

Enhancing Critical Thinking Through Augmented Reality-Based Nervous System E-Modules

Muhammad Nizar Maulana¹, Dadang Jaenudin¹, Irvan Permana¹,
Indriyani Rachman^{1,2}, Toru Matsumono³

nijarmaulana@email.com, dadang.jaenudin@unpak.ac.id, irvanpermana@unpak.ac.id,
r-indriyani@kitakyu-u.ac.jp, matsumoto-t@kitakyu-u.ac.jp

¹Graduate School, Universitas Pakuan, Bogor, Indonesia

²Graduate School of Environmental Engineering, The University of Kitakyushu, Kitakyushu, Japan

³Faculty of Environmental Engineering, The University of Kitakyushu, Kitakyushu, Japan

Article Info

Article history:

Submission jan 26, 2026
First Revised may 31, 2026
Accepted jun 21, 2026
Published jul 31, 2026

Keywords:

augmented reality learning
biology education
critical thinking skills
digital learning module
education technology

ABSTRACT

This study aims to develop an integrated nervous system e-module using Augmented Reality and to analyze its feasibility and effectiveness in improving the critical thinking skills of 11th-grade students. This study was primarily motivated by findings indicating deficiencies in students' analytical reasoning skills in science, with a specific focus on biology. This study employed the Research and Development method using the ADDIE model, which includes the Analysis, Design, Development, Implementation, and Evaluation stages. The study subjects consisted of 34 11th-grade students. The effectiveness test was conducted using a one-group pretest-posttest design. Critical thinking skills were measured using Ennis's indicators. The research results show that the e-module developed met very high feasible criteria based on evaluations by experts and practitioners, including 1 media expert, 1 content expert, and 15 teachers. Calculation results show that the CVI score falls into the "very good" category. Achieving a score so close to perfection proves that the integration of Augmented Reality technology into the science module has been presented accurately, systematically, and in accordance with applicable language and graphic standards. The results of the e-module's implementation proved effective in enhancing students' critical thinking skills, as evidenced by an increase in the average score from the pretest to the posttest with an N-gain in the moderate category, where the greatest progress occurred in the "Advanced Clarification" and "Basic Support" indicators. The decrease in the standard deviation (SD) indicates that this e-module can reduce gaps in students' understanding. Thus, this e-module is effective and suitable for use in enhancing students' critical thinking skills.

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Corresponding Author:

Irvan Permana
Universitas Pakuan
Email: irvanpermana@unpak.ac.id

How to cite:

Maulana, M. N., Jaenudin, D., Permana, I., Rachman, I., & Matsumono, T. (2026). Enhancing Critical Thinking Through Augmented Reality-Based Nervous System E-Modules. *Pedagogia: Jurnal Ilmiah Pendidikan*, 18(1), 67–81. <https://doi.org/10.55215/pedagogia.v18i1.89>

Introduction

Significant transformations have occurred across various domains of life, particularly in education, driven by rapid advances in science and digital technology. Within this transformation, technology has become an integral component of science learning, particularly in supporting students' understanding of concepts that are abstract and difficult to visualize. Byukusenge et al. (2023) emphasize that the development of learning technology is crucial for responding to the needs of science education, as many students continue to experience difficulties because scientific materials are often presented verbally and with limited variation. In essence, science learning should emphasize scientific processes while fostering logical, critical, and creative thinking so that students develop sound reasoning skills (Permanasari, 2016; Yuliati, 2017).

Consequently, science teachers are increasingly required to develop innovative learning approaches that make learning more meaningful, contextual, and responsive to students' needs. Educational technology can function as an important pedagogical tool by facilitating students' understanding of complex contextual materials and enabling them to establish deeper connections between scientific concepts and natural phenomena (Joshi, 2026; Listiadi, 2026; Etyarisky & Marsigit, 2022). Such integration is particularly important in preparing students to respond to the demands of 21st-century education while ensuring that educational goals can be achieved and meaningfully assessed (Supena et al., 2021). Ultimately, embracing these technologically enriched environments empowers students to transition from passive recipients of information into active, critical problem-solvers. By fostering such dynamic learning ecosystems, educators can cultivate a generation of scientifically literate individuals who are well-equipped to navigate future global challenges.

In the landscape of contemporary education, teachers are expected to cultivate interactive and innovative learning environments that support the development of the four essential 21st-century competencies: creativity, critical thinking, collaboration, and communication (Supena et al., 2021; Trisnawati & Sari, 2019). However, despite Generation Z's inherent adaptability to digital devices, the integration of technology within educational settings remains sub-optimal. In practice, instructional media are predominantly conventional and monotonous, with educators frequently relying on PowerPoint presentations laden with dense text and static two-dimensional images (Prasetya et al., 2026; Supriono & Rozi, 2018). This overreliance on passive delivery methods often fails to capture the interest of digital-native students, consequently hindering their cognitive engagement and active participation. Therefore, there is a pressing need to adopt more dynamic, interactive multimedia tools that effectively bridge the gap between students' digital fluency and the pedagogical demands of modern curricula.

Such limited visualization may reduce student engagement and constrain opportunities for developing an in-depth conceptual understanding of scientific phenomena. This condition is particularly problematic in science education, where students need to move beyond memorizing information toward interpreting phenomena, reasoning scientifically, and constructing conceptual relationships. Although interactive technologies have emerged as potential alternatives, their implementation in science classrooms remains relatively limited. One promising technology is Augmented Reality (AR), which can integrate virtual visual objects into the real environment in real time and display three-dimensional structures from multiple perspectives, thereby making abstract scientific concepts more tangible and accessible to learners (Efendi et al., 2021).

The application of AR consequently provides opportunities to create more immersive, interactive, and meaningful science learning experiences and potentially address limitations associated with conventional instructional approaches (Patmaniar et al., 2024). This potential

is particularly relevant to one of the central challenges in science education, namely enabling students to connect theoretical knowledge with real-life problems through higher-order thinking processes. Critical thinking is essential in this regard because students should not merely memorize scientific concepts but should also be able to analyze information, evaluate evidence, and independently formulate solutions to problems (Marini et al., 2026; Larson et al., 2024; Yuningsih et al., 2018). Without appropriate instructional media that stimulate these cognitive processes, the development of such competencies may remain constrained.

Digital learning instruments that can connect scientific content with real-world contexts are therefore increasingly important for supporting students' cognitive engagement. By embedding digital elements within authentic environments, AR can strengthen conceptual understanding and potentially overcome some of the challenges associated with problem-based learning, particularly when students are required to interpret complex phenomena and apply scientific concepts to contextual problems (Sriwahyuni, 2026; Utami, 2024; Ramdani et al., 2020). Thus, the integration of AR represents not merely a technological innovation but also a pedagogical opportunity to facilitate deeper conceptual engagement and higher-order thinking.

The urgency of this issue is further demonstrated by empirical conditions identified through observations at a senior high school. A preliminary study involving 105 students revealed an average critical thinking score of 49.45, with the majority of students classified within the low category. This finding was further supported by interviews with 21 science teachers from various schools, which indicated that the learning media predominantly used in science instruction remained conventional. The convergence of these findings suggests a discrepancy between the increasing demands for technology-enhanced, higher-order science learning and the current instructional practices experienced by students. This discrepancy highlights the need for innovative and interactive learning media that can more effectively support students' critical thinking development while addressing the limitations of conventional instructional practices.

This condition highlights the need for learning media that are not only digitally accessible but also capable of providing meaningful visualization, interaction, and opportunities for students to actively engage in scientific reasoning. In response to this need, an e-module integrated with augmented reality is proposed as an instructional solution for supporting the development of students' critical thinking skills. E-modules provide electronic learning materials that can incorporate animations, audio, and navigational features to create more interactive learning experiences, facilitate independent learning, and support the achievement of learning objectives (Sari et al., 2026; Latifah et al., 2020). The integration of AR within an e-module further provides opportunities to transform abstract scientific concepts into more concrete and contextual representations, thereby potentially strengthening students' engagement with scientific content and cognitive processes.

Despite the potential of e-modules and AR to enhance science learning, the integration of these two approaches remains important to investigate, particularly in relation to the development of students' critical thinking skills within the context of the identified instructional problems. Conventional e-modules may still provide a relatively monotonous learning experience; therefore, incorporating AR can introduce more dynamic visualization and interaction that connect digital representations with students' real-world learning environments. The novelty of this study lies in the integration of augmented reality into an e-module as a unified learning medium designed not only to improve the accessibility and attractiveness of digital science learning but also to deliberately support the development of critical thinking skills.

This integration is expected to address the identified gap between students' need for more engaging and cognitively stimulating learning experiences and the continued dominance of conventional learning media in science classrooms. The development of such a medium is therefore urgent because it responds simultaneously to the low critical thinking performance identified in the preliminary study and the need for more innovative technology-supported science learning. Accordingly, this study aims to develop an augmented reality-integrated e-module that provides an interactive and meaningful science learning experience and supports the improvement of students' critical thinking skills.

Method

This research employed a Research and Development (R&D) methodology anchored in the ADDIE design framework (Cresswell & Creswell, 2017). This development model comprises five systematic stages: Analysis, Design, Development, Implementation, and Evaluation. Selected through a purposive sampling approach, the study participants consisted of 34 eleventh-grade students from a public high school in Bogor. To assess the pedagogical impact, an effectiveness test was conducted utilizing a one-group pretest-posttest design. Within this framework, students' critical thinking skills were measured based on Ennis's established indicators. The tangible output of this development process was an electronic biology module focusing on the coordination system, innovatively integrated with AR technology. The integration of this immersive AR feature is specifically intended to visualize abstract biological processes, thereby stimulating higher-order cognitive functions. By rigorously following this structured R&D framework, the study ultimately aims to produce a valid, practical, and effective instructional tool that addresses the contemporary challenges of science education.

The Analysis Phase involves literature reviews and field observations to identify learning material needs, analyze content, and assess students' critical thinking skills through preliminary studies. The Design Phase focuses on designing the structure of the e-module and the augmented reality interface to be integrated into the e-module. The design and development phase focuses on designing the electronic module content and integrating 3D objects into the augmented reality application, which is then validated by experts in the fields of media and subject matter. This validation process involves collaboration between 3 academics (lecturers) and 15 practitioners (science teachers) to assess the suitability of the e-module product and the research instruments used. This stage focuses on four main parameters: content suitability, presentation, language, and graphic aspects. Data analysis was conducted using the Content Validity Ratio (CVR) method to measure the relevance of instrument items to the tested domain through the categories "appropriate" or "inappropriate." Subsequently, the Content Validity Index (CVI) was used to calculate the average CVR score of the items deemed valid by the experts (Almanasreh et al., 2019).

The implementation phase was carried out through a series of learning sessions organized into three main activities, 1) chapter 1 on the components of the nervous system, 2) chapter 2 on the central and peripheral nervous systems, and 3) chapter 3 on nervous system disorders. Each chapter was conducted using an integrated AR e-module involving 34 eleventh-grade students at the classroom by Problem Based Learning (PBL) model. This phase was carried out comprehensively to assess the practicality and final quality of the electronic module based on user feedback as a basis for product refinement. Therefore, this phase involved the design of pre- and post-tests to measure the product's effectiveness in enhancing critical thinking skills.

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The data collection instruments consist of media and material validation sheets, a critical thinking skills test based on Ennis's indicators comprising 20 multiple-choice questions administered during both the pretest and posttest, and a student feedback questionnaire. The validity and reliability of the critical thinking skills instrument will be tested to determine the extent to which a research instrument has a high level of accuracy and the level of stability and consistency of an evaluation instrument through Cronbach's Alpha testing. Quantitative data from the critical thinking ability test results will be analyzed using the N-gain test to determine the effectiveness of the e-module in enhancing students' critical thinking skills. Before calculating the N-gain value from the pre-test and post-test scores, the data must pass prerequisite tests such as normality and homogeneity tests. Once the data is proven to be normally distributed, the gain index value can be calculated using the applicable formula. N-Gain values can be categorized into three groups: high ($0.70 \leq n \leq 1.00$), moderate ($0.30 \leq n < 0.70$), and low ($0.00 \leq n < 0.30$).

Results and Discussion

Analysis Stage

The analysis stage was conducted to identify the basic requirements for developing e-modules for the nervous system (Maulita et al., 2023). Based on the analysis of teaching material requirements, it was found that 73% of students preferred digital-based teaching materials over printed ones. This is in line with the research by Rahmaningtyas et al (2022), which explains that electronic books are more popular because they are easy to carry and can be accessed anywhere and anytime, while conventional books are rarely preferred because they are difficult to access anywhere and are relatively more expensive. Although the variety of media used by teachers is quite high (97.3%), as many as 64.9% of students feel that the teaching materials currently available are not effective in supporting their learning process. Students expect teaching materials that have attractive visualisations, easy-to-understand language, interactivity, and contextual content. This is supported by Fitrio & Merliza (2023) statement that the teaching materials needed in the learning process are attractive, innovative, and easy to use in order to create interactive learning.

An analysis of learning difficulties shows that 62.2% of students consider biology to be a difficult subject due to the complex and abstract nature of the material. This is in line with the statement that many students still find it difficult to understand biology lessons, leading to misconceptions (Marjana et al., 2026; Resbiantoro & Setiani, 2022). Specifically, the nervous system material was identified as the most difficult to understand. According to Syamsurizal & Ardianti (2021), what makes biology material difficult is the characteristics of biology material, which contains abstract concepts that are difficult to understand. This forms the basis for curriculum analysis to determine learning outcomes, where students are expected to be able to understand the relationship between the structure of the nervous system and its function in responding to stimuli.

Critical thinking skills are the main focus at this stage. Initial analysis results indicate the need to develop teaching materials that can facilitate critical thinking indicators. This finding is reinforced by data from the 2024 education report card, which shows a significant decline in students' critical thinking scores, from 59.68 to 55.48. In line with this, the learning

quality score also declined from 64 to 62. This condition is reinforced by the results of a preliminary study of 105 students. The test results show that the average critical thinking score is only 49.45. Of the total respondents, 65.71% or around 69 students scored below 60, which is classified as moderate/low. based on an analysis of external and internal factors, it was found that school infrastructure, such as internet access and smartphone use in schools, was adequate to support the use of interactive e-modules. All of this analysis data formed the basis for the decision to develop an integrated augmented reality human nervous system e-module to strengthen students' critical thinking skills.

Design Stage

Based on the results of the needs analysis, an e-module on the human nervous system was developed that integrates AR. Based on a needs analysis of teaching materials, an AR enhanced e-module on the human nervous system was developed. Its primary purpose is to enhance critical thinking skills among eleventh-grade students. The material presented includes, 1) neuron structure; 2) central and peripheral nervous systems; 3) mechanisms of nerve function; and 4) nervous system disorders. The initial design process and implementation of the e-module were developed through the Canva platform, integrating Augmented Reality developed through the Assemblr Studio platform and integrating various other features to support the improvement of critical thinking skills.

The module is designed with an attractive layout, using a combination of colours, images and animations. The content of the module covers material divided into three chapters, namely nerve components, the central-peripheral nervous system, and nervous system disorders. Each chapter consists of theory, instructional videos and various interactive activities such as augmented reality (**Figure 1**).

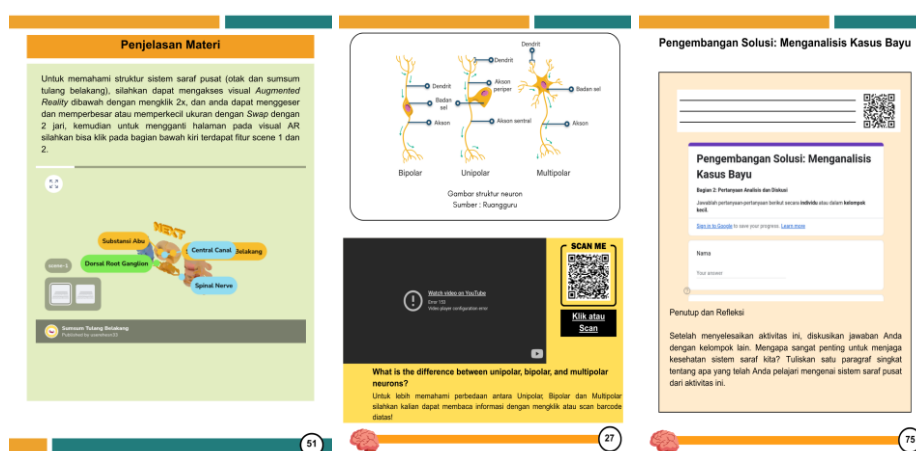


Figure 1. Interactive Activities

The designed e-module is integrated with AR to provide a highly interactive learning experience. While conventional AR applications typically require users to scan a barcode or marker via a smartphone camera to render 3D models, this project specifically develops a self-contained electronic platform. Consequently, the system is engineered to bypass the need for external camera-based scanning features. Instead, the interactive 3D objects are seamlessly embedded and directly accessible within the e-module's interface, as illustrated in **Figure 2**. This seamless integration significantly enhances user accessibility by eliminating potential technical barriers associated with third-party scanning applications. Ultimately, by streamlining the interaction process, students can maintain their cognitive focus entirely on the instructional material rather than navigating complex technological requirements (Ditasona et al., 2026; Sriwahyuni, 2026).

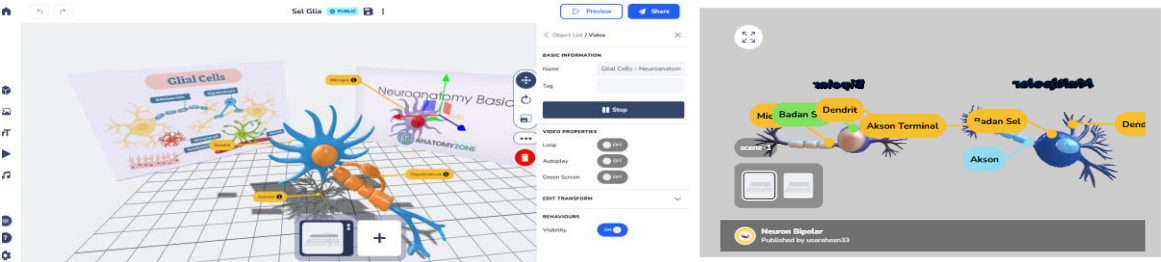


Figure 2. Augmented Reality Display

Development Stage

Within the development phase, the e-module undergoes a rigorous validation process to determine its viability. This assessment involves critical evaluations by both content specialists and media professionals to guarantee that the digital module is appropriate for practical application. The results of e-module development must be validated before use. According to Fitriyah et al. (2023), module validation particularly by experts, i.e. subject matter experts and media experts, must be conducted before the e-module is used in learning activities. This ensures that the e-module to be used is valid and appropriate for its intended purpose. The findings of this validation are presented below.

Table 1. Validity Results from Experts

Aspect	Percentage
Subject Matter Expert	
Content Suitability	98%
Presentation Suitability	92%
Language Suitability	95%
Kesesuaian dengan Suitability for critical thinking skills	95%
Average per expert	95.6%
Media Expert	
Cover Page Display Presentation	79%
Table of Contents Presentation	93%
Presentation on each page and subchapter	89%
Usefulness and practicality	100%
Augmented Reality Quality	75%
Augmented Reality Functionality	93%
Suitability and Graphics	100%
Average per expert	89.8%

The e-module incorporating augmented reality was rigorously evaluated by an expert and a panel of 15 high school science teachers. According to the data presented in Table 1, this evaluation yielded a mean validation score of 92.7%. This “highly valid” rating confirms that the instructional material meets the necessary educational standards and is deemed appropriate for classroom implementation based on the expert’s validation. To further substantiate these findings, the validation results were analyzed utilizing the CVR and CVI calculation methods with 15 high school science teachers. The detailed outcomes of this quantitative analysis are provided in Table 2.

Table 2. CVR and CVI Results

No	Aspect	CVR	CVI
1	Content Quality	1	1
2	Presentation Quality	0,95	0,87
3	Language	1	1
4	Graphics	1	1

Based on the validation results by science teachers, the analysis showed that in terms of content, language, and graphic design, a CVR score of 1.00 was obtained, meaning that all assessment items were considered highly essential by the experts or valid. Meanwhile, in

the presentation suitability aspect, a CVR score of 0.95 was obtained, meeting the validity criteria. This indicates that, in terms of both content and technical aspects, the developed e-module has met the functional requirements as a learning tool at schools. In addition to the analysis by aspect, a CVI calculation was also performed to assess the overall quality of the instrument. The results showed a CVI score of 0.99, which falls into the excellent category. Based on this assessment, the augmented reality-integrated e-module on the nervous system is deemed suitable and ready to be piloted in classroom learning.

Implementation Stage

The implementation stage of the AR integrated e-module, focusing on the human nervous system, was carried out as a limited classroom trial involving eleventh-grade students at a state senior high school. The primary content of this validated electronic module was systematically distributed into three main chapters to ensure a structured learning progression: chapter 1 explored the fundamental components of the nervous system, chapter 2 examined the central and peripheral nervous systems, and chapter 3 addressed various nervous system disorders. This initial phase served as a crucial step to evaluate the module's functionality and practicality in a real educational setting.

Prior to initiating the core instructional activities, the teacher provided a comprehensive introductory session to familiarize students with the e-module, granting them sufficient time to navigate its interactive features. Subsequently, the learning process was orchestrated utilizing the PBL model. The strategic combination of the PBL framework with immersive AR technology during this limited trial was intentionally designed to observe and measure the improvement in students' critical thinking skills. By engaging with complex, problem-based scenarios and visualizing abstract biological mechanisms through the e-module, students were encouraged to analyze information deeply, thereby facilitating both content comprehension and higher-order cognitive development (Sari et al., 2026; Meirani et al., 2026; Handayani et al., 2024).

Results of Critical Thinking Skills Improvement

To evaluate the progress in critical thinking abilities, a comparison was conducted between pre-assessment and post assessment scores. The evaluation utilized a consistent set of 20 multiple-choice items for both stages. A summary of the descriptive statistic for these results is presented in the table below.

Table 3. Descriptive Statistics of Critical Thinking Skills

	N	Range	Minimum	Maximum	Mean	Standard deviation	Sig. (Shapiro-Wilk)
Pretest	34	63	15	80	59.97	16.85	0.001
Posttest	34	25	75	100	88.35	6.72	0.072

Based on **Table 3** above, it can be seen that the use of e-modules has a significant positive impact on the critical thinking skills of students. This can be seen from the increase in the mean score, which rose by 28.38 points. Furthermore, the standard deviation decreased from 16.85 to 6.72. This decrease indicates that e-modules can reduce the gap in understanding between students. As a result, students' abilities become more evenly distributed at a higher level. To decide between parametric and non-parametric statistical methods, a normality assessment was performed during the initial data analysis. Given the sample size of 34 participants (N=34), the Shapiro-Wilk test was prioritized for its superior precision in small samples (under 50). Based on the test results, it was found that the pretest data was not normally distributed with a significance value of 0.001 and the posttest data was normally distributed with a value of 0.072. This caused the hypothesis test to switch to using non-parametric statistics, namely the Wilcoxon Signed Rank Test.

Table 4. Results of the Wilcoxon Signed Rank Test

Aspect	Category	N	Mean
Negatif Rank	Post-test < Pre-test	0	0.00
Positive Ranks	Post-test > Pre-test	34	
Ties	Post-test = Pre-test	0	
Total		34	
Test Statistics		Posttest-Pretest	
Asymp. Sig. (2-tailed)		.000	

Based on **Table 4**, the results show that none of the students experienced a decline or had the same score between the pretest and posttest results. Thus, all students experienced an increase in critical thinking skills. Meanwhile, based on the statistical test table in the figure, the Asymp. Sig value is < 0.05 , so it means there is a significant effect. Since the value obtained is 0.000, the findings demonstrate a substantial shift in the student's ability to think critically following the implementation of the e-module. Consequently, this robust empirical evidence confirms that the interactive AR integrated e-module serves as a highly effective pedagogical intervention for elevating students' higher-order cognitive capabilities in science education.

This is demonstrated through hypothesis testing using a Paired Samples t-Test analysis to compare students' critical thinking skill achievements before (pre-test) and after (post-test) using the e-module. Based on the descriptive data obtained (**Table 5**), there is a significant increase in the students' average critical thinking scores. The linear relationship between the pre- and post-intervention conditions is reinforced by the correlation results (Paired Samples Correlations), which show a positive result, significant, and consistent improvement in students' critical thinking abilities. result proves that the use of the AR integrated e-module exerts a statistically highly significant difference or influence on students' critical thinking skills.

Table 5. Paired Sampel Test and Effect Size (Cohen's d)

Variabel	N	Mean	SD	Correlation (r)	Sig. (p) Correlation	t	df	Sig. (2- tailed)	Effect Size (Cohen's d)
Pre-test	34	56.94	16.11	0.815	0.000	-	33	0.000	2.481
Post-test	34	82.14	9.14			14.468			

Based on the data analysis conducted, this study also measures the effectiveness of developing an AR integrated e-module in improving students' critical thinking skills. N-Gain score reached 0.5992 and the precentages is 59.92%, which means quite effective to be implemented in the learning. The magnitude of the effectiveness or the actual impact of the developed media, an effect size test was conducted using Cohen's d formula. Based on the calculation results, a Cohen's d value of 2.481 was obtained. According to the interpretation criteria, a treatment is categorized as the strong or large effect category. Theoretically and practically, the high effectiveness of this AR integrated e-module in boosting critical thinking skills occurs due to the characteristics of AR technology itself. Through the utilization of AR, learning objects that are abstract or difficult to observe directly can be visualized into interactive three-dimensional (3D) objects in real-time.

According to [Fatih and Monika \(2021\)](#), students' learning abilities are well-facilitated through augmented reality technology. Moreover, the integration between digital objects and the physical environment in AR allows students to more easily comprehend complex spatial relationships and various abstract concepts. Consequently, this visualization stimulates students' curiosity and facilitates them in conducting analysis, evaluation, and problem-solving components that constitute the primary indicators of critical thinking skills.

These findings align with a study by [Ditasona et al. \(2026\)](#), in which students reported finding it easier to learn and expressed greater interest in learning through the use of e-modules. Meanwhile, the implementation of electronic modules rooted in PBL significantly enhances the development of critical thinking skills. This aligns with the research found that the use of electronic modules based on PBL is effective in supporting the development of critical thinking skills ([Rahmani & Hikmawan, 2025](#); [Gunawan et al., 2024](#)). Thus, the use of electronic modules especially problem-based ones greatly supports activities that foster students' critical thinking skills. Furthermore, interactive electronic modules significantly enhance student engagement in learning, thereby improving critical thinking skills. This is supported by research conducted by [Latifah et al. \(2020\)](#), which found that the use of interactive electronic modules can enhance students' critical thinking skills.

Through interactive and attractive three-dimensional object visualizations, AR technology is capable of optimizing students' learning experiences. The process of directly observing, manipulating, and interacting with these AR-based geometric solid models helps students shift from simple visual understanding toward deeper, more reflective learning, while simultaneously stimulating higher-order cognitive skills. According to [Qorimah & Utama \(2022\)](#), AR technology offers distinct advantages in delivering more interactive, attractive, and user-friendly learning experiences. In addition to having a simple and flexible model structure that can be easily combined with other learning media, the utilization of AR also tends to be efficient, as it requires relatively affordable costs for both its production and operational processes.

Evaluation Stage

The final stage of the development framework, evaluation was conducted to assess the overall quality, practicality, and pedagogical effectiveness of the newly developed AR integrated e-module after its implementation across chapters one to three. Rather than solely measuring student proficiency, this stage fundamentally aimed to evaluate how successfully the e-module's interactive design facilitated subject matter comprehension and stimulated critical thinking skills. To assess the product's cognitive impact, data were drawn from a 20-item multiple-choice assessment designed specifically to reflect the module's instructional goals. Furthermore, a comprehensive questionnaire was administered to gather direct user feedback regarding the e-module's usability, interface interactivity, and its capacity to enhance learning motivation. Collectively, these empirical findings served as critical benchmarks to determine whether the AR integrated e-module had successfully met its design objectives as a valid, engaging, and highly effective educational tool.

The development of an AR integrated e-module on the nervous system has successfully produced a digital learning resource that is valid, practical, and has broad implications. This instructional framework focuses on examining the interactions between various development elements at each specific stage ([Rayanto & Sugianti, 2020](#)). Such a systematic approach ensures that the entire e-module development process proceeds smoothly. The development cycle commences with an analysis phase, which is aimed at identifying the root causes of existing learning issues and determining the specific needs for the e-module's creation. Building upon the insights gathered during this initial analysis, the subsequent phases of design, development, implementation, and evaluation are methodically executed to finalize a robust and interactive educational product.

Furthermore, [Jibril & Çakır \(2023\)](#) state that augmented reality technology opens up avenues for deeper student interaction, fosters learning motivation, and provides educational value that boosts learning effectiveness. Meaningful student learning experiences can be realized due to the role of AR in providing a self-directed, active, interactive, discovery-based, and error-safe blended learning ecosystem ([Prasetya et al., 2026](#); [Utami, 2024](#); [Fatih](#)

& Monika, 2021). Therefore, the implementation of this technology serves as a solution to various instructional barriers while simultaneously creating an interactive learning ecosystem to optimize students' potential, knowledge, and skills. Consequently, the use of AR can assist students in comprehending more complex contexts.

The findings of this research offer significant implications for science education, demonstrating that an AR integrated e-module, particularly when coupled with a PBL model, can effectively enhance students' critical thinking skills and engagement. Practically, it provides educators with a validated, self-contained pedagogical tool that seamlessly visualizes abstract biological concepts without the burden of external scanning applications. However, this study is not without its limitations. The research was conducted on a relatively small purposive sample of 34 eleventh-grade students within a single institution, which may restrict the broad generalizability of the results to other educational contexts. Furthermore, the instructional content was limited exclusively to the human nervous system, and the module's optimal performance inherently relies on the availability of compatible electronic devices. Therefore, future studies are recommended to involve larger, more diverse demographic groups, expand the subject matter, and consider varying technological infrastructures to further validate the e-module's broader applicability.

Conclusion

Findings from this study indicate that the AR integrated e-module on the nervous system serves as an effective instructional medium to foster critical thinking of eleventh-grade students. Data reveals a substantial growth in students critical thinking skills, evidenced by the significant upward trend in their mean scores after using the module. Statistically, the effectiveness of using this media is classified as quite effective. In addition, the use of this e-module has succeeded in reducing the gap in understanding among students, as indicated by a decrease in the standard deviation score. Thus, the integration of AR technology in e-modules is able to provide an interactive learning experience and facilitate the understanding of abstract biological concepts compared to conventional media. Future development of the e-module should expand beyond the nervous system to include other abstract biology topics that require complex 3D visualization, alongside intensive training for teachers given that the use of Augmented Reality technology among educators is still very limited.

Author Contributions

Conceptualization was contributed by MNM, DJ, and IP; methodology by MNM, IP, and IR; and formal analysis by MNM, DJ, IP, and TM. Investigation was conducted by MNM, DJ, and IP, with the original draft written by MNM, DJ, and IP. Review and editing were performed by MNM and IP, while supervision was provided by DJ, IP, IR, and TM.

Funding

This research received no external funding.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Use of Artificial Intelligence

Generative AI was used to assist in drafting portions of the manuscript. All AI-generated text was critically reviewed, revised, and verified by the authors. The authors assume full responsibility for the accuracy and integrity of the final manuscript.

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