*International Journal of Learning, Teaching and Educational Research*
*Vol. 25, No. 7, pp. 846-863, July 2026*
*https://doi.org/10.26803/ijlter.25.7.38*
*Received Feb 18, 2026; Revised Jun 22, 2026; Accepted Jul 10, 2026*

# The Effectiveness of an Augmented Reality-Integrated Physics Textbook on Students' Critical and Computational Thinking Skills

**Mutahharah Hasyim*, Abdul Haris, Riskawati, and Mahir**
Department of Physics Education,
Makassar State University, Indonesia

**Kasman**
Educational Technology Study Program,
University of Muhammadiyah Makassar, Indonesia

**Abstract.** The development of high-level thinking skills, especially critical thinking (CT) and computational thinking (CompT), is a major demand for 21st-century science education. However, conventional physics instruction often fails to optimise the development of these skills owing to the abstract nature of physics concepts and the limitations of technological pedagogical integration. This research aims to develop and evaluate an augmented reality-based physics textbook based on integration (ARI physics textbook) as well as test its effectiveness in improving students' CT and CompT skills. This research method uses a mixed-methods design. The qualitative approach is carried out through expert validation of textbooks and research instruments. The quantitative approach used a quasi-experimental one-group pre-test–post-test design involving 35 students of class X, purposively sampled from one of the public high schools in Makassar City, Indonesia. Data were collected using expert validation sheets, practicality questionnaires, and validated CT and CompT test instruments. The results showed that AR-based physics textbooks have a very high level of validity and practicality, with a significance of >0.001. Inferential analysis showed a significant improvement in the CT and CompT skills of students after the intervention, with the N-Gain in the 'moderate' category, and the Cohen's effect size in the 'large' category for CT and the 'very large' category for CompT. These findings indicate that the integration of augmented reality is effective pedagogically as a cognitive catalyst in physics learning.

**Keywords:** augmented reality; physics textbook; critical thinking; computational thinking

Citation:
Hasyim, M., Haris, A., Riskawati, Mahir, & Kasman (2026). The Effectiveness of an Augmented Reality-Integrated Physics Textbook on Students' Critical and Computational Thinking Skills. *International Journal of Learning, Teaching and Educational Research*, *25*(7), 846–863. https://doi.org/10.26803/ijlter.25.7.38

*Corresponding author: Mutahharah Hasyim; *muthahharah@unm.ac.id*

# 1. Introduction

## 1.1. Critical Thinking and Computational Thinking in Physics Education

The paradigm shift in education in the 21st century demands an emphasis on mastering high-level thinking skills that can transcend disciplinary boundaries. In this context, the two cognitive competencies that emerge as the main foundations are critical thinking (CT) and computational thinking (CompT) skills. Critical thinking is defined as an intellectual process that is skilled in conceptualising, applying, analysing, synthesising, and evaluating information (Braun et al., 2020; Potter, 2022). CT can be the basic foundation for rational decision-making and effective problem-solving (Adhikari, 2023; Saiz & Rivas, 2023).

Meanwhile, CompT is understood as a mental framework that involves formulating problems and their solutions so that they are carried out by information-processing agents (Denning & Tedre, 2021; Kelly & Gero, 2021). CompT has evolved from a concept limited to computer science to a fundamental literacy required in various fields of science (Tekdal, 2021). The convergence of these two skills creates a powerful synergy: CT provides a framework for evaluating the validity and relevance of information, while CompT offers a systematic methodology for deconstructing and modelling complex problems.

## 1.2 Challenges in Physics Learning

The contemporary science education landscape, particularly in the physics domain, provides an ideal yet challenging context for the actualisation of CT and CompT. Physics, a discipline concerned with understanding natural phenomena through the construction and validation of theoretical models (Borsboom et al., 2021; Coccia, 2020), is a means of training in integrated critical and computational thinking (Lee et al., 2020; Vieyra & Himmelsbach, 2022). The process of formulating hypotheses, designing experiments, analysing data, and revising models iteratively are direct manifestations of CT skills (Palts & Pedaste, 2020).

In parallel, when faced with complex physical problems, individuals naturally decompose the problem into simpler components (Tang et al., 2021), identify patterns in data or system behaviour, abstract fundamental principles from surface details, and design a logical sequence of solution steps. The whole process reflects the core dimensions of CompT exactly. Ironically, however, the inherent potential of physics as a medium for developing CT and CompT skills is often not actualised in conventional pedagogical practice.

The reality of the physics classroom in many educational contexts has been characterised by a student-centred approach and is no longer orientated to the transmission of knowledge alone. Learning models like this no longer reduce physics to a collection of algorithmic formulas and procedures to be solved (De Silva et al., 2020). Students no longer miss out on the opportunity to engage in the learning process. However, the opportunities that engage students in learning have not been able to touch the authentic knowledge-construction process at the heart of the development of CT and CompT (Kafri, 2022; Saad & Zainudin, 2022; Taconis & Bekker, 2023). Students are only engaged in knowledge content exercises to apply formulas, not to question assumptions, analyse models, or strategise solutions (Ling et al., 2023; Taconis & Bekker, 2023). These challenges are compounded by the abstract nature of physics concepts, such as electromagnetic fields, quantum wave functions, or relativity, which are difficult to visualise with only the traditional devices such as static whiteboards and textbooks (Miani, 2021; Yuji, 2025). This abstraction creates significant cognitive barriers, hinders the formation of accurate mental processing models and limits the capacity of students to perform the qualitative and quantitative reasoning required for CT and CompT.

**1.3 Augmented Reality in Science Education**

The education community has witnessed the emergence of Information and Communication Technology (ICT) as a potential catalyst for pedagogical transformation in response to these challenges (Chacón et al., 2023; Nykyporets, 2024). One of them is augmented reality (AR), which has gained significant traction owing to its unique ability to bridge the gap between the abstract world of theoretical concepts and the physical reality that students can observe (Algerafi et al., 2023; Koumpouros, 2024).

Augmented reality maintains real-world context while enriching it with layers of superimposed digital information (Dargan et al., 2023; Mendoza-Ramírez et al., 2023; Turner, 2022). The characteristics of AR allow for the visualisation of invisible concepts and the manipulation of virtual objects in physical space, thus creating an immersive and interactive learning experience (Scavarelli et al., 2020). For example, students can 'see' the lines of the magnetic field around a magnet, 'manipulate' the orbits of planets in the solar system, or 'observe' the interference of sound waves in three-dimensional space.

Various empirical studies have supported the effectiveness of AR in the context of science education. Comprehensive meta-analyses by Fadzil et al. (2022), Lin and Yu (2023), and Yu (2024) conclude that AR results in statistically significant improvements in learning achievement compared to non-AR methods, with impressive effect sizes. These findings are consolidated by other studies that have identified the positive impact of AR on student engagement (Drljević et al., 2022; Wang, 2022), intrinsic motivation, and conceptual understanding (Aldeeb et al., 2024; Chen et al., 2023; Gill et al., 2024), especially for content that requires spatial visualisation and multi-representational modelling. The mechanism underlying the effectiveness of AR is thought to be related to its ability to reduce the cognitive load associated with mental visualisation, allowing valuable cognitive resources to be reallocated to higher-level thinking processes such as analysis and evaluation.

**1.4 Research Gap and Novelty**

However, when we examine the existing literature on the application of AR in science education through a critical lens, several important limitations and gaps emerge. First, many AR implementations are supplemental and fragmented in nature from a pedagogical integration perspective (Alzahrani, 2020; Gil et al., 2022). The applications of AR are often developed as separate entities from the core curriculum and teaching materials only as a technological 'gimmick', which is interesting but not integrated cohesively into the learning sequence (You & He, 2022). This approach fails to harness the full potential of AR as a catalyst for pedagogical transformation, as the technology does not change the nature of cognitive tasks fundamentally or the interactions of students with content. Second, most studies have measured the impact of AR on variables such as conceptual comprehension, retention, and motivation, but relatively few have investigated its effect explicitly on the development of specific high-level thinking skills such as CT and CompT. In fact, the claim that AR supports the development of these skills is often put forward, but it is rarely tested empirically with valid and reliable instruments (Nikou et al., 2024; Tudor Car et al., 2022).

Based on a comprehensive gap analysis, this study is designed to develop and evaluate a physics textbook integrating AR. The main innovation of this research lies in its holistic approach to technology integration, in which AR is not added as a supplement but integrated dialectically into the textbook fabric itself. The learning design that underlies the ARI physics textbook is designed intentionally to engage students in an enquiry cycle that requires the application of CT skills (such as analysing evidence, evaluating conclusions, and identifying biases) and CompT (such as decomposing problems, recognising patterns, and designing algorithms). In other words, AR technology serves as a cognitive catalyst that enables the types of tasks and questions that require and develop CT and CompT authentically.

The novelty of this research can be articulated in two dimensions, namely pedagogical integration through the development of a framework for the deep and meaningful integration of AR into physics textbooks, and simultaneous empirical investigations of the impact of interventions on two critical cognitive constructs, CT and CompT, using specially developed and validated assessment instruments to measure these constructs in a physics context. The present study assesses the validity and practicality of the ARI physics textbook based on evaluations from subject matter experts, media- and learning-design specialists, teachers, and students. In addition, it investigates whether instruction using the textbook results in statistically significant improvements in critical thinking (CT) and computational thinking (CompT) skills.

### 1.5 Research Objectives and Contributions

This research aims to make a significant contribution to both educational practice and theoretical discourse. On a practical level, this research will produce innovative textbook prototypes ready for adoption and adaptation by physics educators. On a theoretical level, the findings of this study will deepen our understanding of how immersive technologies such as AR can be utilised optimally to cultivate the cognitive skills most needed in the 21st century. Thus, this research does not only respond to the immediate challenges in physics education it but also contributes to the broader educational goal of preparing learners to become critical thinkers, competent problem solvers, and tech-savvy citizens in an increasingly complex and technology-driven society.

## 2. Methods

### 2.1 Research Design

This study used a quantitative quasi-experimental approach with a one-group pre-test–post-test design (Matović & Ovesni, 2023; Siedlecki, 2020; Takács et al., 2020). In the early stages, a qualitative phase was conducted to obtain expert validation of the product design and the CT and CompT skill measurement tools. This phase directly addressed research questions about the validity and theoretical feasibility of the ARI physics textbook and the research instruments. This study design was selected to measure how well the ARI physics textbook helps to improve the CT and CompT skills of students before and after the learning intervention. The quantitative phase aims to answer whether there are significant changes in these skills after students use the textbook.

### 2.2. Participants and Research Context

This study involved 35 students from a single grade X class at a State High School in Makassar City, Indonesia. The researchers used purposive sampling (Ames et al., 2019; Etikan, 2016), selecting this class because of its strong academic record and good technological readiness. The research was conducted over four months, including the product design stage, expert validation, and limited trials. The learning context took place in physics class X with topics that require conceptual visualisation and abstract modelling, such as the motion of objects on an oblique plane, as shown in Figure 1.


**Figure 1: ARI physics textbook visualisation**

### 2.3. Instruments and Data Collection

The first instrument is an expert validation sheet designed to evaluate the feasibility of the ARI physics textbook. Three groups of experts took part in the validation: physics material experts, learning media experts, and learning-design experts. Each aspect was rated on a 4-point Likert scale (1 = not feasible to 4 = very feasible) (Ibiyemi et al., 2019). The evaluation covered content suitability, concept accuracy, AR visual quality, pedagogical integration, and instructional clarity. The second instrument to measure the level of practicality of the ARI physics textbook was used to survey teacher and student responses. This questionnaire evaluates the ease of use, clarity of instruction, integration of AR with book materials, and perception of learning benefits. The data from this questionnaire are used to support expert validation findings from the end-user perspective.

The third instrument measures the critical thinking skills of students through a multiple-choice test adapted from Ennis (Saulius & Malinauskas, 2021), and tailored to physics learning. Three validators assessed its content validity on a 1–5 scale, and the results were analysed using Aiken's V coefficient (Roebianto et al., 2023). The average Aiken's V was 0.88, which is considered highly valid, as shown in Table 1. This indicates that the instrument is suitable for measuring the critical thinking skills of students.

**Table 1: Results of CT instrument validation analysis using Aiken's V**

| No | Indicator CT | Validator 1 | Validator 2 | Validator 3 | Aiken's V | Category |
|---|---|---|---|---|---|---|
| **1** | Provide a simple explanation | 3.75 | 3.5 | 3.75 | 0.89 | Highly Valid |
| **2** | Build basic skills | 3.5 | 3.75 | 3.5 | 0.86 | Highly Valid |
| **3** | Summing up | 3.75 | 3.75 | 3.5 | 0.89 | Highly Valid |
| **4** | Provide further explanation | 3.5 | 3.5 | 3.75 | 0.86 | Highly Valid |
| **5** | Setting strategies and tactics | 3.75 | 3.75 | 3.75 | 0.92 | Highly Valid |
| | | **Mean** | | | 0.88 | Highly Valid |

The fourth instrument is a CompT skill test that uses a physics-based problem-solving tool to assess four main areas: decomposition, pattern recognition, abstraction, and algorithmic thinking (Denning & Tedre, 2021). Three experts validated the instrument, and analysis with Aiken's V gave an average score of 0.89, which is considered highly valid, as shown in Table 2.

**Table 2: Results of CompT instrument validation analysis using Aiken's V**

| No | Indicator CT | Validator 1 | Validator 2 | Validator 3 | Aiken's V | Category |
|---|---|---|---|---|---|---|
| **1** | Decomposition | 3.75 | 3.75 | 3.50 | 0.89 | Highly Valid |
| **2** | Pattern recognition | 3.50 | 3.75 | 3.50 | 0.86 | Highly Valid |
| **3** | Abstraction | 3.75 | 3.50 | 3.75 | 0.89 | Highly Valid |
| **4** | Algorithmic thinking | 3.75 | 3.75 | 3.75 | 0.92 | Highly Valid |
| | | **Mean** | | | 0.89 | Highly Valid |

### 2.4 Data Analysis Techniques

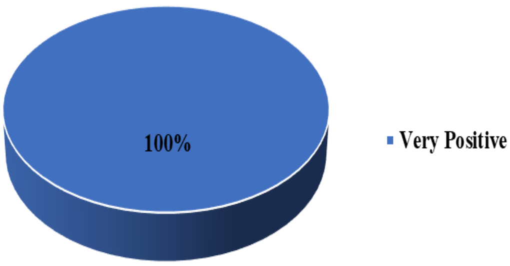
The validity analysis of the ARI physics textbook was carried out using the method of understanding between two experts or Gregory analysis to assess the feasibility of content and language (Gregory & McDaniels, 2005; Gregory, 2021). Two independent experts reviewed the physics material and assessed its language quality. The analysis showed a Gregory coefficient of understanding of 1.00 (≥ 0.80), which means the textbook is highly valid and suitable for learning. Practicality data from teacher and student questionnaires were analysed quantitatively by calculating the average and the percentage achieved for each indicator. The critical and computational thinking skills of students were described using pre-test and post-test scores to show their abilities before and after the learning intervention.

To measure the effectiveness of the ARI physics textbook, a paired sample t-test compared pre-test and post-test scores for CT and CompT. Before this test, a normality check was performed at the $\alpha = 0.05$ significance level (Aslam, 2024; Kwak, 2023). The improvement in students' skills was measured using N-Gain (Triyono et al., 2024), which was classified as low ($g < 0.30$), medium ($0.30 \le g < 0.70$), or high ($g \ge 0.70$). Effect sizes were also calculated using Cohen's $d$, with small ($d = 0.20$), medium ($d = 0.50$), and large ($d \ge 0.80$) categories to assess the practical impact of the intervention (Cohen et al., 2021).

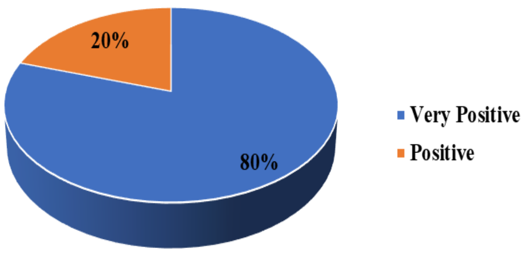
## 3. Results and Discussions

### 3.1. Practicality of the ARI Physics Textbook from the Perspectives of Teachers and Students

In addition to validity, the research questions also include the practical aspects of using the ARI physics textbook in the context of real learning. The results of the teachers' response showed an average score of 3.75 (very positive category), while the students' response showed 80% very positive and 20% positive, with no negative response.




(a)




(b)

**Figure 2: Percentage of response of teachers (a) and students (b) to the ARI physics textbook**

These findings align with the technology acceptance model (TAM), which posits that people accept technology based on how useful they perceive it to be (perceived usefulness) and how easy it is to use (perceived ease of use) (Han & Sa, 2022; Kamal et al., 2020). The positive response from both teachers and students shows that the ARI physics textbook meets both criteria. Compared to previous studies which reported the resistance of teachers to new technologies owing to technical complexity or additional workload (Stacey et al., 2023), the results of this study suggest that the integration of AR into familiar print-digital textbooks can reduce barriers to adoption. This reinforces the position of this research as a sustainable and realistic model of AR integration for school contexts.

### 3.3. Effectiveness of the ARI Physics Textbook on Students' Critical Thinking Skills

Table 3 shows the results of the descriptive analysis of students' critical thinking skills before and after using the ARI physics textbook. The average scores increased from the pre-test to the post-test, suggesting that students' critical thinking skills improved after the intervention. However, the post-test scores were more spread out than the pre-test scores, which means that the amount of improvement varied among students.

**Table 3: Descriptive statistics**

| Statistics | Mean | SD | Min | Max |
|---|---|---|---|---|
| **Pre-test** | 56.69 | 7.90 | 42.00 | 75.00 |
| **Post-test** | 69.56 | 15.09 | 31.82 | 100.00 |

A normality test was conducted before performing inferential analysis to determine whether parametric tests were appropriate. The Shapiro–Wilk test results in Table 4 indicate that the pre-test and post-test data for critical thinking ability are normally distributed ($p > 0.05$). Therefore, the data meet the normality assumption, allowing for valid analysis using the paired sample t-test.

**Table 4: Tests of normality (Shapiro–Wilk)**

| Data | Statistic | df | Sig. | Remarks |
|---|---|---|---|---|
| **Pre-test** | 0.940 | 35 | 0.058 | Normal |
| **Post-test** | 0.958 | 35 | 0.199 | Normal |

The paired-samples t-test results in Table 5 indicate a statistically significant difference between the pre-test and post-test critical thinking scores of students. The significance value was below the set threshold, suggesting that using the ARI physics textbook helps to improve the critical thinking skills of students (Wibowo, 2023).

**Table 5: Paired-samples test of CT skills**

| Pair | Mean Difference | SD | Std. Error Mean | t | df | Sig. (2-tailed) |
|---|---|---|---|---|---|---|
| **Post-test – Pre-test** | 12.87 | 10.39 | 1.76 | 7.36 | 34 | 0.001 |

To clarify the level of effectiveness of the increase that occurred, the normalised gain (N-Gain) analysis was performed and presented in the form of a category distribution in Figure 3. The distribution showed that most students experienced improved critical thinking skills in the medium to high category, which indicates that learning interventions are not only statistically effective, but also pedagogically relevant.

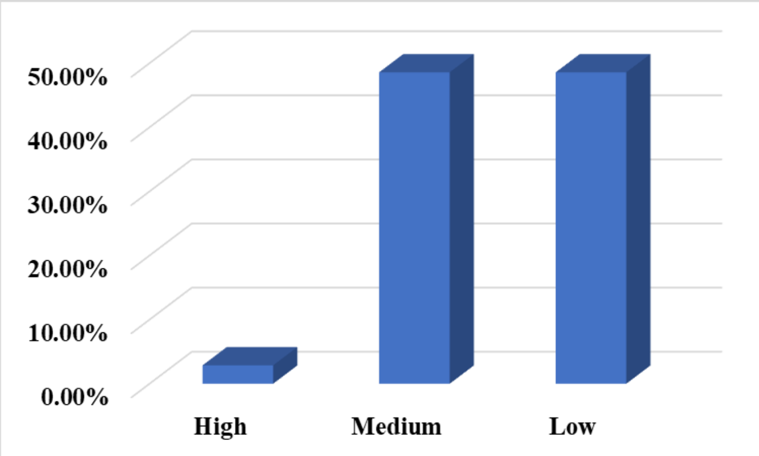



**Figure 3: Distribution of N-Gain category of students' critical thinking skills**

Furthermore, to assess the strength of the impact of the intervention practically, an effect size calculation was performed using Cohen's *d*, as shown in Table 6. The effect size value in the large category confirms that the improvement of the critical thinking skills of students after learning using the ARI physics textbook has a substantial and meaningful impact in the context of physics learning.

**Table 6: Effect size of the intervention (Cohen's *d*)**

| Comparison | *N* | Mean (Pre-test) | Mean (Post-test) | Mean Difference | SD of Difference | Cohen's *d* | Effect Magnitude |
|---|---|---|---|---|---|---|---|
| **Pre-test vs Post-test** | 35 | 56.69 | 69.56 | 12.87 | 10.39 | 1.24 | Large |

The research aimed to determine whether students' critical thinking skills improved after using the ARI-Physics Textbook. The average score increased from 56.69 before the lessons to 69.56 after. A paired-samples t-test showed that this improvement was statistically significant ($p = 0.001$), and Cohen's *d* of 1.24 indicates a strong effect of the intervention. These results suggest that the ARI physics textbook helps students to develop their critical thinking skills. This improvement aligns with higher-order thinking theory, which holds that critical thinking develops when students analyse, evaluate, and synthesise information rather than just following procedures (Alexander, 2023; Kwangmuang et al., 2021; List & Sun, 2023).

The AR feature allows students to explore physical phenomena visually and interactively (Lai & Cheong, 2022; Prit Kaur et al., 2022), so they can test hypotheses, compare representations, and evaluate cause-and-effect relationships more deeply. This process is in line with the CT indicators, according to Ennis, especially in the aspect of explaining, concluding, and setting strategies (Septiany et al., 2024; Yu & Zin, 2022). Compared to previous studies that reported moderate improvement in CT through the use of conventional digital media (Higashigaito et al., 2022), the results of this study show that pedagogically integrated AR is able to produce stronger effects (Garzón et al., 2020; Perifanou et al., 2023). This reinforces the claim that visual-interactive technology has great potential in stimulating critical thinking skills (Martono & Aloysus, 2025), as long as it is designed to support the inquiry and reflection process.

### 3.4. Effectiveness of the ARI Physics Textbook on Students' Computational Thinking Skills

Table 7 shows the results of the descriptive analysis of students' computational thinking skills before and after using the ARI physics textbook. The data reveal a significant increase in average scores from the pre-test to the post-test, and the distribution of scores stayed fairly consistent. The low and similar standard deviation values for both tests suggest that most students improved their computational thinking skills at a similar rate.

**Table 7: Descriptive statistics**

| Statistics | Mean | SD | Min | Max |
|---|---|---|---|---|
| **Pre-test** | 58.49 | 3.19 | 52.50 | 63.50 |
| **Post-test** | 81.24 | 3.18 | 75.25 | 86.25 |

The paired sample t-test results in Table 9 show a statistically significant difference between students' pre-test and post-test scores in computational thinking skills. The significance value was much lower than the accepted threshold, indicating that using the ARI Physics Textbook greatly improves computational thinking skills.

**Table 8: Tests of normality (Shapiro–Wilk)**

| Data | Statistic | df | Sig. | Remarks |
|---|---|---|---|---|
| **Pre-test** | 0.959 | 35 | 0.216 | Normal |
| **Post-test** | 0.959 | 35 | 0.219 | Normal |

Test results paired sample t-test presented in Table 9 shows that there is a very statistically significant difference between the pre-test and post-test scores of students' computational thinking skills. The significance value obtained was far below the established level of trust, which indicates that learning using the ARI physics textbook has a very strong impact on improving computational thinking skills (Wibowo, 2023).

**Table 9: Paired-samples test of CompT skills**

| Pair | Mean Difference | SD | Std. Error Mean | t | df | Sig. (2-tailed) |
|---|---|---|---|---|---|---|
| **Post-test – Prtest** | 22.75 | 0.61 | 0.10 | 2219.73 | 34 | 0.000 |

To more comprehensively describe the level of effectiveness of the upgrade, the analysis normalised gain (N-Gain) is carried out and presented in the form of a category distribution in Figure 3. The distribution showed that the majority of students were in the category of high improvement, which confirms that learning interventions are effective not only in terms of statistical significance, but also from the point of view of pedagogical relevance (Kraft, 2020; Wong & Li, 2020).

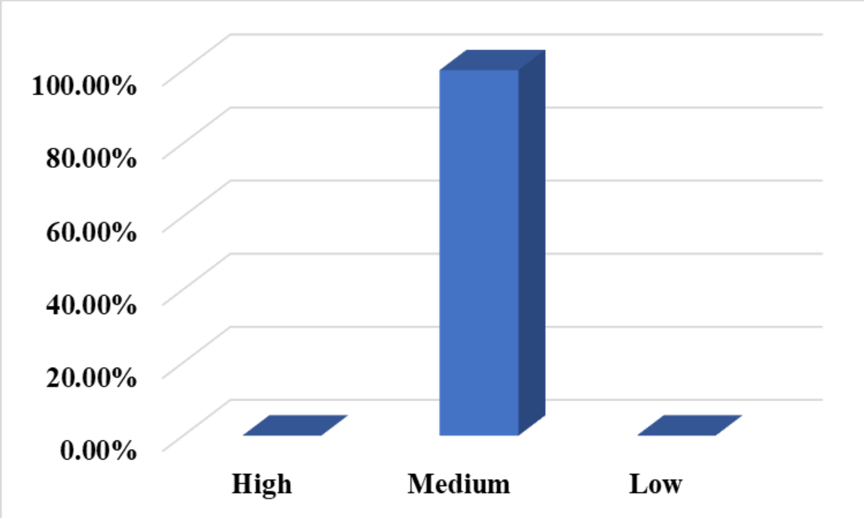



**Figure 4: Distribution category N-Gain CompT skills students**

Furthermore, the strength of the impact of the intervention was analysed through the calculation of effect size using Cohen's *d*, as shown in Table 10. The effect size value, which is in the very large category, confirms that the use of the ARI physics textbook has a very substantial influence on the development of the computational thinking skills of students, as well as has strong practical implications in the context of 21st century skill-based physics learning.

**Table 10: Effect size of the intervention (Cohen's *d*)**

| Comparison | N | Mean (Pre) | Mean (Post) | Mean Difference | SD of Diffe-rence | Cohen 's *d* | Effect Magnitude |
|---|---|---|---|---|---|---|---|
| **Pre-test vs Post-test** | 35 | 58.49 | 81.24 | 22.75 | 0.61 | > 2.00 | Very Large |

This study has examined how using the ARI physics textbook affects the CompT abilities of students. The results showed a clear improvement, with average scores rising from 58.49 before the intervention to 81.24 after. Statistical analysis confirmed a significant difference ($p < 0.001$), and Cohen's *d* was greater than 2.00, indicating a very large effect. These findings suggest that the learning intervention strongly supports the CompT development of students (Akugizibwe & Ahn, 2020; Higashigaito et al., 2022; Rich et al., 2021). In theory, these results align with the definition of computational thinking, which highlights decomposition, pattern recognition, abstraction, and algorithmic thinking (Lee & Malyn-Smith, 2020; Qian & Choi, 2023).

The AR feature allows students to visualise physics systems dynamically, breaking down complex problems into simpler components (Del Cerro Velázquez & Morales Méndez, 2021), as well as designing solution steps systematically. Compared to previous research that generally associated CompT with learning programming or robotics (Hsu et al., 2022), this study expands the scope of the literature by showing that AR-based physics learning is also a very effective vehicle for developing CompT. This reinforces the view that CompT is a crossdisciplinary skill that can be developed in an authentic, non-computational context.

The results of this study show that the ARI physics textbook is valid, practical, and effective at improving the critical thinking and computational skills of students. Each research question was answered with empirical evidence, covering validity, practicality, and the enhancement of both critical thinking and computational abilities. These results support cognitive load theory, which suggests that external visualisation can lower intrinsic cognitive load and help students to focus on higher-level thinking. The findings also support previous research showing that immersive technologies like AR can serve as a cognitive catalyst rather than just a visual aid. The main contribution of this study is the combined use of AR and textbooks to develop two advanced cognitive skills, an area that has not been widely studied. This research does not only support earlier findings but also broadens the theoretical and practical understanding of how AR can be used in physics education.

## 4. Conclusion

This study has evaluated the validity, practicality, and effectiveness of the ARI physics textbook for improving the CT and CompT skills of high school students. The findings show that the textbook has a very high level of theoretical validity, as validators agreed fully on its content and language. Teachers and students also gave very positive feedback, suggesting that the ARI physics textbook is practical and suitable for use in physics classes. Quantitative analysis revealed a significant improvement in the CT and CompT skills of students after using the textbook. The effect size was large for CT and even larger for CompT, showing that the intervention had a strong practical impact, not just statistical significance.

All research questions were answered with evidence from the study. These results are important for both science education practice and theory. In practice, the ARI physics textbook offers educators a new way to help students develop higher-level thinking skills through immersive technology. Theoretically, the study supports the idea that AR can be an effective cognitive tool when used thoughtfully in teaching, rather than just as a visual aid. However, the study has some limitations, including using only one group without a control group, and a small, specific sample. Future research should use a stronger experimental design, include more and diverse students, and examine the long-term effects of the ARI physics textbook on the advanced thinking skills of students.

**Conflict of Interest**
The author declares no conflict of interest in the study and acknowledges Philippine Normal University-Manila for its support.

**Acknowledgments**
Thank you to the Rector and Chairman of LP2M State University of Makassar, who provided the opportunity and support for the realisation of this article as an output of research funding.

**Funding Information**
This research was funded by the Directorate of Research and Community Service of the Republic of Indonesia with the master contract number 084/C3/DT.05.00/PL/2025 and the derivative contract number 2940/UN.36.11/LP2M/2025.

**Gen-AI Tools Declaration**
ChatGPT (OpenAI, 2026) and Grammarly (Grammarly Inc., 2026) were used to refine the language and grammar of the manuscript. The authors performed all research design, data analysis, and interpretations.

## 9. References

Adhikari, N. P. (2023). The use of critical thinking for organizational decisions. *GS WOW: Wisdom of Worthy Research Journal*, *1*(1), 47–55. https://doi.org/10.5281/zenodo.10440809

Akugizibwe, E., & Ahn, J. Y. (2020). Perspectives for effective integration of e-learning tools in university mathematics instruction for developing countries. *Education and Information Technologies*, *25*(2), 889–903. https://doi.org/10.1007/s10639-019-09995-z

Aldeeb, F. H., Sallabi, O. M., Elaish, M. M., & Hwang, G.-J. (2024). Enhancing students' learning achievements, self-efficacy, and motivation using mobile augmented reality. *Journal of Computer Assisted Learning*, *40*(4), 1823–1837. https://doi.org/https://doi.org/10.1111/jcal.12989

Alexander, P. A. (2023). "Here be dragons!" Mapping the realm of higher-order, critical, and critical-analytic thinking. *Educational Psychology Review*, *35*(2), 42. https://doi.org/10.1007/s10648-023-09762-0

Algerafi, M. A. M., Zhou, Y., & Oubibi, M. (2023). Unlocking the potential : A comprehensive evaluation of augmented reality and virtual reality in education. *Electronics*, *12*(18). https://doi.org/10.3390/electronics12183953

Alzahrani, N. M. (2020). Augmented reality: A systematic review of its benefits and challenges in e-learning contexts. *Applied Sciences*, *10*(16). https://doi.org/10.3390/app10165660

Ames, H., Glenton, C., & Lewin, S. (2019). Purposive sampling in a qualitative evidence synthesis: A worked example from a synthesis on parental perceptions of vaccination communication. *BMC Medical Research Methodology*, *19*(1), 1–9. https://doi.org/10.1186/s12874-019-0665-4

Aslam, M. (2024). Testing normality of data for uncertain level of significance. *Journal of Statistical Theory and Applications*, *23*(4), 480–499. https://doi.org/10.1007/s44199-024-00098-4

Borsboom, D., Maas, H. L. J. Van Der, Dalege, J., Kievit, R. A., & Haig, B. D. (2021). Theory construction methodology: A practical framework for building theories in psychology. *Perspectives on Psychological Science*, *16*(4), 756–766. https://doi.org/10.1177/1745691620969647

Braun, H. I., Shavelson, R. J., Zlatkin-Troitschanskaia, O., & Borowiec, K. (2020). Performance assessment of critical thinking: conceptualization, design, and implementation. *Frontiers in Education*, *5*(156), 1–10. https://doi.org/10.3389/feduc.2020.00156

Chacón, E. F., Pacheco, A., Ortiz, Y. G., Palacios, C., & Rojas, E. P. (2023). Educational innovation : The architecture of digital technologies as a catalyst for change in university teacher training. *Scientific Reports*, 1–8. https://doi.org/10.1038/s41598-023-48378-w

Chen, C.-H., Chan, W.-P., Huang, K., & Liao, C.-W. (2023). Supporting informal science learning with metacognitive scaffolding and augmented reality: effects on science knowledge, intrinsic motivation, and cognitive load. *Research in Science & Technological Education*, *41*(4), 1480–1495. https://doi.org/10.1080/02635143.2022.2032629

Coccia, M. (2020). The evolution of scientific disciplines in applied sciences: dynamics and empirical properties of experimental physics. *Scientometrics*, *124*(1), 451–487. https://doi.org/10.1007/s11192-020-03464-y

Cohen, S. D., Sharma, H., & Sharma, R. (2021). Primitive values of rational functions at primitive elements of a finite field. *Journal of Number Theory*, *219*, 237–246. https://doi.org/https://doi.org/10.1016/j.jnt.2020.09.017

Dargan, S., Bansal, S., Kumar, M., Mittal, A., & Kumar, K. (2023). Augmented reality : A comprehensive review. *Archives of Computational Methods in Engineering*, *30*(2), 1057–1080. https://doi.org/10.1007/s11831-022-09831-7

Del Cerro Velázquez, F., & Morales Méndez, G. (2021). Application in augmented reality for learning mathematical functions: A study for the development of spatial intelligence in secondary education students. *Mathematics*, *9*(4). https://doi.org/10.3390/math9040369

Denning, P. J., & Tedre, M. (2021). Computational thinking: a disciplinary perspective. *Informatics in Education*, *20*(1), 361–390. https://doi.org/10.15388/infedu.2021.21

Drljević, N., Botički, I., & Wong, L.-H. (2022). Investigating the different facets of student engagement during augmented reality use in primary school. *British Journal of Educational Technology*, *53*(5), 1361–1388. https://doi.org/https://doi.org/10.1111/bjet.13197

Etikan, I. (2016). Comparison of convenience sampling and purposive sampling. *American Journal of Theoretical and Applied Statistics*, *5*(1), 1. https://doi.org/10.11648/j.ajtas.20160501.11

Fadzil, M., Hanid, A., Nihra, M., & Mohamad, H. (2022). Effects of augmented reality application integration with computational thinking in geometry topics. In *Education and Information Technologies*. Springer US. https://doi.org/10.1007/s10639-022-10994-w

Garzón, J., Kinshuk, Baldiris, S., Gutiérrez, J., & Pavón, J. (2020). How do pedagogical approaches affect the impact of augmented reality on education? A meta-analysis and research synthesis. *Educational Research Review*, *31*, 100334. https://doi.org/https://doi.org/10.1016/j.edurev.2020.100334

Gil, S., Singh, U., Gutierrez, J., & Marks, S. (2022). Pedagogical design in education using augmented reality : A systematic review. *Interactive Learning Environments*, *32*(8). https://doi.org/10.1080/10494820.2023.2195445

Gill, A. S., Irwin, D., Long, P., Sun, L., Towey, D., Yu, W., Zhang, Y., & Zheng, Y. (2024). Enhancing learning in design for manufacturing and assembly: the effects of augmented reality and game-based learning on student's intrinsic motivation. *Interactive Technology and Smart Education*, *22*(1), 61–80. https://doi.org/10.1108/ITSE-11-2023-0221

Gregory, R., & Mcdaniels, T. (2005). Acceptable input: Using decision analysis to guide public policy deliberations. *Decision Analysis*, *2*(1), 4–16. https://doi.org/10.1287/deca.1050.0035

Gregory, V. L. (2021). Gregory research beliefs scale: Preliminary confirmatory factor analysis of convergent construct validity. *Journal of Evidence-Based Social Work*, *18*(5), 534–549. https://doi.org/10.1080/26408066.2021.1875096

Han, J.-H., & Sa, H. J. (2022). Acceptance of and satisfaction with online educational classes through the technology acceptance model (TAM): the COVID-19 situation in Korea. *Asia Pacific Education Review*, *23*(3), 403–415. https://doi.org/10.1007/s12564-021-09716-7

Higashigaito, K., Euler, A., Eberhard, M., Flohr, T. G., Schmidt, B., & Alkadhi, H. (2022).

contrast-enhanced abdominal CT with clinical photon-counting detector CT: assessment of image quality and comparison with energy-integrating detector CT. *Academic Radiology*, *29*(5), 689–697. https://doi.org/https://doi.org/10.1016/j.acra.2021.06.018

Hsu, T.-C., Chang, C., Wu, L.-K., & Looi, C.-K. (2022). Effects of a pair programming educational robot-based approach on students' interdisciplinary learning of computational thinking and language learning. *Frontiers in Psychology*, *13-2022*. https://www.frontiersin.org/journals/psychology/articles/10.3389/fpsyg.2022.888215

Ibiyemi, A., Mohd Adnan, Y., Daud, M. N., Olanrele, S., & Jogunola, A. (2019). A content validity study of the test of valuers' support for capturing sustainability in the valuation process in Nigeria. *Pacific Rim Property Research Journal*, *25*(3), 177–193. https://doi.org/10.1080/14445921.2019.1703700

Kafri, B. A. L. (2022). Critical thinking (CT) in sustainable higher education: Ensuring consistent CT perception-practice and identifying gaps between college instructors' and students' perceptions in advanced academic writing courses in the UAE. *Thinking Skills and Creativity*, *46*, 101182. https://doi.org/https://doi.org/10.1016/j.tsc.2022.101182

Kamal, S. A., Shafiq, M., & Kakria, P. (2020). Investigating acceptance of telemedicine services through an extended technology acceptance model (TAM). *Technology in Society*, *60*, 101212. https://doi.org/https://doi.org/10.1016/j.techsoc.2019.101212

Kelly, N., & Gero, J. S. (2021). Design thinking and computational thinking: a dual process model for addressing design problems. *Design Science*, *7*(e8), 1–15. https://doi.org/10.1017/dsj.2021.7

Koumpouros, Y. (2024). Revealing the true potential and prospects of augmented reality in education. *Smart Learning Environments*, *0*. https://doi.org/10.1186/s40561-023-00288-0

Kraft, M. A. (2020). Interpreting effect sizes of education interventions. *Educational Researcher*, *49*(4), 241–253. https://doi.org/10.3102/0013189X20912798

Kwak, S. (2023). Are only p-values less than 0 . 05 significant ? A p-value greater than 0.05 is also significant! *Journal of Lipid and Atherosclerosis*, *12*(2), 89–95.

Kwangmuang, P., Jarutkamolpong, S., Sangboonraung, W., & Daungtod, S. (2021). The development of learning innovation to enhance higher order thinking skills for students in Thailand junior high schools. *Heliyon*, *7*(6). https://doi.org/10.1016/j.heliyon.2021.e07309

Lai, J. W., & Cheong, K. H. (2022). Educational opportunities and challenges in augmented reality: Featuring implementations in physics education. *IEEE Access*, *10*, 43143–43158. https://doi.org/10.1109/ACCESS.2022.3166478

Lee, I., & Malyn-Smith, J. (2020). Computational thinking integration patterns along the framework defining computational thinking from a disciplinary perspective. *Journal of Science Education and Technology*, *29*(1), 9–18. https://doi.org/10.1007/s10956-019-09802-x

Lin, Y., & Yu, Z. (2023). A meta-analysis of the effects of augmented reality technologies in interactive learning environments (2012–2022). *Computer Applications in Engineering Education*, *31*(4), 1111–1131. https://doi.org/https://doi.org/10.1002/cae.22628

Ling, A., Yann, T., Ong, S., Sim, Y., Jared, N., & Jie, H. (2023). STEM Problem solving: inquiry, concepts, and reasoning. *Science & Education*, 381–397. https://doi.org/10.1007/s11191-021-00310-2

List, A., & Sun, Y. (2023). To clarity and beyond: situating higher-order, critical, and critical-analytic thinking in the literature on learning from multiple texts. *Educational Psychology Review*, *35*(2), 40. https://doi.org/10.1007/s10648-023-

09756-y

Martono, D., & Aloysus, S. (2025). Development of E-LKPD guided inquiry web augmented reality biodiversity material based on nepenthes variation to improve critical thinking abilities and psychomotor skills of e-phase students. *Journal of World Science*, *4*(8), 1095–1109. https://doi.org/10.58344/jws.v4i8.1486

Matović, N., & Ovesni, K. (2023). Interaction of quantitative and qualitative methodology in mixed methods research: integration and/or combination. *International Journal of Social Research Methodology*, *26*(1), 51–65. https://doi.org/10.1080/13645579.2021.1964857

Mendoza-Ramírez, C. E., Tudon-Martinez, J. C., Félix-Herrán, L. C., Vargas-Martínez, A., & Lozoya-Santos, J. D. J. (2023). Applied sciences augmented reality : Survey. *Applied Science*, *13*(18). https://doi.org/10.3390/app131810491

Miani, L. (2021). *Highlighting Interdisciplinarity between Physics and Mathematics in historical papers on special relativity: Design of blended activities for pre-service teacher education*. (Thesis, University of Bologna).

Nikou, S. A., Perifanou, M., & Economides, A. A. (2024). Development and validation of the teachers ′ augmented reality competences ( TARC ) scale. *Journal of Computers in Education*, *11*(4), 1041–1060. https://doi.org/10.1007/s40692-023-00288-6

Nykyporets, S. (2024). Information and communication technology (ICT) as a catalyst for lifelong learning and professionl growth. *Distance Education in Ukraine: Innovative, Normative-Legal, Pedagogical Aspects*, *1*(4), 125–136. https://doi.org/10.18372/2786-5495.1.18888

Palts, T., & Pedaste, M. (2020). A model for developing computational thinking skills. *Informatics in Education*, *19*(1), 113–128. https://doi.org/10.15388/INFEDU.2020.06

Perifanou, M., Economides, A. A., & Nikou, S. A. (2023). Teachers' views on integrating augmented reality in education: Needs, opportunities, challenges and recommendations. *Future Internet*, *15*(1). https://doi.org/10.3390/fi15010020

Potter, J. (2022). Critical analysis of critical thinking. *Journal of Media Literacy Education*, *14*(1), 108–123. https://doi.org/10.23860/JMLE-2022-14-1-8

Prit Kaur, D., Mantri, A., & Horan, B. (2022). Design implications for adaptive augmented reality based interactive learning environment for improved concept comprehension in engineering paradigms. *Interactive Learning Environments*, *30*(4), 589–607. https://doi.org/10.1080/10494820.2019.1674885

Qian, Y., & Choi, I. (2023). Tracing the essence: ways to develop abstraction in computational thinking. *Educational Technology Research and Development*, *71*(3), 1055–1078. https://doi.org/10.1007/s11423-022-10182-0

Rich, P. J., Mason, S. L., & O'Leary, J. (2021). Measuring the effect of continuous professional development on elementary teachers' self-efficacy to teach coding and computational thinking. *Computers & Education*, *168*, 104196. https://doi.org/https://doi.org/10.1016/j.compedu.2021.104196

Roebianto, A., Savitri, S. I., Aulia, I., Suciyana, A., & Mubarokah, L. (2023). Content validity: Definition and procedure of content validation in psychological research. *TPM - Testing, Psychometrics, Methodology in Applied Psychology*, *30*(1), 5–18. https://doi.org/10.4473/TPM30.1.1

Saad, A., & Zainudin, S. (2022). A review of project-based learning (PBL) and computational thinking (CT) in teaching and learning. *Learning and Motivation*, *78*, 101802. https://doi.org/https://doi.org/10.1016/j.lmot.2022.101802

Saiz, C., & Rivas, S. F. (2023). Critical thinking, formation, and change. *Journal of Intelligence*, *11*(12). https://doi.org/10.3390/jintelligence11120219

Saulius, T., & Malinauskas, R. K. (2021). Involvement of critical thinking education in university studies: A qualitative research. *European Journal of Contemporary Education*, *10*(1), 113–126. https://doi.org/10.13187/ejced.2021.1.113

Scavarelli, A., Arya, A., & Teather, R. J. (2020). Virtual reality and augmented reality in social learning spaces : a literature review. *Virtual Reality*, *0123456789*. https://doi.org/10.1007/s10055-020-00444-8

Septiany, L. D., Puspitawati, R. P., Susantini, E., Budiyanto, M., Purnomo, T., & Hariyono, E. (2024). Analysis of high school students' critical thinking skills profile according to Ennis indicators. *IJORER : International Journal of Recent Educational Research*, *5*(1), 157–167. https://doi.org/10.46245/ijorer.v5i1.544

Siedlecki, S. L. (2020). Understanding descriptive research designs and methods. *Journal of Clinical Nurse Specialist*, *February*, 8–12. https://doi.org/10.1097/NUR.0000000000000493

Silva, B. M. De, Higdon, D. M., Brunton, S. L., & Kutz, J. N. (2020). Discovery of physics from data : universal laws and discrepancies. *Frontiers in Artificial Intelligence*, *3*(25), 1–17. https://doi.org/10.3389/frai.2020.00025

Stacey, M., McGrath-Champ, S., & Wilson, R. (2023). Teacher attributions of workload increase in public sector schools: Reflections on change and policy development. *Journal of Educational Change*, *24*(4), 971–993. https://doi.org/10.1007/s10833-022-09476-0

Taconis, R., & Bekker, T. (2023). Challenge-based learning as authentic learning environment for STEM identity construction. *Frontiers in Education*, *8*. https://doi.org/10.3389/feduc.2023.1144702

Takács, V. L., Bubnó, K., Ráthonyi, G. G., Bába, É. B., & Szilágyi, R. (2020). Data warehouse hybrid modeling methodology. *Data Science Journal*, *19*(1), 1–23. https://doi.org/10.5334/dsj-2020-038

Tang, H. S., Haynes, R., & Houzeaux, G. (2021). A review of domain decomposition methods for simulation of fluid flows: concepts , algorithms , and applications. In *Archives of Computational Methods in Engineering* (Vol. 28, Issue 3). Springer Netherlands. https://doi.org/10.1007/s11831-019-09394-0

Tekdal, M. (2021). Trends and development in research on computational thinking. *Education and Information Technologies*, *26*, 6499–6529. https://doi.org/10.1007/s10639-021-10617-w

Triyono, A., Nuary, R. H., Permatasari, N., Yuni, Y., & Wibowo, T. (2024). The level of effectiveness of TPS and conventional methods judging from students ' geometry learning results using the N-Gain test. *Journal of Mathematics Education*, *10*(May), 142–156.

Tudor Car, L., Kyaw, B. M., Teo, A., Fox, T. E., Vimalesvaran, S., Apfelbacher, C., Kemp, S., & Chavannes, N. (2022). Outcomes, measurement instruments, and their validity evidence in randomized controlled trials on virtual, augmented, and mixed reality in undergraduate medical education: systematic mapping review. *JMIR Serious Games*, *10*(2), e29594. https://doi.org/10.2196/29594

Turner, C. (2022). Augmented reality , augmented epistemology , and the real-world web. *Philosophy & Technology*, 1–28. https://doi.org/10.1007/s13347-022-00496-5

Vieyra, R., & Himmelsbach, J. (2022). Teachers' disciplinary boundedness in the implementation of integrated computational modeling in physics. *Journal of Science Education and Technology*, 153–165. https://doi.org/10.1007/s10956-021-09938-9

Wang, Y. (2022). Effects of augmented reality game-based learning on students' engagement. *International Journal of Science Education, Part B*, *12*(3), 254–270. https://doi.org/10.1080/21548455.2022.2072015

Wibowo, F. C. (2023). Effects of augmented reality integration (ARI) based model physics independent learning (MPIL) for facilitating 21st-century skills (21-CS). *Journal of Technology and Science Education*, *13*(1), 178–192.

Wong, B. T., & Li, K. C. (2020). A review of learning analytics intervention in higher education (2011–2018). *Journal of Computers in Education*, *7*(1), 7–28.

https://doi.org/10.1007/s40692-019-00143-7

You, F., & He, H. (2022). A review of sustainable urban regeneration approaches based on augmented reality technology : A case of the Bund in Shanghai. *Sustainability*, *14*(19). https://doi.org/10.3390/su141912869

Yu, L., & Zin, Z. M. (2022). The critical thinking-oriented adaptations of problem-based learning models : a systematic review. *Frontiers in Education*, *8*. https://doi.org/10.3389/feduc.2023.1139987 OPEN

Yu, Z. (2024). RETRACTED ARTICLE: Meta-analyses of effects of augmented reality on educational outcomes over a decade. *Interactive Learning Environments*, *32*(8), 4739–4753. https://doi.org/10.1080/10494820.2023.2205899

Yuji, O. (2025). Visualization of theoretical frameworks in fundamental electromagnetics education. *Bulletin of KIKAN Education*, *11*, 1–23. https://doi.org/10.15017/7347995