Promoting AR-Scaffolded Inquiry Model in Science Learning to Improve Students' Critical Thinking and Communication Skills

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***Abstract*—Junior high school students in Indonesia often face difficulties in analyzing and communicating scientific issues related to daily life due to limited scaffolding for exploring abstract concepts and insufficient guidance for scientific communication. Inquiry-based learning fosters students' critical thinking and communication skills, while Augmented Reality (AR) strengthens these processes by enhancing visualization and engagement in science learning. However, no study has yet integrated inquiry and AR to improve critical thinking and communication skills in science learning. Therefore, to address this gap, this study analyzes the effect of the Augmented Reality–Scaffolded Inquiry (AR-SI) model, which combines interactive AR visualization of scientific phenomena with structured scaffolding stages to guide students' inquiry processes, on students' critical thinking and communication skills. A quasi-experimental study with a non-equivalent control group design was employed to evaluate the model's effectiveness. The sample consisted of 60 ninth-grade students from one of the public junior high schools in Semarang City, Indonesia, selected through convenience sampling. The experimental class (30 students) received the AR-Scaffolded Inquiry treatment, while the control class (30 students) engaged in the conventional inquiry method routinely used in the school's science classes. Data were collected through pre-test, intervention, and post-test procedures. Results show that students in the experimental group demonstrated greater improvement in both critical thinking and communication skills, with N-gain scores of 0.56 and 0.89, respectively, compared to 0.35 and 0.65 in the control group. These findings indicate that integrating AR-SI can effectively enhance students' higher-order thinking and communicative competence. The AR-SI model thus presents a promising technology-integrated pedagogical framework for fostering essential 21st-century scientific competencies.**

***Keywords*—augmented reality, communication skills, critical thinking skills, scaffolded inquiry learning, science learning**

I. Introduction

The rapid transformation toward the Society 5.0 era has placed increasing demands on students to master 21st-century competencies, particularly the 4Cs: critical thinking, creative thinking, collaboration, and communication. These competencies are essential for developing higher-order thinking, problem-solving abilities, and effective participation in scientific and social discourse. However, students in Indonesia continue to face considerable challenges in achieving these competencies. Research in [1] reports that junior high school students still demonstrate limited ability to apply scientific knowledge to daily life, experience difficulties in problem-solving, and require more time to make decisions. Similarly, studies in [2] show that students often struggle to express opinions, engage in discussions, and make evidence-based judgments. These conditions reflect the persistence of learning environments that emphasize rote memorization rather than exploration and reasoning, thereby offering limited scaffolding for critical and communicative engagement in science learning.

In the context of science education, students' learning challenges are further compounded by the abstract and complex nature of scientific concepts, which are often difficult to visualize through conventional teaching methods based on text or 2D images [3–5]. Topics such as the digestive system or neural coordination require dynamic visualization and interaction to be understood meaningfully by students [6, 7]. Yet, hands-on learning is frequently constrained by limited laboratory resources, time, and safety considerations [8]. These conditions highlight the need for pedagogical innovations that can make abstract scientific phenomena more accessible and meaningful while simultaneously fostering students' reasoning and communication skills. In response, various studies have explored the integration of digital technologies, particularly Augmented Reality (AR) to improve students' communication, conceptual understanding, and scientific reasoning [9–12]. AR enables students to interact directly with 3D representations of abstract concepts, providing immersive experiences that strengthen mental visualization and cognitive retention [13].

Beyond visualization, effective science learning requires structured pedagogical frameworks that actively promote critical thinking and communication. Inquiry-based learning is recognized as one such model, encouraging students to

investigate questions, test hypotheses, and communicate their findings through evidence-based reasoning [14–17]. However, despite its effectiveness, inquiry learning often poses cognitive challenges that require scaffolding, an adaptive instructional support that guide students through complex problem-solving processes [18–20]. Scaffolding not only helps students construct knowledge systematically but also facilitates their ability to express reasoning clearly and logically. When combined with AR, scaffolded inquiry offers the potential to enhance students' analytical and communicative engagement through interactive visualization and guided inquiry exploration [21–24].

Existing studies have predominantly examined AR and inquiry learning separately, focusing either on visualization or on process engagement. Few studies have explicitly investigated their integration to enhance both critical thinking and communication skills in a unified pedagogical framework. This research addresses that gap by developing and implementing an Augmented Reality–Scaffolded Inquiry (AR-SI) model designed to improve students' higher-order thinking and scientific communication. Therefore, this study aims to analyze whether learning through the AR-SI model significantly enhances students' critical thinking and communication skills compared to conventional inquiry-based learning.

II. Literature Review

A. AR-Scaffolded Inquiry Model in Science Learning

Contemporary science education is increasingly aimed at cultivating students who can think critically, communicate effectively, and apply scientific reasoning to address real-world problems. This shift reflects the broader transformation of educational paradigms that emphasize inquiry, collaboration, and technology integration as central components of 21st-century learning. Science learning, therefore, is not only concerned with content mastery but also with developing students' ability to construct explanations, analyze evidence, and engage in meaningful discussions about scientific phenomena [25]. To achieve these outcomes, educators must design learning environments that combine conceptual understanding with inquiry-based exploration supported by digital technology, thereby making scientific learning more interactive, evidence-oriented, and student-centered.

In response to these needs, various studies have explored the use of computing technology to enhance students' engagement [9], conceptual understanding [10], and scientific reasoning skills [11, 12]. This is particularly relevant for Generation Z students, who have grown up in an era where digital interaction is an integral part of daily life [26]. Consequently, the integration of Education 4.0 principles as well as personalized, data-driven, and gamified learning environments is becoming increasingly essential [27, 28]. Among emerging educational technologies, Augmented Reality (AR) has gained special attention because it allows students not only to visualize scientific structures but also to interact with them dynamically. For instance, AR enables students to visualize the digestive system or observe neural impulse transmission processes in real time [13], transforming abstract concepts into tangible experiences that promote deeper understanding and engagement. Studies have shown that AR can increase students' motivation, conceptual retention, and spatial reasoning in science learning [21–23]. Furthermore, AR encourages innovation and adaptability, preparing students to face the continuous evolution of digital and social environments [29–31].

However, technology alone is not sufficient to ensure effective science learning. Meaningful engagement requires structured guidance that supports students in navigating complex inquiry tasks. This is where the scaffolded inquiry approach plays a crucial role. Inquiry-based learning positions students as investigators who construct knowledge through questioning, experimenting, and reasoning based on evidence [32–34]. Yet, without scaffolding, students may struggle to organize ideas, connect data with conclusions, or remain engaged in inquiry activities [18–20]. Scaffolding provides adaptive instructional support that helps students move from initial dependence toward independent mastery, facilitating problem-solving, data evaluation, and systematic communication of results. Prior studies confirm that scaffolded inquiry strengthens both conceptual understanding and scientific process skills while enhancing confidence and persistence in learning [17].

Integrating AR into the scaffolded inquiry model offers a pedagogical synergy that can optimize both visualization and reasoning processes. In this model, AR acts as an interactive medium that allows students to manipulate 3D scientific objects, simulate experiments, and explore causal relationships, while the scaffolding components provide structured guidance through prompts, feedback, or digital cues that direct students' inquiry activities. This combination supports critical thinking by engaging students in analysis, inference, and evidence-based reasoning [14, 15], while also developing communication skills through collaborative exploration, peer discussion, and presentation of findings [24, 35]. AR further facilitates visualization of abstract phenomena and complex mechanisms that are otherwise inaccessible in traditional learning [36, 37].

B. Student Critical Thinking

Critical thinking is an essential component of scientific literacy and a central goal of 21st-century education. According to Ennis [38], critical thinking refers to "reasonable reflective thinking that is focused on deciding what to believe or do," emphasizing interpretation, inference, evaluation, explanation, and self-regulation. Within the context of science learning, critical thinking enables students to analyze problems, evaluate assumptions, interpret data, and identify relevant evidence to construct logical conclusions [39–42]. According to Mediawati and Azizi [43], students who possess strong critical thinking skills can analyze and evaluate information effectively, draw conclusions based on relevant evidence, and engage in open-minded reasoning processes. These skills also foster intellectual autonomy, encouraging students to question the validity of claims, anticipate potential consequences, and make well-reasoned decisions [44, 45]. Similarly, Facione [46] asserts that critical thinking encompasses both cognitive and dispositional dimensions, including inquisitiveness, open-mindedness, and systematic reasoning, which are vital for developing reflective and independent

thinkers.

In science education, critical thinking serves as the cognitive foundation for inquiry-based learning, problem-solving, and scientific communication. Students must not only understand scientific content but also evaluate sources, construct arguments, and justify their reasoning using empirical evidence. Research has demonstrated that active learning environments, such as those supported by digital technologies and guided inquiry can significantly enhance critical thinking by promoting exploration, hypothesis testing, and reflection [47, 48]. Furthermore, the use of scaffolding strategies, including question prompts and guided reflection, can help students move from surface-level reasoning to deeper analytical thinking [14, 41]. In this regard, integrating technology such as Augmented Reality (AR) into scaffolded inquiry models provides dynamic visualizations and interactive feedback that support the development of critical thinking. AR-based learning allows students to engage with abstract scientific concepts in authentic contexts, enabling them to analyze relationships, infer mechanisms, and evaluate outcomes which are core indicators of critical thinking proficiency.

C. Student Communication Skill

Communication skills are fundamental to effective science learning, as they enable students to articulate their ideas, explain reasoning, and engage meaningfully in scientific discourse. Communication in the learning process is not merely the act of exchanging information but a complex cognitive process involving listening, interpreting, and constructing meaning collaboratively [49]. In science education, the curriculum explicitly incorporates communication as a dimension that supports integrity, awareness, tolerance, systematic thinking, and the ability to express ideas using precise scientific language [50]. Effective communication skills allow students to express their understanding of scientific phenomena clearly and coherently, both orally and in writing [51–54]. This competence helps students formulate structured explanations, use appropriate terminology, and justify their arguments logically. Moreover, communication in science learning is not a one-way process; it also demands active listening, the ability to respond constructively, and meaningful interaction with peers and teachers [32, 53, 55].

Beyond expressing ideas, communication skills play a critical role in supporting the development of higher-order thinking processes such as reasoning, problem-solving, and decision-making. Empirical evidence shows that when students are given opportunities to communicate their reasoning through discussion, argumentation, or written explanation, their understanding becomes more refined and conceptually integrated [56]. According to Reith-Hall *et al*. [49, 50], communication-centered learning enhances students' reflective thinking and self-regulation, allowing them to become more confident and self-aware learners. Furthermore, communication skills have been found to correlate positively with critical thinking, as students who communicate effectively tend to analyze and evaluate information more deeply [57, 58]. In the context of science learning, models such as inquiry-based learning and collaborative problem solving can foster both critical and communicative competence by engaging students in scientific argumentation and peer dialogue [59]. Therefore, communication skills must be intentionally nurtured in learning environments that provide structured scaffolding and interactive media to encourage expression, feedback, and reasoning within authentic scientific contexts.

III. Materials and Methods

A. Research Methods

This study employed quasi-experimental with a non-equivalent control group design to examine the effectiveness of the AR-Scaffolded Inquiry learning model in enhancing students' critical thinking and communication skills. This design allows for the comparison of learning outcomes between an experimental class and a control class that received different instructional treatments while maintaining similar learning environments.

B. Participants

The research was conducted at one of the public junior high schools (SMP Negeri) located in Semarang City, Indonesia. The study was implemented during the 2024/2025 academic year. Two ninth-grade classes were selected as research samples through convenience sampling, considering accessibility and the school's scheduling arrangements. Each class consisted of 30 students, resulting in a total of 60 participants. The experimental class received treatment using the AR-Scaffolded Inquiry learning model, while the control class participated in regular inquiry-based learning that followed the school's existing teaching materials and instructional procedures. The learning implementation in both classes was carried out over three weeks, with equivalent learning objectives and assessment coverage to ensure fairness across conditions.

C. Instrument Validation

Two primary instruments were employed in this study, a critical thinking test in essay format and a communication skills questionnaire. Both instruments were developed and validated through expert judgment to ensure content relevance, construct alignment, and clarity of items. The critical thinking instrument was developed based on the indicators proposed by [38], which include: (1) elementary clarification, (2) building basic support, (3) inference, (4) advanced clarification, and (5) strategies and tactics. The test initially consisted of 15 open-ended essay items developed to assess students' critial thinking abilities within science learning contexts. The validation process was conducted through expert judgment involving two science education lecturers and one science teacher, resulting in a validity coefficient of 0.84, indicating that the instrument was highly valid and suitable for research purposes.

Following the validation, a limited field try-out was conducted with 30 students from a class not involved in the main study to examine the quality and reliability of each test item. The students' responses were analyzed using ANATES V.4 software, which is specifically designed to evaluate the psychometric properties of educational test items, including validity, reliability, level of difficulty, and discriminating power. The analysis results showed that five items were rejected due to low discriminating power or poor validity, three items required revision, and seven items were accepted

without modification. The rejected items were excluded from the final version, while the revised items were refined and subsequently included in the test. Thus, the final critical thinking test consisted of 10 validated and reliable essay items, all of which were used in the main study to measure students' critical thinking skills before and after the learning intervention.

Meanwhile, the communication skills instrument was developed in the form of a questionnaire adapted from [60]. It measured two main indicators of communication competence: (1) oral communication skills, which include the ability to express ideas clearly and interact effectively during discussions or presentations, and (2) written communication skills, which involve the ability to organize and convey ideas coherently in written form using appropriate scientific language. The questionnaire consisted of 20 Likert-scale statements reflecting both written and oral communication performance. Expert judgment involving two science education lecturers and one science teacher, resulting in a validity coefficient of 0.76, indicating that the instrument was valid and feasible for data collection. The validated questionnaire was directly implemented in the data collection phase to measure students' communication skills in both the experimental and control groups.

D. Data Collection Technique

Data collection was conducted in two phases, pre-test and post-test for both the experimental and control classes. The pre-test aimed to identify students' initial levels of critical thinking and communication skills before the intervention, while the post-test was administered after the completion of learning activities to assess improvement. In the experimental class, students participated in the AR-Scaffolded Inquiry learning sessions, which integrated Augmented Reality (AR) media with structured scaffolding to guide inquiry-based problem-solving. The implementation of learning in this class followed a series of instructional phases illustrated in Fig. 1. Meanwhile, the control class received learning through a conventional inquiry model supported by 2D images as visual aids, using the school's regular learning materials and teacher-led guidance without AR integration or structured scaffolding support.

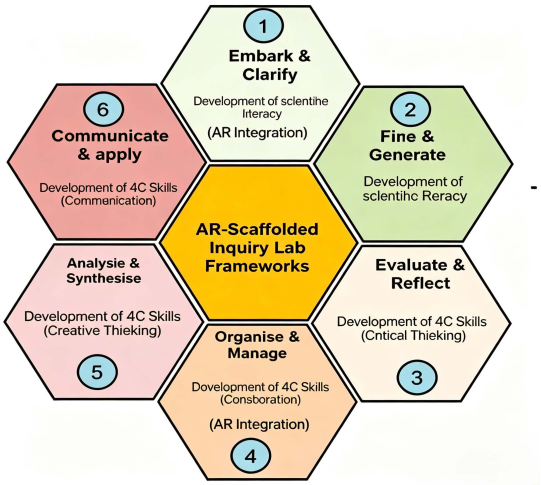

Fig. 1. AR-scaffolded inquiry lab frameworks.

E. Data Analysis Technique

Data were analyzed using both descriptive and inferential statistical techniques. Descriptive statistics, including the mean and normalized gain (N-Gain), were used to illustrate the improvement in students' critical thinking and communication skills. Prior to conducting inferential tests, prerequisite analyses were performed. The normality of the data was examined using the Shapiro–Wilk test, and the result indicated that the data were normally distributed. Homogeneity was then tested using Levene's Test for Equality of Variances, and the results confirmed that the data were homogeneous. Since the assumptions for parametric testing were met, hypothesis testing was carried out using the paired t-test to determine the significance of differences between pre-test and post-test scores in both the experimental and control groups.

To evaluate the effect of the AR–Scaffolded Inquiry model, the following research hypotheses were tested:

H_0: There is no significant improvement in students' critical thinking and communication skills after learning with the AR–Scaffolded Inquiry model.

H_a: There is a significant improvement in students' critical thinking and communication skills after learning with the AR–Scaffolded Inquiry model.

This test uses $\alpha = 0.05$, and the decision-making is as follows.

H_a accepted if $\alpha \geq P_{value}$

H_a rejected if $\alpha < P_{value}$

Overall, the combination of descriptive analysis, assumption testing, and inferential procedures provides a rigorous analytical framework that ensures the accuracy, validity, and interpretive clarity of the findings regarding the effectiveness of the AR–Scaffolded Inquiry model on students' critical thinking and communication skills.

IV. Result and Discussion

A. Students' Critical Thinking Skills

The quantitative analysis of students' critical thinking skills was conducted to determine the effectiveness of the AR-Scaffolded Inquiry learning model compared to the conventional inquiry approach assisted by 2D images. The data were obtained from pre-test and post-test results administered to both classes. The results for the experimental and control classes are presented separately. The data from the pre-test and post-test of critical thinking skills of the experimental class are presented in Fig. 2.

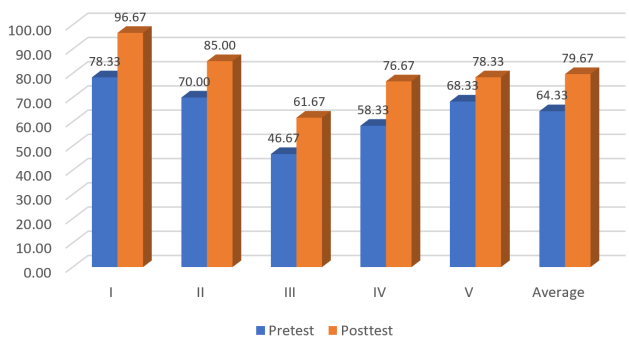

Fig. 2. Average pre-test and post-test scores of students' critical thinking skills in experimental class.

Based on the analysis of the experimental class data, learning through the AR-Scaffolded Inquiry model resulted

in a substantial improvement in students' critical thinking skills. As shown in Fig. 2, the students' average pre-test score was 64.33, which increased to 79.67 in the post-test following the implementation of the AR-Scaffolded Inquiry model. The N-gain score was calculated at 0.56, which is categorized as moderate according to [61]. These findings indicate that the integration of Augmented Reality media with scaffolded inquiry activities effectively supported students in developing a deeper understanding of scientific concepts, enhancing analytical reasoning, and promoting reflective thinking throughout the learning process. Among the critical thinking indicators, elementary clarification obtained the highest post-test score, whereas inference demonstrated the lowest improvement. The pre-test and post-test results of the control class are presented in Fig. 3.

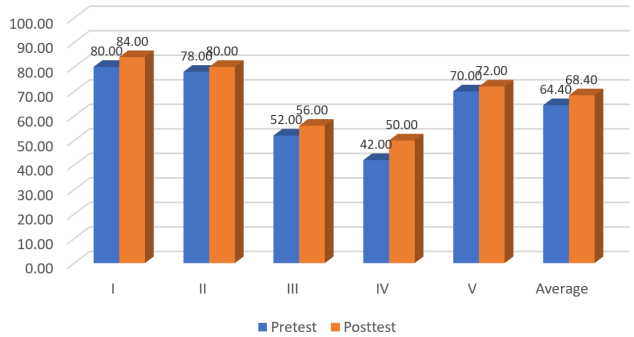

Fig. 3. Average pre-test and post-test scores of students' critical thinking skills in control class.

In contrast, the control class, which received instruction through a conventional inquiry model assisted by 2D images, showed a lower degree of improvement. As displayed in Fig. 3, the average pre-test score in the control class was 64.40, which increased slightly to 68.40 in the post-test. The N-gain value was 0.35, which is also categorized as moderate [61]. Indicator-level analysis revealed that elementary clarification achieved the highest score, whereas advanced clarification showed the lowest. Although an improvement was observed, the gain remained relatively limited, indicating that conventional inquiry learning supported by static 2D visuals was less effective in stimulating students' critical thinking processes, particularly in connecting scientific ideas to real-world contexts and in constructing evidence-based reasoning.

Based on the inferential statistical analysis, the independent t-test of the post-test data between the experimental and control classes yielded a significance value (Sig. 2-tailed) of 0.025, which is lower than $\alpha = 0.05$. This result indicates a statistically significant difference in students' critical thinking skills between the two groups. Accordingly, the null hypothesis (H_0) is rejected and the alternative hypothesis (H_a) is accepted. Therefore, it can be concluded that the implementation of the Augmented Reality–Scaffolded Inquiry (AR-SI) model was significantly more effective in improving students' critical thinking skills compared to the conventional inquiry model assisted by 2D images. This finding highlights that the integration of interactive AR visualization with structured scaffolding created a more meaningful and reflective learning environment that effectively fosters students' higher-order thinking skills.

The significant difference between the experimental and control groups demonstrates that the integration of Augmented Reality–Scaffolded Inquiry (AR-SI) effectively enhances students' critical thinking skills in science learning. This improvement can be attributed to the way AR-SI allows students to engage directly with dynamic scientific visualizations while receiving structured guidance throughout all phases of inquiry. In this study, the AR-SI model was implemented in a practical-oriented setting to ensure that students could connect hands-on experimentation with digital visualization and scaffolded reasoning. The learning sequence began with students conducting laboratory activities involving reflex and voluntary movements to observe physiological responses directly. After gathering data, students completed a worksheet that guided them to describe observations, identify variables, and formulate preliminary explanations. They then explored AR-based visualizations embedded in the scaffolded inquiry worksheet, enabling them to examine neural pathways, ion exchange processes, and synaptic mechanisms through three-dimensional interactive models. Scaffolded prompts directed students to analyze discrepancies between their predictions and the AR simulations, interpret how neural impulses propagate in the human body, and justify the physiological responses observed during the practicum. This integration of physical experimentation, AR-enhanced conceptual exploration, and structured scaffolding provided the foundational conditions under which students' critical thinking skills could develop.

The AR-SI learning process shaped how students organized their reasoning during inquiry activities. The structured sequence of hands-on experimentation, guided worksheets, and AR-supported exploration encouraged students to follow a logical flow when processing information, from observation to explanation. By engaging with scaffolded questions and visual cues at each inquiry stage, students were supported in monitoring their own thinking, revisiting initial assumptions, and refining explanations based on evidence. This process fostered a more systematic approach to scientific reasoning, preparing students to engage more deeply with higher-order thinking tasks and setting the foundation for the development of multiple dimensions of critical thinking observed in the experimental class.

Students in the experimental class demonstrated the development of multiple dimensions of critical thinking, particularly in their ability to analyze causal relationships, evaluate evidence, and construct justified scientific explanations. Using AR, they were able to observe biological mechanisms that are normally invisible, such as impulse transmission, synaptic activity, and ion exchange within neurons, which enabled them to make evidence-based interpretations. As illustrated in Fig. 4, during reflex testing activities, students interpreted how stimuli travel through sensory and motor pathways by linking AR-based neural pathway visualizations with the outcomes of their laboratory experiments. These forms of reasoning reflect essential components of critical thinking, including explanation, interpretation, and inference. This finding aligns with prior research showing that mobile AR applications can enhance students' reasoning and visualization abilities in science

contexts [62], and that AR-supported cultural or contextual learning can strengthen analytical and representational thinking [63]. Likewise, the study by Zhang *et al*. [64] demonstrates that progressive scaffolding steps substantially improve students' reasoning abilities by supporting them as they construct knowledge systematically.

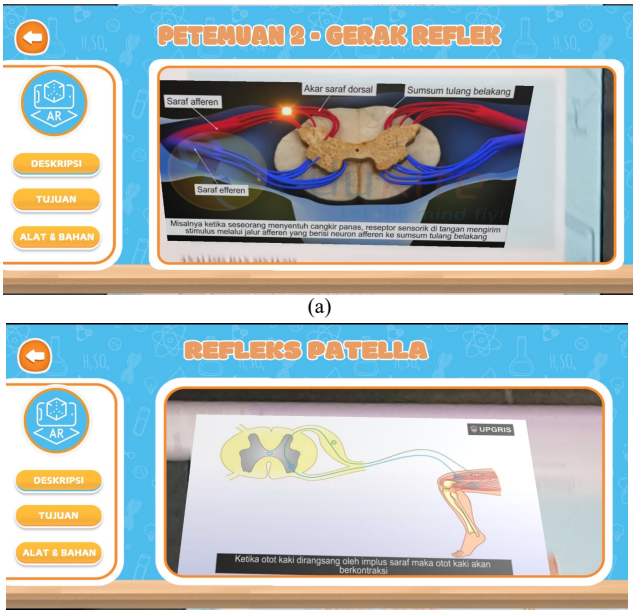

Fig. 4. Visualization of the augmented reality–scaffolded inquiry (AR-SI) (a) locomotor–nervous system (b) locomotor–muscular system.

The distinctive feature of the AR-SI model lies in its dual mechanism that combines immersive AR visualization with systematic scaffolding across inquiry phases. Unlike conventional AR-based learning that primarily emphasizes visualization, AR-SI incorporates guided questioning, reflection prompts, and iterative feedback loops that direct students to analyze, critique, and synthesize information. These scaffolding components encouraged students to articulate complex neural processes, identify relevant variables, distinguish between reflex and voluntary responses, and construct mechanistic explanations that connect real-time observations with scientific theory. In comparison to traditional inquiry learning, AR-SI addresses the challenge of abstract concept exploration by embedding real-time AR representations that make microscopic or intangible biological processes visible and cognitively accessible. This synergy enables students not only to observe and explore phenomena but also to interpret, reason, and construct scientific understanding more effectively.

Among the indicators of critical thinking, elementary clarification achieved the highest gain in the experimental class. Students showed improved ability to describe biological events clearly and logically, such as explaining the sequence of nerve impulse transmission during reflex actions or identifying key structures involved in synaptic processes when visualized through AR. The immersive AR representations supported students in recognizing essential elements of a concept, distinguishing relevant from irrelevant information, and verbalizing these ideas coherently. This aligns with previous research showing that inquiry-based science learning with AR strengthens students' ability to construct scientific explanations and engage in fundamental reasoning [65]. Conversely, the inference indicator demonstrated the lowest improvement. Drawing conclusions and generating hypotheses from observed data, for example predicting how disrupted ion channels could influence signal transmission, requires higher-order reasoning skills that usually develop over longer periods and with more sustained scaffolding support. Similar findings in informal science learning contexts using AR and metacognitive scaffolding also reported limited growth in students' inferential reasoning despite improvements in conceptual understanding [65]. Overall, these results show that the combination of interactive visualization and structured scaffolding in AR-SI learning not only improves conceptual comprehension but also systematically supports the development of multiple dimensions of critical thinking.

B. Students' Communication Skills

The quantitative analysis of students' communication skills was conducted to examine the effectiveness of the AR-Scaffolded Inquiry (AR-SI) learning model compared to the conventional inquiry approach assisted by 2D images. Data were collected from pre-test and post-test results administered to both the experimental and control classes. The comparative results for each class are presented separately to illustrate the improvement patterns in students' communication performance. Data on students' communication skills in the experimental class are presented in Fig. 5.

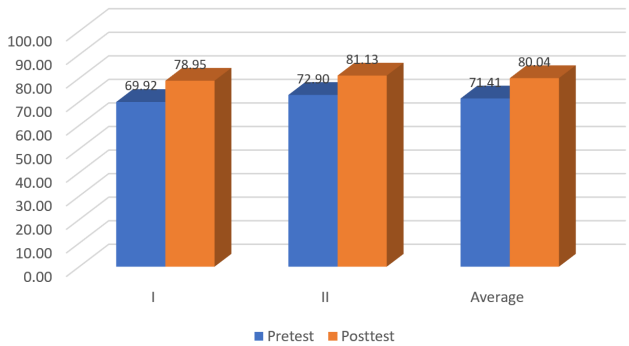

Fig. 5. Average pre-test and post-test scores of students' communication skills in experimental class.

Based on the analysis results in the experimental class, learning through the AR-Scaffolded Inquiry model resulted in a significant improvement in students' communication skills. As presented in Fig. 5, the students' average pre-test score was 71.41, which increased to 80.04 in the post-test after implementing the AR-SI model. The N-gain score was calculated at 0.89, which falls into the high category according to Hake [61]. This result shows that integrating Augmented Reality with structured scaffolding effectively enhances students' communication processes, particularly in expressing ideas clearly, providing relevant explanations, and engaging more confidently in discussions during science learning activities. Among the two communication indicators assessed, written communication showed the highest post-test improvement, while oral communication demonstrated the lowest.

In contrast, the control class taught using a conventional inquiry model assisted by 2D images showed less

improvement. As illustrated in Fig. 6, the average pre-test score was 71.50, which slightly increased to 72.80 in the post-test. The obtained N-gain value was 0.65, categorized as moderate [61]. Although there was some improvement, it was relatively limited. This suggests that using static two-dimensional visuals in the inquiry process was less effective in enhancing students' ability to articulate scientific concepts. It was also less effective in supporting coherent and persuasive communication of reasoning. As in the experimental class, written communication achieved the highest post-test score, whereas oral communication was the lowest.

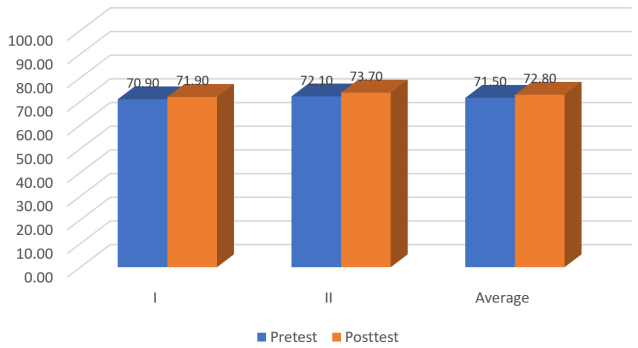

Fig. 6. Average pre-test and post-test scores of students' communication skills in control class.

Based on the inferential statistical analysis, the independent t-test of the post-test data between the experimental and control classes yielded a significance value (Sig. 2-tailed) of 0.017, which is lower than $\alpha = 0.05$. This result indicates a statistically significant difference in students' communication skills between the two groups. Accordingly, the null hypothesis (H_0) is rejected and the alternative hypothesis (H_a) is accepted. Thus, the AR-Scaffolded Inquiry learning model was significantly more effective in enhancing students' communication skills compared to the conventional inquiry model. The improvement suggests that integrating Augmented Reality with scaffolded inquiry activities facilitates concept understanding. It also strengthens students' ability to articulate ideas, exchange arguments, and communicate scientific reasoning clearly and confidently during the learning process.

The improvement in communication skills can be attributed to the interactive and immersive nature of AR-SI learning, which allows students to visualize complex systems and exchange interpretations collaboratively. Augmented Reality facilitates active meaning-making through visual and spatial representations, while scaffolding ensures that communication occurs within structured inquiry stages that promote questioning, reasoning, and articulation of ideas. As shown in Fig. 7, students engaged in collaborative discussions while using AR to explain observed phenomena, ask questions, and justify their interpretations to peers. This aligns with [66–68], which highlighted that learning environments combining visual media and inquiry-based interaction help students organize thoughts coherently and express them verbally and in writing. Through AR-SI, students become active communicators rather than passive recipients, constructing and negotiating meaning with peers, which makes their communication more purposeful and scientifically grounded.

(a) (b)

Fig. 7. Student communication activities (a) teacher assisting students in using AR; (b) peer discussion during inquiry activities.

Interestingly, written communication showed greater improvement than oral communication. This suggests that students felt more confident and organized expressing their ideas in writing, as it provided additional time for reflection and conceptual structuring. In contrast, oral communication required spontaneous articulation and confidence, which some students still found challenging. Similar findings were reported by Lev-ari [34], who noted that students with stronger communication competence tended to display positive interpersonal behavior and greater engagement, while those with weaker oral fluency may experience hesitation or discomfort during group discussions. Moreover, AR-based inquiry activities, which often culminated in written reflections or report sharing, provided more frequent opportunities for students to practice scientific writing than extended oral discourse [69, 70].

Overall, these findings affirm that integrating Augmented Reality with scaffolded inquiry not only enhances conceptual understanding but also effectively develops communication competence, particularly in written expression. This finding is consistent with prior research in technology-integrated STEM learning contexts, which demonstrated that digital interactions enhance students' motivation, confidence, and science communication skills across diverse settings [71, 72].

V. Conclusion

The implementation of the Augmented Reality–Scaffolded Inquiry (AR-SI) model in science learning has proven effective in enhancing students' critical thinking and communication skills. By integrating Augmented Reality visualization with structured scaffolding in inquiry-based learning, students can conceptualize abstract scientific phenomena more concretely, establish meaningful relationships between concepts, and communicate their understanding both orally and in writing. The findings show that students engaged in AR-SI learning demonstrate stronger abilities in providing clear explanations, applying scientific reasoning strategies, and expressing investigation results effectively. Therefore the AR-SI model is highly recommended for adoption by science teachers as an innovative learning approach that not only fosters critical thinking and scientific communication but also promotes active and engaging classroom interactions.

Considering that the improvement in critical thinking skills was at a moderate level, future studies are encouraged to implement the AR-SI model over longer instructional periods to examine its sustained effects and potential for achieving higher levels of improvement. Future research is recommended to apply the AR-SI model in different

educational levels, across various science topics or disciplines to test its adaptability and broader impact on students' scientific literacy and learning engagement.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

The authors' contributions to this article include: Muhammad Syaipul Hayat supervised and coordinated the overall research process; Sumarno developed and validated the research instrument; Noora Qotrun Nada designed the Augmented Reality application and research kit; Ali Ismail, Surya Gumilar, and Saprudin, as the Katalis research grant consortium team, provided methodological and statistical consultation; Ade Ihtiar performed the data processing and visualization; Ghurrotul Bariroh analyzed the findings and composed the manuscript draft; Safa Amal Hayati assisted in field data collection. All authors had approved the final version.

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REFERENCES

[1] A. Kadir, T. Zulqarnain, A. Takda, M. S. Assingkily, and M. Ahmad, "Junior high school students' science literacy skills based on the Nature of Science Literacy Test (NOSLiT)," *Jurnal Pendidikan IPA INdonesia*, vol. 14, no. 1, pp. 93–101, 2025. doi: 10.15294/jpii.v14i1.15739

[2] N. Andriani, E. A. Patriot, M. A. Azhari, and A. D. Florentina, "Evaluating argumentation skills: Science literacy and scientific approach in junior high school," *Jurnal Inovasi Pendidikan IPA*, vol. 11, no. 1, pp. 284–295, 2025.

[3] A. M. Amin, R. Adiansyah, and N. Hujjatusnaini, "The contribution of communication and digital literacy skills to critical thinking," *J. Pendidik. Sains Indonesia. (Indonesian J. Sci. Educ*), vol. 11, no. 3, pp. 697–712, 2023. doi: 10.24815/jpsi.v11i3.30838

[4] E. Etkina and G. Planinsic, *The Investigative Science Learning Environment: A Guide for Teacher Preparation and Professional Development*, IOP Publ., 2024.

[5] Y. Hwang, D. Shin, and H. Lee, "Students' perception on immersive learning through 2D and 3D metaverse platforms," *Educ. Technol*. vol. 71, no. 4, pp. 1687–1708, 2023.doi: 10.1007/s11423-023-10238-9

[6] A. Bahri, W. M. Hidayat, K. P. Putra, N. A. Ainun, and N. Arifin, "The relationship between students' perception to the learning media, digital literacy skills, and self-regulated learning with students' learning outcomes in the rural area," *J. Technol. Sci. Educ*., vol. 14, no. 2, pp. 588–606, 2024. doi: 10.3926/jotse.2513

[7] R. R. Tapia, I. Fernández, J. Bobo-Pinilla, and J. Delgado-Iglesias, "Teaching digestive system: Spanish pre-service teacher's learning difficulties and alternative conceptions," *Eurasia J. Math. Sci. Technol. Educ.*, vol. 19, no. 4, 2023. doi: 10.29333/EJMSTE/13037

[8] B. Bermejo *et al*., "AR/VR teaching-learning experiences in Higher Education Institutions (HEI): A systematic literature review," *Informatics*, vol. 10, no. 2, pp. 1–16, 2023. doi: 10.3390/informatics10020045

[9] N. Gericke, P. Högström, and J. Wallin, "A systematic review of research on laboratory work in secondary school," *Stud. Sci. Educ*., vol. 59, no. 2, pp. 245–285, 2023. doi: 10.1080/03057267.2022.2090125

[10] R. Elmoazen, M. Saqr, M. Khalil, and B. Wasson, "Learning analytics in virtual laboratories: A systematic literature review of empirical research," *Smart Learn. Environ*., vol. 10, no. 1, 2023. doi: 10.1186/s40561-023-00244-y

[11] P. P. Nechypurenko, S. O. Semerikov, and O. Y. Pokhliestova, "Cloud technologies of augmented reality as a means of supporting educational and research activities in chemistry for 11th grade students," *Educ. Technol. Q.*, vol. 2023, no. 1, pp. 69–91, 2023. doi: 10.55056/etq.44

[12] M. Kousloglou, E. Petridou, A. Molohidis, and E. Hatzikraniotis, "Assessing students' awareness of 4Cs skills after mobile-technology-supported inquiry-based learning," *Sustain.*, vol. 15, no. 8, 2023. doi: 10.3390/su15086725

[13] A. E. Ibisu, "Development of a gamification model for personalized e-learning," arXiv e-prints, 2024.

[14] M. L. Styers, P. A. Van Zandt, and K. L. Hayden, "Active learning in flipped life science courses promotes development of critical thinking skills," *Life Science Education*, pp. 1–13, 2018. doi: 10.1187/cbe.16-11-0332

[15] R. M. Vieira and C. Tenreiro-vieira, "Fostering scientific literacy and critical thinking in elementary science education," *International Journal of Science and Mathematics Education*, pp. 659–680, 2016. doi: 10.1007/s10763-014-9605-2

[16] A. N. Rau, *Effects Of Inquiry-Based Learning On Science Students*, 2022.

[17] V. H. Nguyen, R. Halpin, and A. R. Joy-Thomas, "Guided inquiry-based learning to enhance student engagement, confidence, and learning," *J. Dent. Educ.*, vol. 11, no. 1, pp. 1–14, 2024.

[18] M. K. Cho, M. K. Kim, M. K. Investigating, M. K. Cho, and M. K. Kim, "Investigating elementary students 'problem solving and teacher scaffolding in solving an ill-structured problem to cite this article: In vestigating elementary students' problem solving and teacher scaffolding in solving an Ill-structured problem," *International Journal of Science and Mathematics Education,* vol. 8, no. 4, p. 274. 2020.

[19] B. J. Reiser, "Why scaffolding should sometimes make tasks more difficult for learners," *Comput. Support Collab. Learn.*, pp. 255–264, 2023. doi: 10.4324/9781315045467-37

[20] S. Tiaradipa, I. Lestari, M. H. E. Hasibuan, and M. Rusdi, "The development of scaffolding in inquiry-based learning to improve students' science process skills in the concept of acid and base solution," *Jurnal Kimia dan Pendidikan Kimia*. vol. 5, no. 2, pp. 211–221, 2020.

[21] F. Prafitasari, "Integration of critical thinking skills in science learning using blended learning system," *Int. J. Element. Edu.* vol. 5, no. 3, pp. 434–445, 2021.

[22] E. B. A.-P. Correia, "Learn to use and use to learn: Technology in virtual collaboration experience," *The Internet and Higher Edu*., vol. 12, pp. 45–52, 2009. doi: 10.1016/j.iheduc.2008.10.006

[23] V. Czok, M. Krug, S. Müller, and J. Huwer, "Learning effects of augmented reality and game-based learning for science teaching in higher education in the context of education for sustainable development," *Sustainability*, 2023.

[24] J. Jerrim, M. Oliver, and S. Sims, "The relationship between inquiry-based teaching and students' achievement. New evidence from a longitudinal PISA study in England," *Learn. Instr.*, vol. 80, 2022. doi: 10.1016/j.learninstruc.2020.101310

[25] D. Fortus, J. Lin, K. Neumann, and T. D. Sadler, "The role of affect in science literacy for all," *International Journal of Science Education*, vol. 44, no. 4, pp. 535–555, 2022. doi: 10.1080/09500693.2022.2036384

[26] D. L. Hilton, *An Exploratory Study Of Generation Z Students' Social Presence Preferences In Formal Online Learning*, pp. 1–23, 2024.

[27] A. Alrayes, T. F. Henari, and D. A. Ahmed, "Chatgpt in education—understanding the bahraini academics perspective," *Electron. J. e-Learning*, vol. 22, no. 2, pp. 112–134, 2024. doi: 10.34190/Ejel.22.2.3250

[28] A. E. Ibisu, "Development of a gamification model for personalized e-learning," arXiv preprint, arXiv:2404.15301, 2024.

[29] W. Cao and Z. Yu, "The impact of augmented reality on student attitudes, motivation, and learning achievements—a meta-analysis (2016–2023)," pp. 1–12, 2023. doi: 10.1057/s41599-023-01852-2

[30] M. Kousloglou, E. Petridou, A. Molohidis, and E. Hatzikraniotis, "Assessing students' awareness of 4Cs skills after mobile-technology-supported inquiry-based learning," *Sustain*., vol. 15, no. 8, 2023. doi: 10.3390/su15086725

[31] R. Yilmaz and F. G. K. Yilmaz, "The effect of generative Artificial Intelligence (AI)-based tool use on students' computational thinking skills, programming self-efficacy and motivation," *Comput. Educ. Artif. Intell.,* vol. 4, no. 4, 100147, 2023. doi: 10.1016/j.caeai.2023.100147

[32] R. A. Wardani and F. N. Pertiwi, "Efektivitas model pembelajaran inquiry berbasis pendekatan scientific literacy terhadap kemampuan berkomunikasi siswa SMP," *J. Tadris Ipa Indones.*, vol. 1, no. 2, pp. 118–128, 2021. doi: 10.21154/Jtii.V1i2.166

[33] S. Hennessy, E. Calcagni, A. Leung, and N. Mercer, "An analysis of the forms of teacher-student dialogue that are most productive for learning," *Lang. Educ.*, vol. 37, no. 2, pp. 186–211, 2023. doi: 10.1080/09500782.2021.1956943

[34] S. Lev-ari, "Interacting with multiple partners improves communication skills," *A cognitive Science A multidisciplinary J.* vol. 44, 2020. doi: 10.1111/cogs.12836

[35] F. Novitra, Festiyed, and Yohandri, "Validity of networked-based inquiry model to improve 21st-century competencies of students," in *Proc. 2nd Int. Conf. Innov.*, vol. 504, pp. 35–41, 2020. doi: 10.2991/Assehr.K.201209.189

[36] P. Reipschlager, T. Flemisch, and R. Dachselt, "Personal augmented reality for information visualization on large interactive displays," *Ieee Trans. Vis. Comput. Graph.*, vol. 27, no. 2, pp. 1182–1192, 2021. doi: 10.1109/Tvcg.2020.3030460

[37] M. Abdinejad, B. Talaie, H. S. Qorbani, and S. Dalili, "Student perceptions using augmented reality and 3D visualization technologies in chemistry education," *J. Sci. Educ. Technol.*, vol. 30, no. 1, pp. 87–96, 2021. doi: 10.1007/S10956-020-09880-2

[38] R. Ennis, "Critical thingking," *Philpapaers.Org*, vol. 6, no. 1, pp. 1–7, 2011.

[39] S. Shuaizhi, A. Binti, and A. Aziz, "Digital survival of elderly population: The impact of media use on social adaptation," *Int. J. Academic Research in Business and Social Science*. vol. 13, no. 6, pp. 2101–2111, 2023. doi: 10.6007/IJARBSS/v13-i6/17618

[40] T. Sidampoi, N. W. Suriani, F. Harahap, M. Rogahang, and J. A. Rungkat, "The influence of problem based learning models on students' critical thinking abilities on human excretion system materials at smp negeri 6 tondano," *Soscied J. Soc. Sci. Educ.*, vol. 7, no. 2, 2024..

[41] T. Thi *et al*., "Significance of listening skills in enhancing the communication skills," *Smart Moves J.* pp. 194–196, 2024. doi: 10.32996/ijels

[42] N. K. Rapi, R. Sujanem, L. Putu, B. Yasmini, and K. Setemen, "Science process skills and critical thinking skills in inquiry-based learning model with project- based assessment," *Int J. of Innovative Research and Scientific Studies*, vol. 8, no. 2, pp. 938–946, 2025. doi: 10.53894/ijirss.v8i2.5393

[43] Mediawati and A. Azizi, "Menganalisis kemampuan berpikir kritis siswa kelas VIII SMP NW Lingkung Kecamatan Kopang pada percobaan perpindahan kalor di mata pelajaran IPA terpadu," *JPIPAS (Jurnal Pendidikan IPA dan Ilmu Sains)*, vol. 1, no. 1, pp. 21–30, 2024. doi: 10.64088/jpipas.v1i1.12

[44] B. Leest and M. H. J. Wolbers, "Critical thinking, creativity and study results as predictors of selection for and successful completion of excellence programmes in Dutch higher education institutions," *Eur. J. High. Educ.*, vol. 11, no. 1, pp. 29–43, 2021. doi: 10.1080/21568235.2020.1850310

[45] A. Toupin and S. Lévesque, "Experiences and perceptions of gynaecological violence: A descriptive exploration of the phenomenon from survivors's standpoints," *Feminist Encounters: A Journal of Critical Studies in Culture and Politics*, vol. 9, no. 1, pp. 1–17, 2025.

[46] P. A. Facione, "Critical thinking: What it is and why it counts," *Insight Assessment*, 2015.

[47] E. R. Lai, "Critical thinking: A literature review," Pearson's Research Reports, 2011.

[48] P. C. Abrami, R. M. Bernard, E. Borokhovski, D. I. Waddington, C. A. Wade, and T. Persson, "Strategies for teaching students to think critically: A meta-analysis," *Review of Educational Research*, vol. 85, no. 2, pp. 275–314, 2015. doi: 10.3102/0034654314558493

[49] E. Reith-Hall and P. Montgomery, "Communication skills training for improving the communicative abilities of student social workers: A systematic review," *Campbell Syst. Rev.*, vol. 19, no. 1, 2023. Doi: 10.1002/Cl2.1309

[50] M. Dissanayake, "Promoting communication skills during basic science teaching in the medical curriculum," *Sri Lanka Anat. J.*, vol. 5, no. 2, pp. 1–23, 2021.

[51] S. N. Margret and N. S. Divya, "An understanding of active listening as a significant" *International Journal of English and Studies (IJOES)*, vol. 7, no. 4, pp. 30–37, 2025.

[52] R. Buana and N. Sholehah, "Integrating collaboration and communication skills: Development of discovery learning-based science module article info," *Jurnal Fisika dan Pendidikan Fisika*, vol. 9, no. 2, pp. 161–169, 2024.

[53] J. V. Reyk, M. Leasa, M. Talakua, and J. R. Batlolona, "Research based learning: Added value in students ' science critical thinking skills," *Jurnal Penelitian Pendidikan IPA*. vol. 8, no. 1, 2022. doi: 10.29303/jppipa.v8i1.1121

[54] W. W. W. P. Net, "The profile of students' communication skills on science learning in elementary schools," *Pegem Journal of Education and Instruction*. vol. 13, no. 1, pp. 117–124, 2022. doi: 10.47750/pegegog.13.01.14

[55] T. Taher, "Analisis keterampilan komunikasi dan kolaborasi siswa introvert dengan pendekatan culturally responsive teaching," *Jambura J. Educ. Chem.*, vol. 5, no. 1, pp. 21–27, 2023. doi: 10.34312/Jjec.V5i1.17463

[56] A. T. Ogan-Bekiroglu and M. Aydeniz, "Assessing students' written argumentation in science: A learning progression," *Science Education*, vol. 97, no. 3, pp. 422–447, 2013. doi: 10.1002/sce.21057

[57] M. Fabian, S. Rabiichuk, N. Mykhalchenko, N. Pavlushchenko, and A. Dzhurylo, "Pedagogical aspects of improving communication skills of university students," *J. Lifestyle Sdg's Rev.*, vol. 4, pp. 1–9, 2024.

[58] A. M. Amin, R. Adiansyah, and N. Hujjatusnaini, "The contribution of communication and digital literacy skills to critical thinking," *J. Pendidik. Sains Indones. (Indonesian J. Sci. Educ.*, vol. 11, no. 3, pp. 697–712, 2023. doi: 10.24815/Jpsi.V11i3.30838.

[59] L. K. Berland and B. J. Reiser, "Making sense of argumentation and explanation," *Science Education*, vol. 93, no. 1, pp. 26–55, 2009. doi: 10.1002/sce.20286

[60] M. D. Zuhri and E. N. Sya'adiyah, "Improving students' critical thinking and communication skil l through blended learning model at university," *J. English Linguist. Lit. Educ.*, vol. 5, no. 2, pp. 463–484, 2023.

[61] R. R. Hake, "Interactive-engagement versus traditional methods: A six-thousand-student survey of mechanics test data for introductory physics courses," *American Journal of Physics*, vol. 66, no. 1, pp. 64–74, 1998. doi: 10.1119/1.18809

[62] N. F. Saidin, N. D. A. Halim, N. Yahaya, and N. N. Zulkifli, "Enhancing students' critical thinking and visualisation skills through mobile augmented reality," *Knowledge Management & e-Learning: An International Journal,* vol. 16, no. 1, pp. 1–41, 2024. doi: 10.34105/j.kmel.2024.16.001

[63] F. A. Kurnianto, E. A. Nurdin, E. I. Pangastuti, and S. Bella, "Monitoring mining impact for geosites using time series NDVI and runoff in the eastern part of southern Java Mountains, Indonesia," *Forum Geografi*, vol. 38, no. 2, pp. 291–301, 2024. doi: 10.23917/forgeo.v38i2.2996

[64] L. Zhang, X. Fu, D. Luo, L. Xing, and Y. Du, "Musical experience offsets age-related decline in understanding speech-in-noise: Type of training does not matter, working memory is the key," *Ear & Hearing*, vol. 42, no. 2, pp. 258–270, 2021. doi: 10.1097/AUD.0000000000000921

[65] C. H. Chen, W. P. Chan, K. Huang, and C. W. Liao, "Supporting informal science learning with metacognitive scaffolding and augmented reality: Effects on science knowledge, intrinsic motivation, and cognitive load," *Res. Sci. Technol. Educ.*, pp. 1–23, 2022.

[66] M. Nurfaizi, B. Ramdhan, and A. Juhanda, "Efektivitas media augmented reality berbasis smartphone terhadap kemampuan komunikasi visual dan motivasi siswa pada pembelajaran biologi," *Biodik J. Ilm. Pendidik. Biol.*, vol. 8, no. 3, pp. 99–109, 2022.

[67] Selindawati, W. R. R. Hayu, and G. Gunadi, "Pengembangan media pembelajaran berbasis augmented reality untuk meningkatkan keterampilan komunikasi pada mata pelajaran ipas," *Karimah Tauhid*, vol. 3, no. 4, pp. 5143–5156, 2024. doi: 10.30997/Karimahtauhid.V3i4.13025

[68] J. Al Dhahrani, S. Rahayu, and D. Suryadi, "Meningkatan kemampuan komunikasi siswa vokasi menggunakan flipbook dengan augmented reality," *Ideas J. Pendidikan, Sos. Dan Budaya*, vol. 10, no. 1, pp. 69, 2024. doi: 10.32884/Ideas.V10i1.1669

[69] M. K. Cho and M. K. Kim, "Investigating elementary students' problem solving and teacher scaffolding in solving an Ill-structured problem," *Int. J. Educ. Math. Sci. Technol*., vol. 8, no. 4, pp. 274–289, 2020. doi: 10.46328/IJEMST.V8I4.1148

[70] F. Ouyang, Z. Chen, M. Cheng, Z. Tang, and C. Y. Su, "Exploring the effect of three scaffoldings on the collaborative problem-solving processes in China's higher education," *Int. J. Educ. Technol. High. Educ*., 2021. doi: 10.1186/s41239-021-00273-y

[71] T. Ribeirinha, M. Baptista, and M. Correia, "The impact of STEM activities on the interest and aspirations in stem careers of 12th-grade Portuguese students in science and technology curriculum," *Europen J. of STEM Edu.* vol. 9, no. 1, pp. 1–12, 2024.

[72] O. O. Salami and E. D. Spangenberg, "Impact of Information and Communication Technology (ICT) facilities on gender differentials in mathematics performance among secondary school students," *Europen J. of STEM Edu.* vol. 9, no. 1, pp. 1–8, 2024.

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