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Strengthening Mindful Scientific Thinking among High School Students through the Integration of Interactive Augmented Reality-Based E-LAPD in the Chemical Bonding Topic

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ABSTRACT

The concept of chemical bonding is an abstract material that requires visualization skills and students' scientific thinking awareness. This study aims to analyze the role of Augmented Reality (AR) integration in E-LAPD as a cognitive bridge to build students' mindful scientific thinking abilities. The study used the 4D Research and Development (R&D) model method modified into define, design, and development stages, and analyzed descriptively exploratively. The research subjects consisted of 25 grade X high school students. The instruments used included observation sheets, response questionnaires, mindful scientific thinking tests, and conceptual understanding tests. The results showed that AR-based E-LAPD had very good validity, with a mindful scientific thinking activity achievement of 82%, student responses of 92.30%, mindful scientific thinking test results of 90%, and an average conceptual understanding of 92. Research findings indicate that the use of AR-based E-LAPD elicited a positive response and showed a trend toward high achievement in indicators of mindful scientific thinking and conceptual understanding. In the context of this exploratory study, AR-based visualization has the potential to serve as a cognitive bridge, fostering learners' awareness of the scientific thinking process. These findings offer preliminary indications regarding the potential of integrating AR into E-LAPD to support more reflective and contextual chemistry learning, although definitive conclusions regarding its effectiveness cannot be drawn in causal terms, given that the study did not employ a control group or inferential testing.

INTRODUCTION

Chemistry is a branch of science that is viewed as both a process and a product (Hemayanti et al., 2020). Chemistry at the high school level consists of numerous areas of study that are systematically organized and interconnected. One of the chemistry topics studied is chemical bonding (Safitri et al., 2018). Chemical bonding is characterized as an abstract concept, making it relatively difficult for students to understand, with a difficulty percentage of 58.5% (Umar et al., 2023). Difficulties in understanding chemical bonding are related to students' ability to connect macroscopic, submicroscopic, and symbolic representations in chemistry. This is because chemical bonding involves molecular structures and interactions among particles that cannot be directly observed.

In modern chemistry learning, the ability to understand microscopic representations is an important competency for developing students' scientific thinking. Difficulties in understanding chemical bonding are also influenced by the limitations of conventional learning. Material delivery that relies predominantly on verbal explanations and two-dimensional images often does not adequately help students understand molecular structures and the processes by which bonds are formed. Research conducted by Vonari et al. (2024) found that difficulties in the sub-concept of ionic bonding were caused by students' limited understanding of the properties of metallic and non-metallic elements.

In view of these problems, educational practices need to adapt to technological developments (Maulana et al., 2019). Digital transformation continues across various areas of life, making learning media increasingly important to develop because it can provide broad access to information and learning materials (Arwansyah et al., 2023). The integration of information technology is an effective solution for improving the quality of chemistry learning because it can provide more contextual and interactive learning experiences (Hayes & Hayes, 2005). One technology that can be utilized in learning is Augmented Reality (AR). Augmented Reality (AR) is a technology that can visualize objects in three dimensions, thereby helping students understand abstract concepts (Indriani et al., 2023). The application of AR in learning helps students visualize molecular shapes and structures more realistically, improving their understanding of abstract molecular geometry concepts (Sari & Dwiningsih, 2025). With the support of Augmented Reality, students can observe molecular structures, bond types, and interactions in dynamic three-dimensional form. This makes the learning process more engaging and facilitates active student involvement (Ritchhart & Perkins, 2000). The use of Augmented Reality (AR) in learning media particularly interactive E-LAPD, can help students visualize microscopic objects more realistically (Ramadhan et al., 2021).

In practice, the use of educational technology also needs to be supported by an approach that encourages active student engagement. One approach that can be used is mindful scientific thinking, which emphasizes awareness during the learning process. Mindful scientific thinking, based on the concept of mindfulness, is a learning approach that emphasizes full awareness throughout the learning process, with the aim of increasing self-awareness in learning, attentional focus, collaborative empathy, openness to new ideas, and active engagement during learning (Langer, 2000). This mindfulness approach provides students with opportunities to improve learning concentration, regulate emotions, direct their attention, and focus on learning tasks (Aqilah et al., 2025). In the context of science education, mindfulness should be positioned not merely as the ability to sustain attention during instruction, but also as a form of metacognitive awareness that supports the process of scientific thinking. Scientific thinking encompasses cognitive processes such as conducting inquiries, analyzing information, drawing inferences, evaluating evidence, and constructing arguments based on observations. Research on higher-order scientific thinking further indicates that scientific thinking is interconnected with scientific reasoning, critical thinking, and metacognition

all of which are essential components of science learning (Andarista & Rosdiana, 2023). Consequently, this study positions "mindful scientific thinking" as a learner's awareness of the scientific thinking processes occurring during instruction; this includes the ability to focus attention on phenomena, remain conscious of one's own thought processes, reflect on understanding, maintain openness to diverse perspectives, and actively engage in inquiry and discussion. This framing ensures that mindfulness does not stand as a construct separate from scientific thinking but instead functions as a dimension of awareness and reflection that supports the learner's engagement in the scientific thinking process. Integrating this awareness becomes increasingly relevant when students encounter abstract chemical concepts. In chemistry education, the scientific thinking process requires students not only to acquire information but also to observe representations, link information to concepts, evaluate their understanding, and reflect on the thinking processes employed. Augmented Reality (AR) technology offers a visual, interactive environment that enables students to observe three-dimensional representations of objects or processes that are difficult to view directly. Research indicates that integrating AR into science and chemistry education can foster conceptual mastery, science process skills, and student engagement when combined with appropriate instructional approaches (Setiawaty et al., 2024). Consequently, the integration of AR into the guided-inquiry-based electronic student activity sheets (E-LAPD) in this study aims not merely to provide visualizations, but to create a learning experience that allows students to observe, explore, reflect upon, and discuss chemical representations with greater awareness. Research conducted by Siregar (2024) found that Augmented Reality (AR) is more effective when combined with a guided inquiry learning model. In that study, the use of AR combined with guided inquiry achieved a percentage of 87.8% and was considered more effective than AR without guided inquiry, which achieved 70% among Grade X high school students.

Several studies have shown that the use of Augmented Reality in chemistry learning is effective in improving conceptual understanding and visualization of submicroscopic representations (Ningrum et al., 2021). However, most of these studies still focus on cognitive learning outcomes and have not addressed the dimension of students' scientific thinking awareness in depth. On the other hand, mindfulness approaches in education have been shown to improve focus, self-reflection, and learning awareness (Feriyanto et al., 2024), but their implementation has predominantly been situated in general educational psychology and has not been specifically integrated into visualization-based chemistry learning. However, that dimension of mindfulness does not automatically represent scientific thinking unless it is linked to scientific reasoning processes such as inquiry, analysis, inference, evidence evaluation, and argumentation. This gap indicates the absence of a learning approach that systematically integrates digital visualization with the development of mindful scientific thinking in the context of abstract chemistry topics. Therefore, this study offers novelty through the integration of Augmented Reality into E-LAPD as a cognitive bridge that not only facilitates conceptual

visualization but also develops students' awareness of scientific thinking in a reflective and contextual manner.

This study does not merely develop technology-based learning media but offers a new approach to chemistry learning that transforms the learning process from simply understanding concepts into becoming aware of scientific thinking processes. Through the integration of Augmented Reality and guided inquiry in E-LAPD, this study positions digital visualization as a cognitive bridge connecting submicroscopic representations with students' reflective awareness. Thus, chemistry learning is no longer oriented toward knowledge transfer alone, but toward developing deep scientific awareness.

RESEARCH METHOD

This study employs the Research and Development (R&D) method using the 4D model, modified into three stages: define, design, and development. Data analysis was conducted using a descriptive-exploratory approach to obtain an initial overview of product feasibility, student responses, and trends in mindful scientific thinking and conceptual understanding following the use of the Augmented Reality-based E-LAPD. As the study involved a single class without a control group and did not utilize inferential testing, the results are interpreted as preliminary, exploratory findings and are not intended to test effectiveness or causal relationships.

The research was conducted in one high school class consisting of 25 students. The subjects were selected purposively by considering the suitability of the learning material and the availability of facilities supporting the use of Augmented Reality

The define stage was conducted through an analysis of learning needs and identification of students' difficulties in understanding chemical bonding concepts. The design stage included designing an Augmented Reality-based E-LAPD integrated with a guided inquiry learning model. The development stage was conducted through implementing learning using the E-LAPD and collecting research data. The research instruments included mindful scientific thinking observation sheets, student response questionnaires, mindful scientific thinking tests, and chemical bonding conceptual understanding tests. The instruments were validated by chemistry education experts and media experts to ensure the suitability of the indicators with the mindful scientific thinking construct. The indicators of mindful scientific thinking included attentional focus, self-awareness in learning, self-reflection, openness to new ideas, and active engagement in learning.

The data were analyzed descriptively using percentages to describe the achievement of each indicator. The percentage was calculated using the following formula (Arikunto, 2021):

$$P = (f / N) \times 100\%$$

where P is the percentage, f is the score obtained, and N is the maximum score. The results were then interpreted to describe the role of Augmented Reality-based

visualization in supporting the development of students' mindful scientific thinking using the following interpretation categories.

Table 1. Percentage Interpretation

Percentage	Category
0% - 20%	Very low
21% - 40%	Low
41% - 60%	Moderate
61% - 80%	High
81% - 100%	Very high

(Source: Arikunto, 2021)

This study was limited by the small number of subjects and the absence of a control class, therefore, it was exploratory in nature as an initial study and was not intended to test effectiveness between groups, but rather to describe the role of Augmented Reality visualization in chemistry learning and its relationship with mindful scientific thinking.

RESULTS AND DISCUSSION

RESULTS

The results showed that Augmented Reality-based chemical bonding visualization has the potential to support and strengthen students' mindful scientific thinking in chemical bonding, as indicated by the trends in test results and student responses during the development stage. During the design stage, assessment instruments, media selection, format, and learning device designs were prepared.

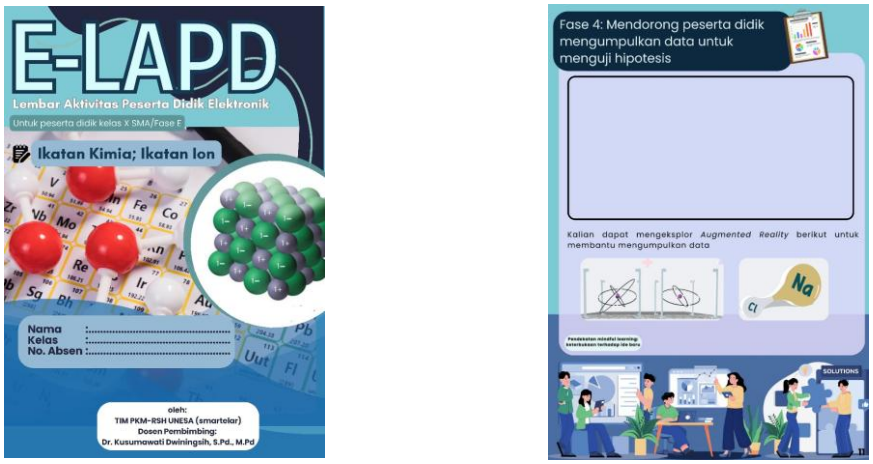


Figure 1. Design of E-LAPD Integrated with Augmented Reality (AR)
Source: Personal documentation (2026)

During the development stage, after the learning media had been completed, validity testing was conducted by validators in the areas of content and media. Validation was conducted to ensure that the E-LAPD met feasibility standards in terms of content and media.

Table 2. E-LAPD Validation Results

Validity Aspect	Mode Score	
	Content	Media
Content Validity	5	4
Construct Validity	5	4

Research data, processed by the authors (2026)

After the validation test, data collection was conducted at SMA Negeri 22 Surabaya. This study produced a strategy for strengthening high school students' mindful scientific thinking through the integration of an interactive Augmented Reality (AR)-based E-LAPD with a guided inquiry learning model on chemical bonding. Data sources were obtained from observations of mindful scientific thinking, student response questionnaires, mindful scientific thinking tests, and chemical bonding conceptual understanding tests. The student observation data are presented in Table 3.

Table 3. Observation Data on Students' Mindful Scientific Thinking Activities

No	Mindful Scientific Thinking Indicator	Average score	Percentage
1	Focus on representations of chemical concepts	3,8	76%
2	Awareness of the thought processes involved in understanding chemical concepts	3,76	75,2%
3	Ability to reflect on the understanding of chemical bonding concepts	4,28	85,6%
4	Empathy during collaborative efforts to understand chemical bonding concepts	4,2	84%
5	Openness to various representations of chemical concepts	4,2	84%
6	Active engagement in concept exploration through chemical visualization	4,36	87,2%
	Average	**4,1**	**82%**

Research data, processed by the authors (2026)

Based on the observation data on students' mindful scientific thinking activities in the table, the percentages obtained from the six mindful scientific thinking indicators are presented in Figure 2.

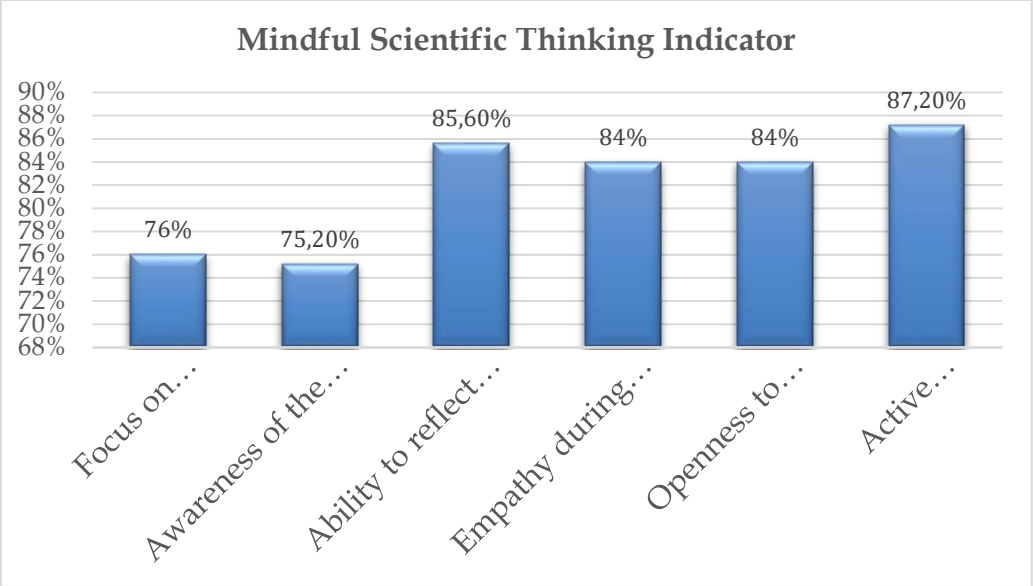


Figure 2. Percentage of Mindful Scientific Thinking Activities
Source: Research data, processed by the authors (2026)

Figure 2 shows that the average result of observations of students' mindful scientific thinking activities was 82%. This result indicates that students were in the very good category in terms of mindful scientific thinking.

Next, student response questionnaire data regarding the interactive E-LAPD integrated with Augmented Reality were analyzed to determine the practicality of using the interactive E-LAPD. The student response questionnaire data are presented in Table 4.

Table 4. Student Response Questionnaire Data

No.	Statement	Persentase	Criteria
1.	Teaching and learning activities are more enjoyable with the Augmented Reality-based E-LAPD.	100%	Very good
2.	Teaching and learning activities feel boring when using the Augmented Reality-based E-LAPD. (Negative statement)	72%	Good
3.	Using the Augmented Reality-based E-LAPD makes me more active in chemistry lessons on chemical bonding.	88%	Very good
4.	I am not interested in using it again after the learning session ends. (Negative statement)	76%	Very good
5.	I feel motivated to study harder with the Augmented Reality-based E-LAPD.	96%	Very good
6.	I am able to use the Augmented Reality-based E-LAPD smoothly.	92%	Very good

No.	Statement	Persentase	Criteria
7.	The instructions for using this learning media are easy to follow.	100%	Very good
8.	The display and features are not confusing.	96%	Very good
9.	The Augmented Reality-based E-LAPD uses language that is difficult to understand.	88%	Very good
10.	The font type, size, and spacing used in the Augmented Reality-based E-LAPD are appropriate and easy to read.	96%	Very good
11.	I can understand the meaning of each chemical bonding concept.	100%	Very good
12.	I can relate chemistry material to everyday experiences.	96%	Very good
13.	I can stay focused and fully present throughout the learning process.	100%	Very good
	Average	**92,30%**	**Very good**

Research data, processed by the authors (2026)

Based on the student response questionnaire regarding the use of the Augmented Reality-based interactive E-LAPD on chemical bonding, the average percentage was 92.30%, categorized as very good. This indicates that three-dimensional visualization through Augmented Reality helps students build deeper mental representations of chemical bonding concepts. The media were considered capable of creating a learning atmosphere that is enjoyable, interactive, easy to use, and able to increase students' motivation, focus, and active engagement in the learning process.

Next, the students' mindful scientific thinking test data were analyzed to determine the effectiveness of the Augmented Reality-based E-LAPD in fostering the mindful scientific thinking approach. The test results are presented in Table 5.

Table 5. Students' Mindful Scientific Thinking Test Data

No.	Mindful Scientific Thinking Aspect	Percentage	Category
1.	I strive to understand the meaning behind every concept I learn.	98%	Very good
2.	I pay attention to subtle changes in the chemical phenomena I observe.	95%	Very good
3.	I try to view chemistry problems from various perspectives.	90%	Very good
4.	I am aware when my attention begins to drift away from the lesson.	70%	Good

No.	Mindful Scientific Thinking Aspect	Percentage	Category
5.	I try to connect chemistry material to everyday experiences.	86%	Very good
6.	I am open to new ideas or opinions from my peers.	93%	Very good
7.	I recognize what I understand and what I do not yet understand.	90%	Very good
8.	I am interested in trying new approaches to grasp difficult concepts.	88%	Very good
9.	I reflect on the mistakes I make when solving problems.	89%	Very good
10.	I feel focused and fully present during the lesson.	89%	Very good
11.	I try to adjust my study methods when old strategies prove ineffective.	86%	Very good
12.	I enjoy learning activities that are challenging and thought-provoking.	91%	Very good
13.	I recall key points from previous lessons to help me understand new material.	91%	Very good
14.	I feel actively engaged during discussions with my peers.	87%	Very good
15.	I realize that everyone may have a different way of thinking when it comes to understanding chemistry.	97%	Very good
16.	I use my study time with full attention and awareness.	90%	Very good
17.	I find it easier to understand when I am fully focused on what I am learning.	94%	Very good
18.	I try to link chemistry topics to environmental issues or real-life situations.	88%	Very good
19.	I notice when I start to lose interest and try to regain my focus.	88%	Very good
20.	I feel that learning chemistry becomes meaningful when I truly understand it.	98%	Very good
	Average	**90%**	**Very good**

Based on the data in Table 5, the students' mindful scientific thinking test results reached 90%. The 90% result provides a descriptive indication that students reported a high level of learning awareness following the learning activities using the AR-based E-LAPD. Because the study employed a single-group exploratory design without a control

group, this finding should be interpreted as an initial descriptive tendency rather than evidence of the effectiveness or causal contribution of the AR-based E-LAPD.

The students' reflection data on the Augmented Reality-based E-LAPD for strengthening mindful scientific thinking in chemical bonding are presented in Table 6.

Table 6. Students' Reflection Data on Augmented Reality-Based E-LAPD

No.	Reflection Question	Students' General Responses
1.	What new thing did you learn today?	Chemical bonding—specifically ionic bonding in NaCl (salt)studied using a new instructional tool: an AR (Augmented Reality)-based E-LAPD featuring 3D visualizations that aid in understanding molecular structures and the process of chemical bond formation.
2.	How did this learning help you understand chemical bonding differently?	3D visualization renders abstract concepts concrete and easier to grasp; the use of real-life examples makes the material more relatable; the learning method is enjoyable rather than tedious; it helps students realize that chemical bonding is not merely theoretical but a real-world phenomenon; group learning facilitates discussion and shared understanding.
3.	What did you realize about your way of thinking when solving problems?	Requires discussion with peers to prevent miscommunication; necessitates an understanding of basic concepts before tackling problems; visualization accelerates comprehension; demands careful, critical, and logical thinking for problem-solving.
4.	What would you like to improve in the next meeting?	Focus and concentration during study and discussions; active participation and questioning; deep understanding of chemical bonding concepts; precision in completing tasks; critical thinking and problem-solving skills; active engagement in group discussions.

Research data, processed by the authors (2026)

The student reflection data in Table 6 indicate that the use of interactive Augmented Reality (AR)-based E-LAPD has the potential to foster learning awareness and contribute to active participation in chemistry learning. The three-dimensional visualization presented helps students understand abstract chemical bonding concepts concretely while fostering curiosity, enthusiasm, and emotional engagement. In addition, AR-based learning encourages students to think critically, collaborate in groups, and actively participate in discussions to achieve a deeper understanding of the material.

Next, students completed a chemical bonding conceptual understanding test to provide a descriptive overview of their understanding; the results are presented in Figure 3.

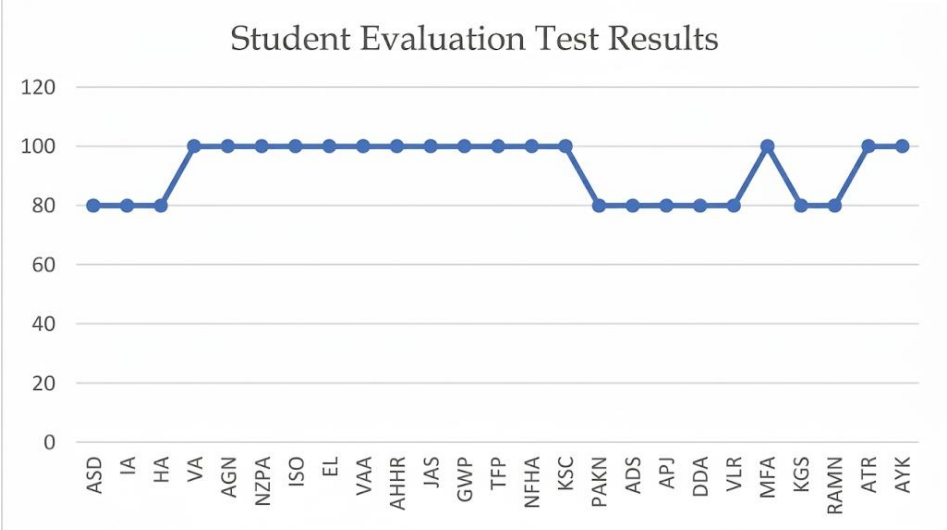


Figure 3. Student Evaluation Test Results
Source: Research data, processed by the authors (2026)

Figure 3 shows the results of the chemical bonding conceptual understanding test. Among 25 students, the average score was 92, categorized as very good. The observed score suggests a high level of conceptual understanding among the participating students after the learning activities. The three-dimensional visualization provided by AR may have supported the formation of mental representations of chemical bonding by making submicroscopic structures more accessible to observation and exploration. However, this interpretation should be considered preliminary because the study did not include a pretest-posttest comparison or a control group.

DISCUSSION

The results showed that Augmented Reality (AR)-based chemical bonding visualization through the integration of E-LAPD with a guided inquiry model has the potential to support the strengthening of high school students' mindful scientific thinking abilities in chemical bonding. Concept visualization through Augmented Reality (AR) technology makes an important contribution to helping students understand abstract chemical bonding concepts. In chemistry learning, many concepts exist at the microscopic level and are difficult to imagine when explained only through text or two-dimensional images. Through AR, molecular structures and bond-formation processes can be visualized in three dimensions, allowing students to observe relationships among atoms more concretely. Three-dimensional visualization through AR helps students build mental representations of molecular structures (Yulianti et al., 2022). Such visualization helps connect macroscopic, submicroscopic, and symbolic representations in chemistry. This is consistent with constructivist theory, which emphasizes that understanding is constructed through learning experiences, as well as the concept of mindfulness, which emphasizes awareness of thinking processes. Therefore, the use of AR-based E-LAPD enables students not only to read the provided material but also to directly explore chemical bonding models, thereby encouraging conceptual understanding.

The use of AR in E-LAPD was accompanied by high descriptive scores on students' mindful scientific thinking indicators (Tari et al., 2026). Based on the study

conducted, students' mindful scientific thinking activities reached 82%, categorized as very good. Although the results were in the very good category, several aspects still require attention, particularly the indicator of awareness of the thinking process in understanding chemistry concepts, which obtained a lower percentage than the other indicators. This indicates that not all students are immediately able to maintain consistent focus during technology-based learning. In addition, the use of Augmented Reality requires device readiness and initial adaptation by students; therefore, broader implementation requires mentoring strategies and strengthened digital literacy. This result is consistent with Langer's (2000) view that mindful learning requires full awareness and cognitive flexibility to achieve meaningful understanding. Meanwhile, the mindful scientific thinking test showed an average of 90%. This result indicates that AR integration in learning encourages students to focus, actively observe phenomena, and reflect on their thinking processes. In the context of mindful scientific thinking, students are encouraged to learn consciously, pay attention to each process that occurs, and remain open to new understandings. Interactive visualization through AR encourages students to observe learning objects in depth, ask questions, and reflect on their observations. This is further supported by the very positive student response to the AR-based E-LAPD, which reached 92.30%, indicating that the media can increase students' engagement and learning awareness during the learning process.

These results are also consistent with previous research by Vonari et al. (2024), which showed that AR technology can improve students' understanding of science concepts and learning engagement. Several studies have reported that three-dimensional visualization through AR helps students understand complex chemistry concepts because it provides more realistic representations than conventional media (Siregar, 2024). In addition, the integration of AR into inquiry-based learning can increase students' exploration and reflection activities. The findings of this exploratory study generally align with previous research indicating that AR-based learning can support conceptual understanding and learner engagement. In this study, the high descriptive scores on the "mindful scientific thinking" indicator provide an initial indication that AR-based E-LAPDs can create learning conditions that foster attention, reflection, openness, and active engagement in chemistry learning. However, these findings cannot be interpreted as evidence that AR-based E-LAPDs directly develop mindful scientific thinking, as the study did not employ a control group or inferential statistical analysis. This is consistent with Langer's (2000) theory that mindful scientific thinking develops when students experience authentic, conscious, and flexible learning in responding to information. Thus, the integration of AR technology into learning devices can serve as an alternative innovation to support meaningful, reflective chemistry learning that is consistent with the characteristics of the Merdeka Curriculum.

The combination of AR and inquiry makes learning interactive, reflective, and meaningful because it simultaneously involves students' cognitive, affective, and social dimensions. This approach is consistent with the deep learning principles of the Merdeka Curriculum, which emphasize deep understanding and continuous learning awareness.

Augmented Reality-based visualization of chemical bonding concepts functions not only as a learning aid but also as a cognitive bridge between submicroscopic representations and students' conceptual understanding. Thus, the use of AR-based E-LAPD not only demonstrates a tendency toward improved understanding of chemical bonding concepts but also helps students become aware of their scientific thinking processes during learning as a science learning strategy that supports the strengthening of mindful scientific thinking and the development of scientific ethics in chemistry learning. These findings indicate that the integration of digital visualization in chemistry learning has strategic potential for developing students' scientific thinking abilities in the era of technology-based learning.

In the long term, the development of Augmented Reality-based E-LAPD has the potential to be integrated into digital learning platforms such as Learning Management Systems (LMS) and extended to other abstract chemistry topics. In addition, this approach has the potential to be developed into broader educational technology products to support digital transformation in science education in Indonesia.

CONCLUSION

This research provides an initial overview of the potential for integrating Augmented Reality visualization in E-LAPD to support chemistry learning oriented towards mindful scientific thinking on chemical bonding material. Descriptive results show that mindful scientific thinking activities obtained an average of 82%, students' responses to the media reached 92.30%, the results of the mindful scientific thinking test reached 90%, and the average understanding of concepts was 92. These achievements show a positive tendency towards attention, awareness of the thinking process, reflection, openness, empathy, and active involvement of students during learning. However, because the research was conducted in one class consisting of 25 students without a control group and analyzed descriptively, the findings cannot yet be used to conclude the effectiveness or causal relationship between the use of AR-based E-LAPD and the development of mindful scientific thinking. Therefore, further research with quasi-experimental designs, larger numbers of subjects, comparison groups, and inferential statistical analyzes are needed to test these initial findings more strongly.

Thus, the primary contribution of this study lies in providing an instructional design that integrates AR-based 3D visualization, E-LAPD, and guided inquiry to link the visualization of chemical concepts with an awareness of scientific thinking processes. This approach demonstrates potential for further development and application to other abstract chemistry topics, supported by more robust empirical testing.

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