product. Practicality testing was conducted through a student response questionnaire, which was then analyzed using Sbi. The student response questionnaire was given to the experimental group using the development e-book.

Table 9. Results of Student Response Questionnaire Analysis

Rated Aspect	Average Score
Material	3.17
Construction	3.21
Media	3.14

The results of this analysis are presented in Table 9. The results of the student response questionnaire analysis indicate that the developed product is practical for classroom use. As shown in Table 9, the e-book was considered practical in terms of material content, construction quality, and media components, reflecting positive student perceptions across all assessed dimensions.

Theoretical validation of instrument test

Instrument validation was conducted by two theoretical validators and one practitioner validator. The eligibility of the learning instrument was obtained from a validation questionnaire and then analyzed using Aiken's V value to determine the validity of the instrument in terms of three aspects, namely material, construction, and language for each item. Data collection instrument validation was used to determine the theoretical validity of the instrument. The validation results show in Figure 1 and Figure 2.

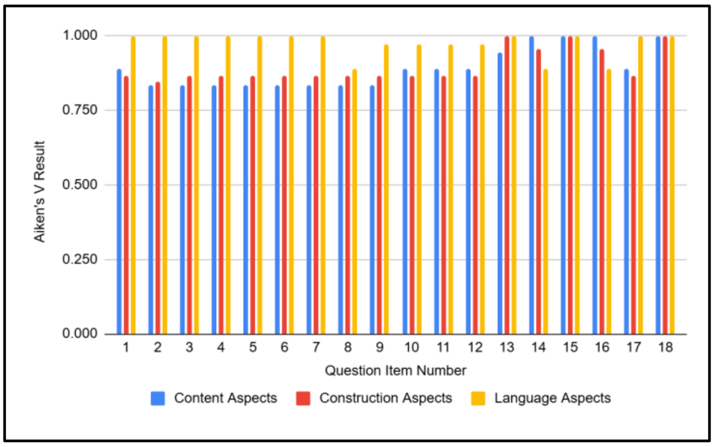

Figure 2. Result of V Aiken's Test Instrument for CTS

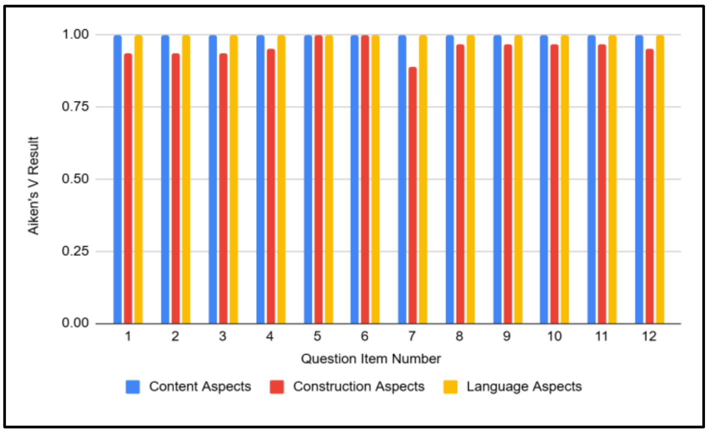

Figure 3. Result of V Aiken's Test Instrument for GRA

The validation results show that all items are theoretically valid in terms of each assessment aspect. However, there are several suggestions from the validators as material for the first revision stage.

Empiric validation of instrument test

Empirical testing was conducted by giving CTS essay questions and multiple choice questions on GRA to students in grades XII-1, XII-5, XII-7, and XII-8. The students' scores were used to analyze the validity, reliability, and difficulty level of the questions. The analysis was conducted using the QUEST program. The QUEST program can be used to analyze test instruments using the Rasch model based on Item Response Theory (IRT). The results of the empirical validity test of the instrument are shown in Figure 3 and Figure 4, then the reliability is shown in Table 10.

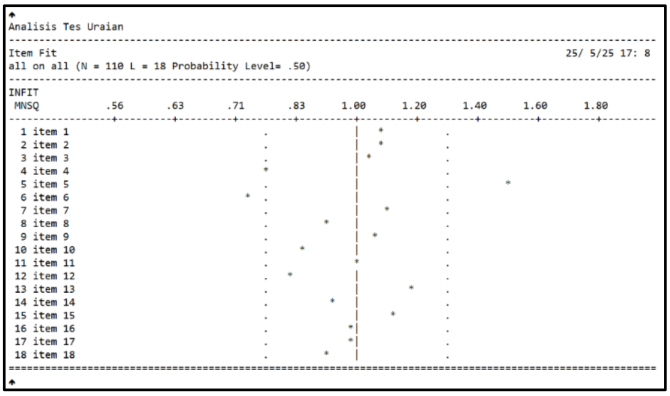

Figure 4. Empirical Validity Analysis Results of Pretest-Posttest CTS Instrument

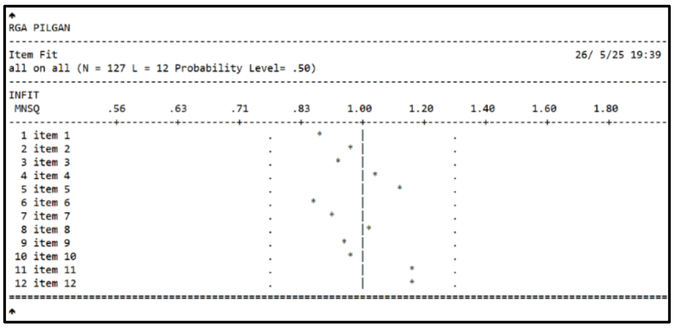

Figure 5. Empirical Validity Analysis Results of Pretest-Posttest CTS Instrument

Table 10. Results of Student Response Questionnaire Analysis

Variables	Reliability Values	Category
CTS	0.75	High
GRA	0.96	Very high

The instruments for CTS and GRA have been qualified to measure students' skills and abilities. Furthermore, these questions are used to compile pretest-posttest questions that will be used to collect data.

Pretest-Posttest Analysis Result

This subsection presents the results of the pretest–posttest analysis conducted to examine changes in students' Critical Thinking Skills (CTS) and Graphical Representation Ability (GRA) following the implementation of different instructional treatments. The analysis aimed to identify students' initial abilities prior to the intervention and to evaluate the effectiveness of the developed AR-assisted guided inquiry e-book compared to other instructional approaches.

Critical Thinking Skills

The pretest and posttest results of students' Critical Thinking Skills (CTS) across the three groups are presented in Figure 6. The results indicate that students' pretest scores were relatively comparable among the groups, suggesting similar initial CTS levels prior to the intervention. Following the instructional treatment, the highest posttest scores were obtained by the experimental group that utilized the developed e-book, compared to the two comparison groups.

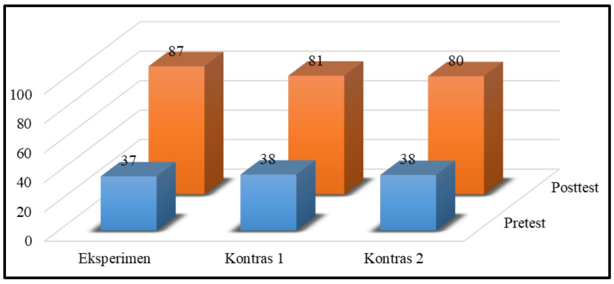

Figure 6. Result of CTS's Pretest-Posttest

To provide a more detailed description of students' learning improvement, a normalized gain (n-gain) analysis was conducted for each CTS indicator in all groups. The n-gain analysis results for each CTS indicator are illustrated in Figure 7.

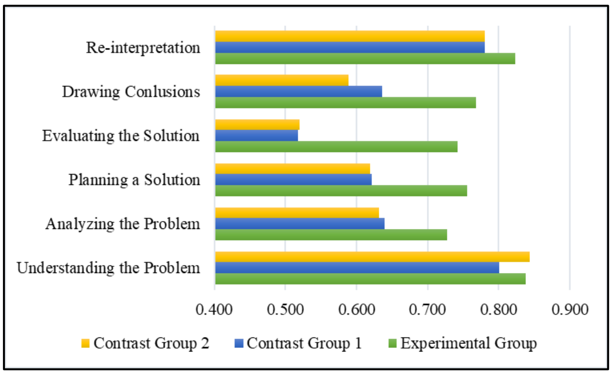

Figure 7. Result of Indicators CTS's N-Gain Analysis Over 3 Group

The average n-gain scores for CTS were 0.792 for the experimental group, 0.683 for comparison group 1, and 0.678 for comparison group 2. These results indicate that the experimental group achieved a higher level of improvement compared to the comparison groups. Among the CTS indicators, the highest improvement was observed in the evaluating solutions indicator. This finding suggests that the inquiry-based e-book effectively supported students in evaluating problem solutions, particularly through the inclusion of the communicating phase, which encourages students to articulate and justify their reasoning processes.

This finding is consistent with previous studies reporting that inquiry-oriented learning supported by augmented reality (AR) activities can enhance students' evaluative and reflective thinking skills. The use of AR enables students to receive clearer interpretations of learning content, engage more critically with learning tasks, and evaluate their own judgments more effectively (Hariyadi et al., 2026). In contrast, students in the comparison groups, who did not experience AR-supported instruction, tended to engage in more confirmatory and passive learning processes with limited evaluative engagement (Yang & Wang, 2023). Such learning conditions may lead to cognitive dissociation, which aligns with conceptual change theory, where insufficient cognitive conflict hinders meaningful restructuring of students' conceptual understanding (Shapiro et al., 2017). AR-based presentations can increase students' responsiveness to learning events or problems, encouraging them to analyze the situations in greater depth as a evaluating progress.

Graphical Representation Abilities

The pretest and posttest results of students' Graphical Representation Ability (GRA) across the three groups are presented in Figure 8. The results show that students' pretest scores were relatively comparable among the groups, indicating similar initial GRA levels prior to the intervention. After the instructional treatment, the highest posttest scores were achieved by the experimental group that used the developed e-book, compared to the two comparison groups.

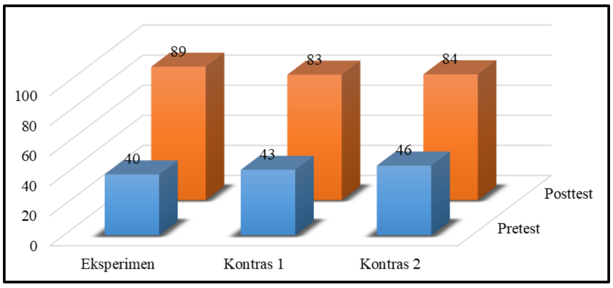

Figure 8. Result of GRA's Pretest-Posttest

To further describe students' learning improvement, a normalized gain (n-gain) analysis was conducted for each GRA indicator in all groups. The n-gain analysis results for each indicator are presented in Figure 9.

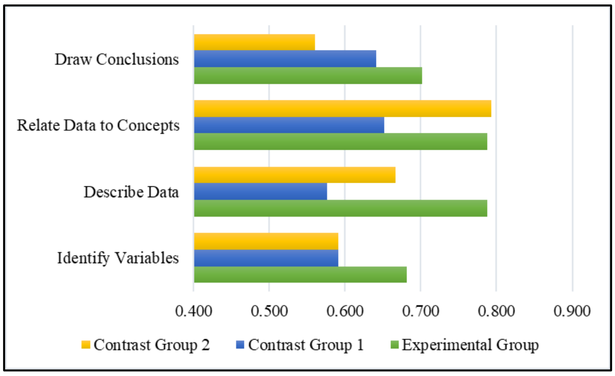

Figure 9. Result of Indicators GRA's N-Gain Analysis Over 3 Group

The average n-gain scores for GRA were 0.808 for the experimental group, 0.697 for comparison group 1, and 0.693 for comparison group 2. These results indicate that the experimental group experienced a greater improvement in GRA compared to the comparison groups. Among the GRA indicators, the highest improvement was observed in the describing data indicator. This suggests that the inquiry-based e-book effectively supported students in describing and interpreting graphical data through the inclusion of simulations and graph-focused practice exercises.

These findings are supported by previous studies reporting that interactive simulations and graphical tasks can improve students' graphical representation skills, particularly in the data description indicator, which involves identifying variables, interpreting data patterns, and explaining relationships in graphs. Inquiry-based learning supports this indicator by enhancing students' ability to describe variables and symbols and interpret macroscopic phenomena represented graphically (Boonmaka & Huntula, 2024). The integration of augmented reality (AR) further strengthens students' ability to describe data by supporting the visualization of invisible or microscopic structures underlying observable data patterns, allowing for clearer observation and interpretation of graphical information (Radu & Schneider, 2019). Although inquiry-based learning alone may have limited impact when students experience difficulty visualizing phenomena (Yuwono et al., 2017), the use of AR provides concrete and dynamic visualizations that facilitate more accurate and coherent data descriptions. Accordingly, the data description indicator exhibited a greater improvement than the other indicators across groups.

Although the descriptive analysis reveals an overall improvement in students' CTS and GRA, inferential statistical analysis is necessary to verify the effectiveness of the instructional treatments. Accordingly, a multivariate analysis of variance (MANOVA) was employed to examine the simultaneous effects of the treatments on CTS and GRA.

Effectiveness of Using E-Book of Thermodynamics Based Guided Inquiry Learning Assisted by Augmented Reality

To ensure the validity of the effectiveness analysis, prerequisite tests were conducted before performing MANOVA.

Manova prerequisite test

The prerequisite tests include normality tests, covariance homogeneity tests, and multicollinearity tests. The normality test uses Shapiro-Wilk because each sample has no more than 50 respondents. The analysis is performed using the SPSS program. If the sig. value is > 0.05, then the data is normally distributed. The analysis of covariance homogeneity is also the same. Meanwhile, multicollinearity analysis can be tolerated if the value is less than 0.6. Multicollinearity analysis is performed to determine the relationship between the two variables. If the two variables are closely related (> 0.6), then the two variables are too closely related so that it can be concluded that the two variables are the same and count as one variable. The results of the normality analysis can be seen in Table 11, the homogeneity analysis can be seen in Table 12, and the multicollinearity analysis can be seen in Table 13.

Table 11. Analysis Result of Normality

Variables	Group	Sig. (Shapiro-Wilk)
CTS	Experiment	0.061
	Contrast 1	0.851
	Contrast 2	0.535

GRA	Experiment	0.125
	Contrast 1	0.264
	Contrast 2	0.448

Table 12. Analysis Result of Homogeneity Covarians

Box's M	**10.436**
f	1.687
df1	6
df2	229691.077
Sig.	0.120

Table 13. Analysis Result of Multicollinearity

Variables	**Pearson Correlation Values**	**Sig.**
CTS	0.275	0.06
GRA	0.275	0.06

The data obtained has met the prerequisite test so that MANOVA and effect size tests can be performed.

Product effectiveness test through partial eta squared value

The product effectiveness results can be seen in the "Partial Eta Squared" column in the SPSS multivariate analysis results. The effectiveness results can be seen in Figure 10. A significance value of less than 0.05 indicates that there is a difference between the experimental group, contrast group 1, and contrast group 2. The magnitude of the difference is reviewed from the partial eta squared value results.

Multivariate Tests[a]

Effect		Value	F	Hypothesis df	Error df	Sig.	Partial Eta Squared	Noncent. Parameter	Observed Power[d]
Intercept	Pillai's Trace	.984	2947.572[b]	2.000	95.000	.000	.984	5895.144	1.000
	Wilks' Lambda	.016	2947.572[b]	2.000	95.000	.000	.984	5895.144	1.000
	Hotelling's Trace	62.054	2947.572[b]	2.000	95.000	.000	.984	5895.144	1.000
	Roy's Largest Root	62.054	2947.572[b]	2.000	95.000	.000	.984	5895.144	1.000
Group	Pillai's Trace	.248	6.782	4.000	192.000	.000	.124	27.128	.993
	Wilks' Lambda	.752	7.261[b]	4.000	190.000	.000	.133	29.042	.996
	Hotelling's Trace	.329	7.733	4.000	188.000	.000	.141	30.932	.997
	Roy's Largest Root	.329	15.795[c]	2.000	96.000	.000	.248	31.589	.999

Figure 10. Analysis Result of Multivariate Test by SPSS Program

The magnitude of the treatment effect was evaluated using Partial Eta Squared (η^2), which yielded a value of 0.141. This result indicates a moderate effect size, suggesting that the instructional treatment accounted for a meaningful proportion of the variance in students' CTS and GRA outcomes. This value indicates that the product has a medium level of effectiveness in improving CTS and GRA. AR-assisted inquiry-based learning media has been proven to be effective in improving students' CTS and GRA compared to inquiry-based learning media without AR assistance, especially learning media that is often used by teachers, namely PowerPoint presentations.

The MANOVA results revealed a statistically significant multivariate effect of instructional treatment on CTS and GRA ($p < 0.05$), indicating that at least one of the instructional approaches led to different learning outcomes compared to the others.

Beyond the treatment given to each group, there were several factors that caused differences in the pretest-posttest scores of the students. For example, the test results when the test was conducted in the morning differed from those when it was conducted in the afternoon (Mthimunye & Daniels, 2020). During the day, students tend to be tired, unmotivated, and unable to perform optimally on tests. In addition, the use of AR also has a major drawback in that the devices used are not yet fully adequate for students to access AR. This is in line with research that has been conducted, which found that devices can be a major obstacle in learning (Saha et al., 2021; Oliveira et al., 2019). These are the limitations of this study that can be used as material for evaluation for future research.

E-book Product of Thermodynamics Based Guided Inquiry Learning Assisted by Augmented Reality

The guided inquiry-based e-book that has been developed was designed using Canva software. The developed e-book is presented in Figure 11. Canva software can be used to create attractive learning media designs. On the other hand, the development of guided inquiry-based e-books is designed to present problems that exist around students, for example, how humans breathe in terms of thermodynamics, as shown in Figure 6. The developed e-book also presents questions and exercises to facilitate and strengthen students' thinking skills. AR support in e-books uses a Marker Based Tracking system where access to 3-D object designs must go through markers presented on the e-book pages. AR 3-D objects are stored on a website so that students do not need to download specific applications, which would be burdensome for them. The limitation of AR in the developed e-book is that AR only displays 3-D objects and cannot yet display simulations through AR. Nevertheless, the new learning experience can improve students' skills and thinking abilities.

The e-book presents guided inquiry-based learning materials. Guided inquiry learning consists of several stages that have been adapted from previous research (Llewellyn, 2013). These stages are 1) exploration of phenomena; 2) formulating problems and hypotheses; 3) planning investigations; 4) conducting investigations; 5) analyzing data; 6) constructing new knowledge; and 7) communicating. Inquiry-based learning has been proven to improve CTS (Fattahi & Haghverdi, 2015) This is supported by the level of student activity that is encouraged by the inquiry-based learning model (Zetriuslita & Alzaber, 2013, 2020; Wulandari, 2016). This is in line with previous research that shows that a well-presented inquiry-based learning model can improve students' CTS.

Guided inquiry learning is supported by various learning media, one of which is e-books. In line with previous studies, the results of this study prove that AR-assisted e-books can improve students' CTS (Rahmayani et al., 2024; Fendi et al., 2021) and GRA (Rahmayani et al, 2024; Rahmasari & Kuswanto, 2023; Thees et al., 2020). E-books designed with integrated AR technology improve students' CTS and GRA.

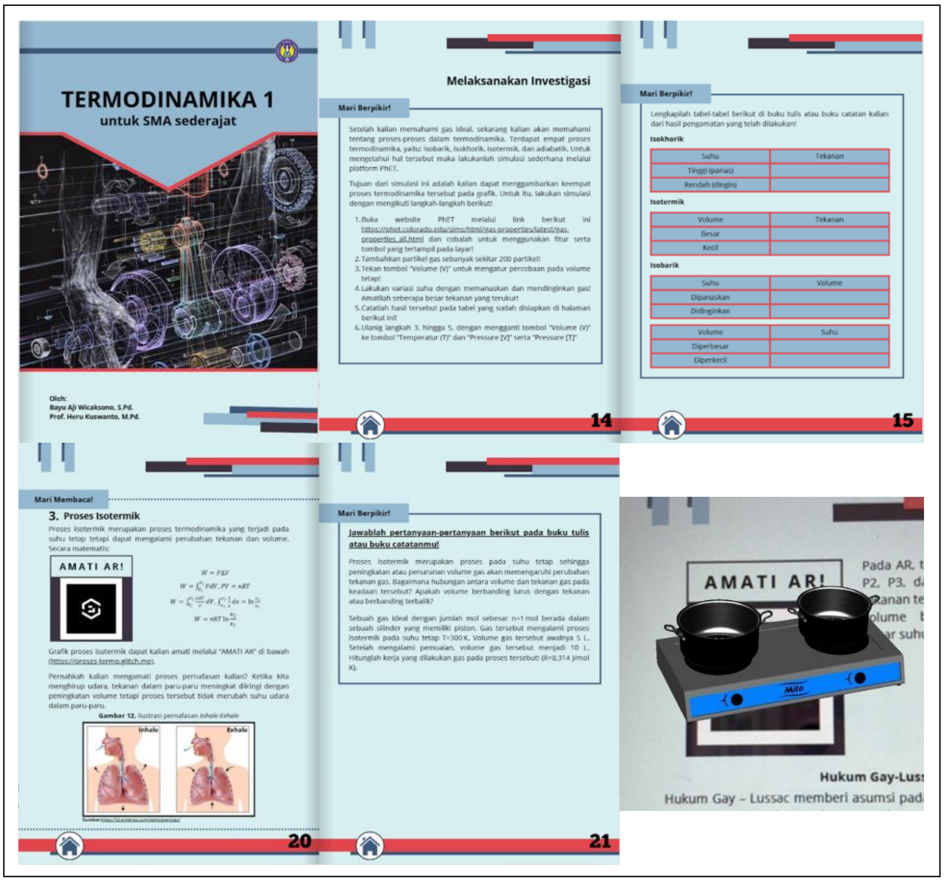

Figure 11. Result of Development E-Book Based Inquiry Learning Assisted with Augmented Reality

The focus of research on CTS and GRA of students is basically aimed at improving the quality of physics learning and physics learning outcomes. High physics learning outcomes of students are influenced by the high level of CTS of students (Syamsinar, 2023). There is a significant correlation between CTS and physics learning outcomes (Damayanti et al., 2022). CTS scores will affect their learning outcome scores (Amto et al., 2019). In addition, representation skills are needed in physics learning to achieve good physics learning outcomes (Widianingtiyas et al., 2015). Students' representation skills have the potential to improve their understanding of concepts and physics learning outcomes (Distrik et al., 2021). The improvement in students' CTS and GRA is expected to improve their physics learning outcomes and enhance a higher quality learning environment.

4. CONCLUSION

Based on the research findings and data analysis, it can be concluded that the inquiry-based e-book assisted by Augmented Reality (AR) developed in this study is feasible, practical, and effective for enhancing students' CTS and GRA in learning thermodynamics in physics. The eligibility of the product falls into the very good category, as determined by evaluations from both expert and practitioner validators. The practicality of the e-book is categorized as good, based on students' responses during the implementation phase. Furthermore, the effectiveness of the e-book in improving both CTS and GRA is classified as moderate. These results suggest that the developed e-book has strong potential as an alternative interactive learning medium to support and enhance the quality of physics instruction at the senior high school level.

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