An Academic Analysis of Students' Abstract Thinking Skills through the Implementation of Augmented Reality in Chemical Bonding Instruction

Yenni Kurniawati[1]*, Yuli Hartati[2], Yuni Fatisa[3], Elvi Yenti[4], Risma Maharani[5]

[1,3,4,5]*Department of Chemistry Education, Universitas Islam Negeri Sultan Syarif Kasim Riau*
[2]*Department of Chemistry Education, Universitas Mulawarman*
Corresponding Email: *yenni.kurniawati@uin-suska.ac.id*

Abstract: Abstract thinking skills are essential for understanding microscopic concepts in chemistry, particularly in topics such as chemical bonding. The purpose of this study is to identify the impact of augmented reality (AR) as a new mode of instructional technology on students' abstract thinking, specifically framed within the context of chemical bonding, as a learning topic. Starting with the quantitive approach, a mixed-methods research design with a sequential explanatory strategy was applied. The participants of the study were tenth graders who were purposefully selected from one of the Madrasah Aliyah Negeri Pekanbaru. Collection of data was through document analysis, essay-based assessments, and semi structured interviews. The results of the study revealed that there was a significant difference in the abstract thinking of the students in the experimental group compared to the students in the control group, $(p=001)$ 73.7 of the students made learning gains. The results at the qualitative level were further enhanced by the fact that different features of AR assisted different types of abstract thinking, such as representational understanding, relational abstraction, reflective awareness and operational abstraction. The results of the study also revealed that AR enhanced student motivation and engagement with the learning material. Based on the results of the study, it can be concluded that the use of AR in chemistry instruction can be an effective instructional pedagogy to enhance students' abstract thinking and engagement in learning.

Keywords: Abstract Thinking Skills, Augmented Reality, Chemical Bonding, Chemistry Learning

How to cite this article :

1. Introduction

Chemistry learning is often challenged by the complexity of abstract and microscopic concepts, that range from the material that cannot be seen (chemical bonds) to that which cannot be observed directly (chemical bonding). To be knowledgeable, students must assess complex concepts such as electron configuration, interparticle attraction, and the structure of the molecules that comprise those bonds. These are arguably the most inaccessible concepts owing to their invisible nature. Each of these concepts does not only involve deep a level of substantive knowledge (Funkhouser & Nicoladis, 2023), but also possesses a greater need for the abstraction of a higher order. Johnstone's triangle, in the context of the study of chemical bonding, best depicts the alignment of the multiple levels of representation that students must operate. Each of the levels of representation must be seamlessly integrated to demonstrate the ability to reason invisible molecular interactions and, as a result, elucidate the bonding relationships. In this study, we characterize abstract thinking as the ability to operate seamlessly across multiple levels of representation, and we assert that augmented reality (AR) supports that integration by providing a bridge between symbolic and dynamic submicroscopic representations.

Students' low abstract thinking ability can lead to shallow conceptual understanding, misconceptions, and poor learning outcomes. Consequently, they are likely to obtain poor learning results. The existing learning environments are predominantly text-based, making it even more difficult for students to visualize concepts and develop the appropriate mental constructs. Increasingly, text-based learning environments are leaving students without the mental frameworks necessary to think abstractly. In the context of learning chemistry, abstract thinking is vital. It is a fundamental building block of Higher Order Thinking Skills (HOTS). Thus, the learning environments students experience need to be reconceptualized. They need to be designed in a way that students think about and visualize abstract concepts. Our work in the chemistry education research area is critical. It highlights the need to modify or adapt the ways in which we teach chemistry.

One promising approach to address these challenges is the utilization of Augmented Reality (AR) technology. AR enables students to visualize three-dimensional virtual objects in a real environment, using digital devices like smartphones or tablets. This technology supports visual-spatial learning and provides an interactive experience that can significantly enhance students' understanding of abstract material (Billinghurst & Dunser, 2012). In the realm of chemistry learning, AR has been proven effective in increasing learning motivation, student engagement, and concept understanding. It achieves this by [specific ways AR enhances motivation, comprehension, and metacognitive skills]. More importantly, AR plays a pivotal role in bridging abstract concepts into a more concrete form, thereby reassuring its effectiveness in the learning process.

Along with the development of educational technology, the application of digital-based media, such as Augmented Reality (AR), has opened up new opportunities to improve the quality of learning. AR allows integration between the

real world and three-dimensional virtual objects, so it can help students visualize concepts that were previously difficult to imagine (Azuma, 1997; (Billinghurst & Dunser, 2012). In the context of learning chemical bonds, AR can display atomic structures, bond formation, and interactions between molecules in an attractive and interactive visual form (Akbar et al., 2024).

Various previous studies have shown that using AR in science learning can improve motivation, concept understanding, and higher-order thinking skills, including abstract thinking (Ibáñez & Delgado-Kloos, 2018). Previous systematic reviews have consistently reported positive effects of augmented reality on students' learning outcomes in science education, particularly in enhancing motivation and conceptual understanding. However, these reviews also identify limitations, including a predominant focus on affective outcomes and a lack of emphasis on higher-order cognitive processes such as abstraction. Addressing this gap, the present study focuses explicitly on abstract thinking in chemistry learning and employs a sequential explanatory design to examine not only whether AR is effective, but also how and why it supports students' abstraction processes. Research by (Abdinejad et al., 2021) found that students who used AR in chemistry learning significantly improved visualization and abstract reasoning abilities. The ability to think abstractly is an aspect of an individual that is seen abstractly, and this can be one of the success factors for a person, both in career and study (Rizti Yovan & Kholiq, 2021). Abstraction ability is divided into: from general experience being able to draw specific conclusions, and vice versa, from specific experience being able to draw general conclusions, and abstraction is not directly an object, but students have developed to interpret the concept of balance well, even being able to utilize combinations in their thinking (Sugandi et al., 2020).

Abstract thinking ability is the ability to imagine an event or event that has not yet occurred. In order to produce good learning outcomes, students can make predictions, draw the right conclusions, and solve problems without having to see directly with objects and events. Generally, students can reflect on events, ideas, and relationships with abstract thinking. They are able to reason both inductively and deductively, able to examine the possibilities that occur and apply abstract concepts (Nandyansah & Suprapto, 2019). The existence of the abstraction process in the learning process is a must because the abstraction process plays an important role in the formation of chemical concepts. But research on abstract thinking skills is still few and less attention by other researchers, especially in chemistry learning. Whereas abstract thinking ability is also an ability to describe chemical concepts in a chemical problem or in other words, abstract thinking can build a problem situation model (Rizka & Hakim, 2017).

Students' ability to think abstractly in solving problems is very necessary, because the results of a person's mental abstraction are schemes that are used to understand something, find a way out or solve problems. Abstract thinking, generalizing, and structuring problems in everyday life are processes of abstraction. Abstraction is an idea or ideas used to describe, understand, and simplify the world. Abstraction is divided into three types, namely empirical, theoretical and reflective abstraction. According to (Nisa et al., 2022) solving problems can show students'

reflective abstraction. Therefore, this study examines reflective abstraction to describe students' abstraction abilities.

In assessing abstract thinking skills, there are four main levels that are often used to assess the development of students' understanding of abstract concepts such as chemical bonds (S. E. Putri et al., 2024), (Jumahat et al., 2016) namely Recognition, Representation, Structural Abstraction, and Structural Awareness. At the Recognition level, students begin to recognize and distinguish abstract chemical objects or concepts, such as atoms, ions, and electrons. For example in chemical bonding: students can identify the difference between ionic bonds and covalent bonds based on common characteristics (e.g., metal vs. non-metal, electron transfer vs. shared use). In this phase, there is an initial awareness of the existence of invisible structures. This level serves as an initial foundation for students to enter more complex symbolic representations (N. M. Putri & Rahmawati, 2024). At the Representation Level, students have been able to form visual or symbolic representations of abstract concepts, such as compiling Lewis structures and or drawing molecular shapes based on VSEPR theory, and using symbols and electron notation in writing electron configurations. The goal: To connect abstract objects with visual forms or symbols that can be understood. Representation is important to clarify complex ideas through visualization and symbolic models (Musa et al., 2023). At the Structural Abstraction Level, students begin to understand and relate the inner structure of a concept, and begin to generalize patterns. In chemical bonding, for example, explaining why atoms form certain bonds based on electron configuration, understanding the relationship between molecular structure and physical and chemical properties of a compound (such as polarity, boiling point, solubility).

This ability shows that students have passed the memorization stage towards deeper conceptual understanding (Priyasmika, 2021). At the Structural Awareness Level, students have reflective awareness of the structure of concepts, can modify representations and evaluate their logical consistency. Example in chemical bonding: students are able to analyze the advantages and limitations of bonding models (such as Lewis model vs molecular orbital model), criticize the representation of bonding in textbooks or diagrams and suggest improvements. This level encourages higher-order reasoning and metacognitive skills towards abstract concepts. Structural awareness is an indicator of advanced abstract thinking and is highly relevant in the development of science literacy (Budiman et al., 2021).

To be able to develop students' abstraction skills, it is important to analyze their initial reflective abstraction level, to what extent the use of AR can support students' abstract thinking skills on chemical bonding material, as one of the basic chemical concepts that are important for further chemical understanding. This study aims to analyze the level of students' abstract thinking ability in Chemical Bonding material before and after the use of Augmented Reality (AR) based learning media, the effectiveness of Augmented Reality in supporting students' abstract thinking process in chemical bonding material, determine the effect of using Augmented Reality (AR) on increasing students' abstract thinking ability in Chemical Bonding material, and

describe student responses to the use of Augmented Reality (AR) media in learning Chemical Bonding material.

2. Method

The study featured a mixed-method approach, using a sequential explanatory design where quantitative data collection and analysis were done first, followed by qualitative analysis to clarify and enrich the quantitative data. This particular design was the most appropriate for examining the effect of Augmented Reality (AR) in enhancing students' abstract thinking skills in bonding chemistry instructions. The primary focus of this research was a State Madrasah Aliyah (MAN) Pekanbaru, Indonesia, in the course of teaching the chemical bonding unit in Grade X chemistry. The participants were all Grade X students of the school. Due to administrative and natural classroom settings, two intact classes were sample chosen using purposive sampling. The selection criteria were (1) students shared similar chemistry performance, and thus, similar academic achievement, (2) the classes had a comparable student count, and (3) both classes had the same chemistry curriculum and teacher. One class was designated as the experimental group, and the other class, as the control group.

Experimental and control groups were assessed for their abstract thinking skills to determine whether the groups were equivalent. Pretest results were subjected to Normality tests (Kolmogorov–Smirnov), and Homogeneity of Variance tests (Levene's). Statistically, both groups were homogeneous and their results were normally distributed, confirming the classes equivalent status. Thus, differences in the posttest performances must be due to the instructional treatment. The experimental group was taught using an Augmented Reality (AR) application named AR Chemical Bond, created by Irene Mugati. The application is targeted at learning chemistry, specifically chemical bonding. The AR media is smartphone-embedded and marker-based. The students' smartphones trigger the AR media. The application helps students visualize concepts in 3D. These include atomic structures, valence electrons, ionic and covalent bonds, and the molecules related to chemical bonding. The AR intervention occurred throughout the chemical bonding unit and across several instructional classes. During each of these AR classes, the students were guided by the teacher to interact with the application, and they discussed the 3D representations of bonds. The AR activities were combined with classroom activities, worksheets, and discussions to strengthen the rational and conceptual understanding of the students.

The control group received conventional chemistry instruction commonly applied at the research site. This instruction consisted of teacher-centered methods, including lecturing, question-and-answer sessions, textbook-based explanations, and the use of static two-dimensional representations such as drawings on the board and textbook images. No AR or interactive digital visualization tools were used in the control group. Both groups received the same learning objectives, content coverage, instructional duration, and assessment instruments. The only instructional difference

between the two groups was the use of Augmented Reality media in the experimental group.

Data on students' abstract thinking skills were collected using an essay-based test instrument developed based on four levels of abstract thinking: recognition, representation, structural abstraction, and structural awareness. The instrument was validated through expert judgment and empirical testing, including validity, reliability, difficulty level, and discrimination index analysis.

Qualitative data were collected through semi-structured interviews with selected students representing different achievement levels and through document analysis. These qualitative data were used to explain and support the quantitative findings. Quantitative data were analyzed using descriptive statistics and inferential analysis. A t-test was conducted to examine differences in posttest scores between the experimental and control groups. The effectiveness of the AR intervention was further analyzed using normalized gain (N-gain) analysis to measure improvement in students' abstract thinking skills.

Qualitative data were analyzed using descriptive thematic analysis, focusing on students' responses related to abstraction processes, learning experiences, and conceptual understanding of chemical bonding. To provide an in-depth explanation of the quantitative patterns, four students were selected for qualitative analysis using maximum variation sampling, representing high, medium, and low levels of learning gains. The purpose of this selection was not statistical representativeness, but analytical depth, allowing the study to explore contrasting abstraction processes across different performance profile. Researchers conducted a sequence of analysis of 2 students in the experimental class and two students in the control class selected based on the category of student achievement levels and the results of interviews that the author felt were able to present the abstract thinking ability of students. The categories of students' abstract thinking abilities analyzed are the ability to think abstractly in the high category of the experimental class (Student A), the medium category of the experimental class (Student B), the high category of the control class (Student C) and the medium category of the control class (Student D). The integration of quantitative and qualitative findings provided a comprehensive interpretation of the research results.

3. Result and Discussion

Quantitative Phase Analysis

The quantitative phase of this research produces data on students' abstract thinking abilities in both classes through essay test questions on chemical bonding material, as shown in Figure 2. Figure 2 shows students' abstraction ability on chemical bonding material before and after treatment. The relatively homogeneous pretest results indicate a relatively similar initial ability. However, a fairly dominant difference was seen in the posttest results of students' abstract thinking skills in the experimental and control classes. The difference in the average pretest score of the experimental and control classes is 0.9, and the difference in the posttest score of the experimental class and control class is 7.4. This means that the average posttest score of abstract

thinking ability of experimental class students is higher than the control class score. Augmented Reality learning media is thought to support students' abstract thinking skills in the learning process because It helps students use their ability to imagine objects that are not faced directly (Vari & Bramastia, 2021).
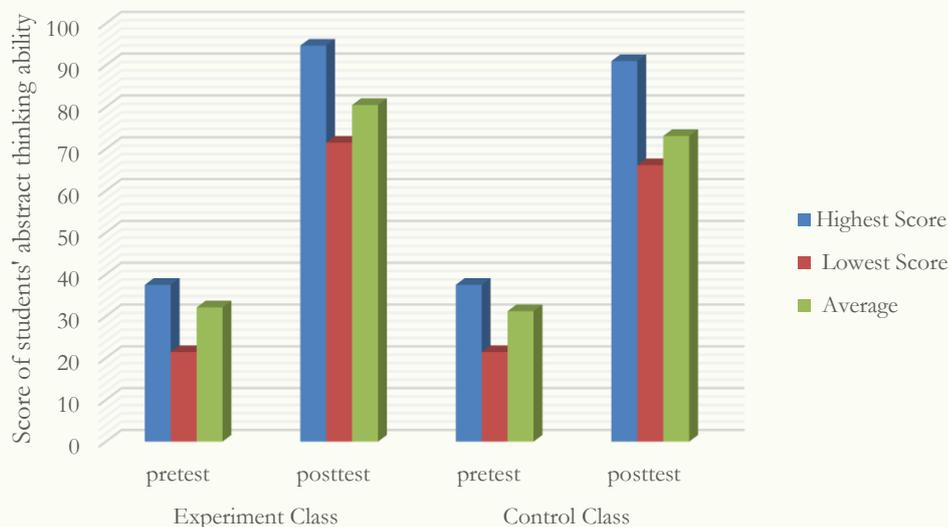

Figure 1. Differences in Students' Abstract Thinking Ability in Both Test Classes

Academically, here are some analytical results that can be assessed from Figure 1:

1. Average Increase in Abstract Thinking Ability

The average score of students in the experimental class increased from 32.1 to 80.5, while that of the control class increased from 31.2 to 73.1. Although both classes showed an increase, the experimental class showed a greater difference in increase (48.4 points) than the control class (41.9 points). This shows that AR in the experimental class effectively improves students' abstract thinking skills, especially in understanding conceptual and invisible chemical bonding material. According to Wijaya et al. (2022), significant improvements in abstract thinking skills occur when students are involved in learning that facilitates the development of conceptual representations and higher-order reasoning, such as models, simulations, or *problem-based learning* approaches.

2. Distribution of Highest and Lowest Scores

The range of values on the graph shows that the experimental class has a higher minimum achievement than the control class, which means that not only a small proportion of students improved, but almost all students experienced significant improvement. According to (Hidayat et al., 2024), this even distribution of improvement reflects that the learning strategy in the experimental class accommodates various levels of students' initial abilities, which is a characteristic of differentiative and student-centered learning.

3. Link to Chemical Bonding Materials and Abstract Thinking

Chemical bonding materials (such as ionic, covalent bonds, Lewis structures, and VSEPR theory) demand students' abilities in:

- Visualize atomic and molecular structures,
- Reasoning based on microscopic concepts,

Abstracting the relationship between structure and properties of compounds.

This study delves into the realm of high-level abstract thinking, a domain that Rahmawati et al. (2022) argue can be optimally developed through visual media, concrete models, and symbolic representation-based approaches in chemistry learning. Our research, which focuses on the innovative use of AR in learning, is oriented towards the visualization and construction of abstract concepts. It effectively aids students in grasping the intricacies of chemical bonding material. This finding is particularly pertinent in the context of the 21st-century curriculum, which places a premium on critical and abstract thinking skills as part of modern science literacy (Trilling & Fadel, 2009).

The practical implications of our research are significant. The difference in the average *post-test* scores of abstract thinking ability between the experimental and control classes was measured using a student t-test. The results of this calculation, presented in Table 1, provide valuable insights into the effectiveness of AR in enhancing students' abstract thinking skills in chemistry education.

Table 1. T-test Results of *Posttest* Scores

Data	t count	df	*Sig (2-tailed)*	Description
Posttest	3.628	74	0.001	Sig < 0.5 (there is a significant difference)

Table 1 shows that the significance value *(2-tailed) of the posttest* is 0.001, meaning the significance value of 0.001 <0.05. This proves that there is a significant difference between the *posttest* scores of the experimental and control classes. The t-test analysis of the posttest data of the experimental class and control class obtained the amount count of 3.628 with df = 74.) This means that the t-test results show a significant difference in ability between the experimental and control classes. So, the average results of the abstract thinking ability of students taught using Augmented Reality (AR) media are higher than those of students who are not treated. Theoretically, this is because Augmented Reality media can describe abstract concepts to understand and organize objects and can stimulate the mentality of students in thinking about a problem that occurs, so Augmented reality has positive potential in learning and improving the quality of the learning process (Maulana et al., 2019).

The difference in students' abstract thinking ability during the posttest in the experimental and control classes was further analyzed using the indicators of abstract thinking ability. The levels of abstract thinking skills measured in this study are recognition, representation, structural abstraction, and structural awareness. The percentage of achievement of each level of students' abstract thinking ability is presented in Figure 3.

The data above shows that the highest student abstract thinking ability in the experimental class occurred at the representation level of 95.7% and the lowest at

the level of structural awareness of 63.2%. While in the control class the highest abstract thinking ability at the representation level was 83.8% and the lowest at the structural awareness level was 55.7%.
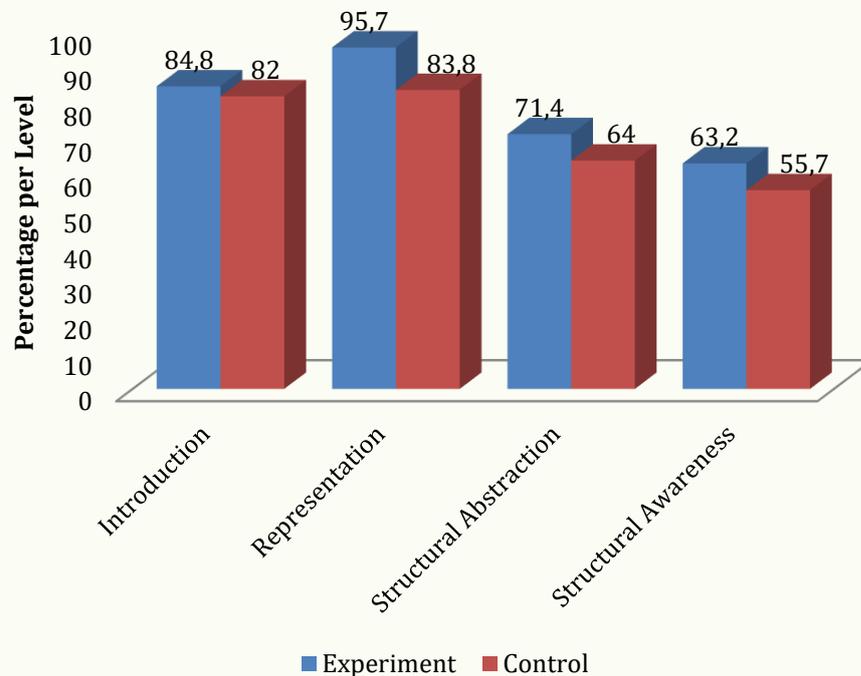

Figure 2. Percentage of Abstract Thinking Ability Levels

Figure 2 generally shows that the application of learning using *Augmented Reality* can support students' abstract thinking skills at each level studied in this study. The highest abstract thinking ability in the experimental class occurred at the representation level of 95.7% and the lowest at the structural awareness level of 63.2%. In the control class, the highest abstract thinking ability at the representation level was 83.8%, and the lowest at the structural awareness level was 55.7%.

The first level measured in this study is the recognition level. The data above shows that the percentage of achievement at the recognition level in the experimental class is 84.8%, and in the control class is 82%. This level shows that experimental and control class students have an excellent category recognition level, because students can identify problems at this level and recall previously learned concepts. This is in line with (Wiryanto, 2014) opinion that students can recognize previously learned structures either in the same activity or in activities that have been carried out (Fajriyah & Susanah, 2022). Moreover, this level is influenced by the difficulty level of low questions, namely understanding (C2), where in this indicator, students only explain, interpret, and understand the problem. The high percentage of achievement of the recognition level in the experimental class was due to using *augmented reality* during the learning process.

The second level in this study is representation. The data above shows that experimental and control class students have an excellent category representation level at this level of representation. This is because, at this level of representation, students can express the results of their thinking in the form of images and symbol (Masamah, 2021). However, in the experimental class, the percentage at this level is higher than in the control class; this is due to the use of *augmented reality* media in the experimental class. *Augmented reality* media can present abstract and concrete material because of the visualization of 3D images (Putra et al., 2024). The high percentage of experimental classes is because, through *augmented reality,* students can see visually, so students will more easily remember and understand the material. This is to the learning pyramid proposed by Edgar Dale (Sari, 2019) that when students see visually, the ability to remember is higher than reading and hearing. Therefore, the level of representation in the experimental class is higher than in the control class.

The next level is structural abstraction. The data above shows that experimental and control classes have a good level of structural abstraction at this level of structural abstraction. Students can develop new strategies for a problem at hand at this level of structural abstraction. They can organize the problem structure in the form of compiling and developing (Fajriyah & Susanah, 2022). The data shows that at this level, students are still in the good category; this is because students are less able to develop new strategies in problem-solving. At this level, it is influenced by the problem's difficulty level, namely applying (C3) and analyzing (C4). The percentage of experimental classes is higher than the control class; this shows that *augmented reality* can support abstract thinking skills at the structural abstraction level.

The last level is structural awareness. The data above shows that the experimental class is in a good category and the control class is in the sufficient category; this shows that the level of structural awareness of the class treated with *augmented reality* media is superior to the class without being treated with the media. At this level of structural awareness, students can provide arguments and reasons for the decisions made (Masamah, 2021) However, here, students are less able to provide reasons and arguments for the existing problems, so at this level, students are still in the good category and sufficient category. Also, at this level, it is influenced by the difficulty level of the problem, namely analyzing (C4) and evaluating (C5), where the increasing level of abstract thinking also increases the problem's difficulty level.

The following are some of the Academic Analysis results that can be extracted from Figure 2:

A. Effectiveness of Augmented Reality (AR)

The increase in scores on all indicators in the experimental class shows that AR significantly supports students' abstraction skills. The graph above compares students' abstraction ability between the experimental class (using Augmented Reality/AR) and the control class (without AR) on five chemical concept abstraction ability indicators, especially chemical bonding material. The experimental class consistently scored higher than the control class. The most

significant increase occurred in explaining the relationship between concepts and using concepts in new situations, which shows that students who learn with AR can better relate and apply chemical concepts in the abstract. AR can visualize abstract concepts such as ionic, covalent, and coordination bonds in 3D, enhance learning experiences with interaction and immersion, and bridge macroscopic, microscopic, and symbolic concepts in chemistry.

B. Improvement of Specific Abstraction Ability

1. Connections between concepts (Indicator 2) and Application of concepts (Indicator 3) showed the most significant improvement, indicating that AR is very effective in helping students see connections between concepts and use them in new contexts.
2. Concept Generalization (Indicator 5) is still a challenge, although it has improved. This shows that although AR helps visualization, students still need to be assisted to develop metacognitive and reflective abilities.

The use of AR in the experimental class proved to have a positive impact on students' abstract thinking skills. This can be explained through several educational theories and previous research results:

1. (Rita & Guspatni, 2024) states that learning will be more effective if information is simultaneously presented in verbal and visual form. AR allows visualization of molecules and chemical bonds in interactive 3D form, which significantly helps the understanding of abstract concepts.
2. According to (Eviota & Liangco, 2020), Augmented Reality increases students' cognitive engagement by integrating the real world and virtual objects, which stimulates attention, motivation, and conceptual understanding in science.

(Abdul Talib et al., 2022) found that the use of AR in chemistry learning not only improved conceptual understanding, but also problem-solving and critical thinking skills, which are key components in abstraction ability.

C. Technology-based Learning as an Innovative Strategy to support the improvement of abstraction skills

AR creates a multimodal, interactive learning environment that stimulates visual, spatial, and logical information processing. In a chemistry context that relies heavily on modeling and abstraction, this technology is a solution to bridge the cognitive gap. From the data displayed on the graph, it can be seen that experimental class students excel in five indicators of abstraction ability:

1. Identifying abstract concepts: Students can recognize bond forms (ionic, covalent, coordination) more clearly through AR visualization.
2. Explaining the relationship between concepts: AR allows students to see the interrelationships between molecular structures, differences in electronegativity, and the types of bonds formed.
3. Using concepts in new situations: The AR interactive model encourages students to conduct cognitive exploration and experimentation with new chemical situations.
4. Predicting logical consequences: Students can use visual representations to estimate molecular shapes and reactivity.

5. Making conceptual generalizations: Although the lowest, this indicator showed improvement, indicating the beginning of higher-level abstraction skills.

These results support the importance of technology integration in science learning, especially chemistry. Abstraction ability is one of the important aspects of higher-order thinking Skills (HOTS), and chemistry learning highly demands this skill.

According to Anderson & Krathwohl's (2001) in (Wilson, 2016) revised taxonomy, abstraction is included in the analysis to synthesis stage. The use of technology such as AR can accelerate the acquisition of such skills due to students:

- Experience meaningful learning.
- Build connections between concepts independently (constructivist approach).
- Learn actively through exploration and manipulation of virtual objects (active learning).

From the analysis of graphs and supporting literature, it can be concluded that the use of Augmented Reality significantly supports the improvement of students' abstraction abilities on chemical bonding materials. Learning that incorporates immersive technologies such as AR needs to be part of chemistry learning innovation in the digital era to support the achievement of 21st century competencies.

To determine the effectiveness of learning using Augmented reality on students' abstract thinking skills on chemical bonding material, the n-gain calculation was obtained from each student's pretest and posttest scores, as shown in Table 4.

Table 2. N-Gain Results

N-Gain Value	Category	Experiment Class		Control Class	
		JS	Percentage	JS	Percentage
g > 0,7	High	28	73,7%	8	21%
0,3 ≤ g ≤ 0,7	Medium	10	26,3%	30	79%
g < 0,3	Low	-	-	-	-
Total			**100%**		**100%**

The results of the Normalized Gain (N-Gain) value in Table 4, which is used to measure the effectiveness of learning based on the increase in pretest and post-test scores in this research, show that 73.7% of students in the experimental class are in the high N-Gain category, which means that most students experience significant improvement in abstract thinking skills after learning. 26.3% were in the medium category, and none were in the low category, indicating the consistency of positive learning outcomes. This shows that the intervention or innovative learning method in the experimental class effectively increases the *abstraction of chemical bonding concepts - concepts* naturally require abstract

thinking skills because they cannot be observed directly (for example, intermolecular forces, orbitals, and ionic/covalent bonds). Meanwhile, in the Control Class, 79% of students were in the moderate category, and only 21% were in the high category. This shows that the improvement is relatively moderate, with most students not reaching the high improvement category. This indicates that conventional learning is less effective in developing abstraction skills on microscopic materials such as chemical bonds.

Academic explanations for this data also reveal that according to the characteristics of Chemical Bonding Materials, which contain abstract concepts such as Lewis structures, VSEPR theory, and ion/covalent bonds that cannot be observed directly, effective learning must be prepared to help students build mental representations or visualizations, through media, simulations, or concrete models based on visual representations with a technology-based approach because it has been proven successful in building students' abstract thinking schemata. This abstraction ability is closely related to the high cognitive level in the Revised Bloom Taxonomy (Wilson, 2016). It is in line with the demands of 21st-century learning (analytical thinking, reasoning, abstraction). The research results, which did not find experimental class students in the low category, concluded that the AR used was effective on average and evenly distributed individually. Meanwhile, in the control class, most students only experienced moderate improvement, possibly due to the conventional method not stimulating enough in-depth processing of abstract concepts.

The results of this phase show that the use of Augmented Reality media in chemistry learning is proven to be practical and significant in improving students' abstract thinking skills, especially in conceptual and invisible chemical bond materials. AR provides an immersive, interactive, and visual learning experience, thus helping students understand abstract concepts, build relationships between concepts, and apply knowledge in new situations. Therefore, integrating AR as an innovative strategy in science learning is highly recommended to support the development of 21st-century competencies.

Qualitative Phase Analysis

The qualitative findings indicate that the 26.3% of students in the experimental group who achieved only medium N-gain levels experienced limitations primarily at the structural abstraction and structural awareness levels. While most qualitative examples illustrate successful abstraction development, it is important to note that not all students benefited equally from AR-based instruction. Students who achieved only medium learning gains demonstrated difficulties at the structural abstraction and structural awareness levels. These students were able to recognize and represent chemical structures, but struggled to generalize bonding principles and evaluate their reasoning processes, indicating that AR visualization alone was insufficient to support higher-level abstraction.

While most qualitative examples illustrate successful abstraction development, it is important to note that not all students benefited equally from AR-based instruction. Students who achieved only medium learning gains

demonstrated difficulties at the structural abstraction and structural awareness levels. These students were able to recognize and represent chemical structures, but struggled to generalize bonding principles and evaluate their reasoning processes, indicating that AR visualization alone was insufficient to support higher-level abstraction.

Interview data revealed that these students were able to recognize concepts and construct representations using AR visualizations; however, they encountered difficulties when required to generalize bonding principles, develop alternative solution strategies, and reflect on their reasoning processes. Although AR facilitated conceptual visualization, some students still relied heavily on surface-level representations and required additional scaffolding to support higher-order abstraction and metacognitive reflection. This explains why their learning gains remained at a moderate level despite exposure to AR-based instruction.

Description of abstract thinking ability of student A

From the results of students' abstract thinking ability in the experimental class, students in the high category were analyzed, as shown in Table 5.

Table 3 Results of Analysis of Abstract Thinking Ability of Student A

No.	Abstraction Level	Analysis
1	*Recognition*	Based on the interview results in Appendix C.11 student A, it can be seen that the student can recall the previous material, namely the atomic structure and periodic system of elements related to chemical problems. This ability to recall and apply previous knowledge is a key component of abstract thinking, as it allows the student to build on existing concepts and apply them to new situations. Student A also understood the problem given well.
2	*Representation*	Based on the results of the interview, it can be seen that student A is able to answer and solve chemical bonding questions in the easy, medium and difficult categories. In these categories, 'easy' problems refer to [definition of easy problems], 'medium' problems refer to [definition of medium problems], and 'difficult' problems refer to [definition of difficult problems]. And student A can also express the results of his thinking into chemical symbols and chemical structures such as making electron configurations and lewis structures.
3	Structural Abstraction (*Structural Abstraction*)	Based on the results of the interview, it can be seen that student A can solve chemical bonding problems by using new strategies or other ways to solve them.

No.	Abstraction Level	Analysis
4	Structural Awareness (*Structural Awareness*)	Based on the results of student interviews, it can be seen that student A is aware of his ability to anticipate the results of problem-solving, can provide conclusions and arguments or reasons correctly for the decisions that have been made, and reflect on decisions made for the next activity.

Table 3 shows that student A can understand the given problem well so that they can think or perform abstraction quickly. Student A performs representation abstraction with

Student A has good ability at the level of structural abstraction because he can answer and solve chemical bonding problems in the easy, medium, and difficult categories correctly and can express the results of his thinking in the form of chemical symbols and Lewis structures such as making electron configurations and lewis structures. Furthermore, student A has good ability at the structural abstraction level because he can develop new strategies for a problem in a way that he created by himself. Student A can provide arguments or reasons for decisions made and connect activities that occur structurally.

Academic Analysis per Abstraction Level

1. Recognition Level

At this stage, student A has shown retention of basic knowledge and can reactivate fundamental concepts such as atomic structure and the periodic system of elements, which are prerequisites for understanding chemical bonding. According to (Weinrich & Sevian, 2017), abstract thinking starts from the ability to recognize previous information, which is the basis for analyzing chemical concepts that are microscopic and cannot be observed directly.

2. Level of Representation

Student A's ability to translate concepts into chemical symbols and models, such as electron configurations and Lewis structures, shows mastery of symbolic representations essential in understanding and solving chemical bonding problems. (Rassyi et al., 2023) stated that chemical triplet representations (macroscopic, submicroscopic, and metaphorical) are key to helping students transform abstract ideas into forms that can be manipulated cognitively.

3. Structural Abstraction

Student A's ability to use new strategies to solve the problem shows that he has developed flexible and adaptive thinking skills. This is important in chemical bonding, as students need to understand and analyze different types of bonds (ionic, covalent, coordination) with different approaches. Based on (Serhan et al., 2019), structural abstraction is an indicator of a student's ability to use conceptual schemes to design alternative solutions to complex problems, such as bond type selection or compound polarity prediction.

4. Structural Awareness

Student A showed metacognitive maturity with the ability to conclude, convey logical reasons, and reflect on the problem-solving process. This is the highest

level of abstract thinking ability. (Den Otter et al., 2022) emphasized that structural awareness is closely related to *scientific reasoning*, where students understand and apply concepts and evaluate their thinking processes for better decision-making in the future.

These results demonstrate the comprehensive mastery of student A, from recognizing concepts to reflecting on the thinking process. This signifies that the learning he received has fostered abstract thinking skills as part of higher-order thinking skills, as emphasized in the Merdeka Curriculum and the Pancasila Learner Profile. Student A has high abstract thinking skills at all levels, which reflects excellent conceptual and metacognitive mastery of chemical bonding material. This ability will greatly support student A in advanced learning, such as metal bonding, molecular shapes, and VSEPR theory, which also requires the integration of logic and symbolic representation.

Description of abstract thinking ability of student B

From the results of students' abstract thinking ability in the experimental class, students in the moderate category were analyzed, as shown in Table 4.

Table 4. Results of Analysis of Abstract Thinking Ability of Student B

No.	Abstraction Level	Analysis
1	*Recognition*	Based on the interview results in Appendix C.11 student B, it can be seen that student B can recall the previous material, namely the periodic system of elements related to chemical bonding problems.
2	*Representation*	Based on the results of the interview, it can be seen that student B can express the results of his thinking in the form of chemical symbols and chemical structures such as making electron configurations and lewis structures.
3	*Structural Abstraction*	Based on the results of the interview, it can be seen that student B is able to answer and solve chemical bond problems but has little difficulty in answering difficult category problems. In easy and medium problems, student B can solve chemical bonding problems by using new strategies and other ways to solve them. Whereas in difficult problems student B cannot solve the problem by using new strategies in solving it.
4	*Structural Awareness*	Based on the results of the interview, it can be seen that student B is able to provide arguments or reasons for the decisions made on easy and medium level questions while on difficult questions students cannot

No.	Abstraction Level	Analysis
		provide reasons for the decisions made. This happened because student B did not master the material.

Table 4 shows that student B can understand the problem or identify the structure of the problem and connect it a little less understanding in the difficult problem category. This gives rise to a slightly longer abstraction, but sometimes, the abstraction in student B is fast in the easy and medium problem categories. Student B can recall previous activities and apply them to the problem at hand. Student B can express the results of his thinking through chemical symbols and structures, such as making electron configurations and Lewis structures. Student B can develop new strategies and other ways of solving problems but cannot create new techniques in solving complex category problems, making it difficult to correct mistakes that have been made and unable to understand and solve problems that develop so that these students are also unable to provide arguments for the decisions made. This process means that abstraction rarely appears when student B solves problems, so student B experiences weakness in mastering and linking material.

The Academic Analysis per Level for student B can be explained as follows:
1. Recognition Level (Recognition)

Student B's ability to recall previous material indicates good long-term memory retention of the basic concepts of the periodic system of elements. This is the initial foundation of abstract thinking because students begin to associate prior knowledge with a new context (chemical bonds). According to (Sutiani et al., 2021), the ability to recognize and associate previously learned information is the initial stage of abstract thinking that plays a role in building chemical conceptual understanding.

2. Level of Representation

Student B can convert verbal concepts into symbolic representations (e.g., electron configuration and Lewis structure). This signifies a strong internal representation ability, which is important in learning chemistry that relies on symbols, models, and images. (Ahmar et al., 2020) mentioned that representational abilities such as drawing Lewis structures or arranging electron configurations are key indicators of the development of *mental models* in science students' abstract thinking.

3. Structural Abstraction Level

Student B's ability to use new strategies in easy and medium problems shows cognitive flexibility, namely the ability to see issues from various points of view. However, the limitations under challenging problems indicate that his abstract thinking skills are not yet fully mature for non-routine or complex situations. According to (Hačatrjana & Namsone, 2024), students at this stage

can build concept structures but still depend on familiar contexts and have difficulties thinking divergently in higher abstract situations.

4. Structural Awareness Level

Students begin to show metacognitive abilities at this level, namely, realizing and evaluating their thinking. Student B could provide arguments for his answers but was limited to questions that were not too complex. The inability to give reasons for difficult problems indicates that mastery of the material and metacognitive reflection have not stabilized at a high level of abstraction. (Orgill et al., 2019) stated that structural awareness requires strong conceptual mastery and the ability to evaluate and modify thinking when facing new or complex problems.

Conclusion The analysis shows that student B has achieved the first three levels of abstract thinking ability (recognition, representation, and structural abstraction) quite well. However, students still face obstacles at the highest level (structural awareness), especially in solving difficult problems that require complex reasoning and intense metacognition. This suggests that learning interventions cannot rely solely on AR assistance to develop abstract thinking skills but require a process that focuses on problem-solving, conceptual modeling, and metacognitive reflection that needs improvement.

Description of students' abstract thinking ability C

The results of the analysis of students' abstract thinking ability in the control class with a high category, represented by student C, are shown in Table 5.

Table 5. Results of Analysis of Abstract Thinking Ability of Student C

No.	Abstraction Level	Analysis
1	*Recognition*	Based on the interview results in Appendix C.11 student C, it can be seen that the student can recall the previous material, namely the atomic structure and periodic system of elements related to chemical problems. Student C also understood the problem given well.
2	*Representation*	Based on the results of the interview, it can be seen that student C is able to answer and solve chemical bonding questions in the easy, medium and difficult categories. And student C can also express the results of his thinking into chemical symbols and chemical structures such as making electron configurations and lewis structures.
3	*Structural Abstraction*	Based on the interview results, it can be seen that student C can solve chemical bonding problems by using new strategies or other ways to solve them.
4	*Structural Awareness*	Based on the results of student interviews, it can be seen that student C is aware of his ability to anticipate the results

No.	Abstraction Level	Analysis
		of problem-solving, can provide conclusions and arguments or reasons correctly for the decisions that have been made, and reflects on the decisions made for the next activity.

Table 5 shows that student C can understand the problems given well, so they can think or abstractabstract quickly. Student C performs representation abstraction well, namely being able to answer and solve chemical bonding problems in the easy, medium, and difficult categories correctly and being able to express the results of their thinking in the form of chemical symbols and Lewis structures, such as making electron configurations and lewis structures. Furthermore, student C has good ability at the structural abstraction level because he can develop new strategies for a problem in a way he created by himself. Student C can provide arguments or reasons for decisions made and connect activities that occur structurally.

Academic Analysis per Level of Abstraction of Student C as follows:

1. Recognition Level

Student C's ability to recall material such as atomic structure and periodic system and understand the problem indicates that long-term memory and initial conceptual understanding are well established. This is the primary foundation of abstract thinking, which is the ability to activate old knowledge to solve new problems. According to (Schumacher & Stern, 2023), activating schemata related to prior learning is an early stage in abstract thinking that integrates new concepts in students' knowledge structure.

2. Level of Representation

Students' ability to solve problems from low to high difficulty levels and communicate ideas through chemical symbols and structural representations indicates a high mastery of chemical representations. (Nelsen et al., 2024) explained that abstract thinking in chemistry is closely related to representational abilities macroscopic, microscopic, and symbolic- that allow students to build a holistic understanding of complex concepts such as chemical bonding.

3. Structural Abstraction Level

Student C showed cognitive flexibility by using new or alternative problem-soltonsolveegies. This indicates that students have achieved divergent thinking skills, namely thinking outside routine or schematic patterns in solving problems. According to (Hendry, 2016), the ability to use new strategies to solve chemical problems indicates that students have built flexible and abstract conceptual mental structures.

4. Level of Structural Awareness

Student C showed mature metacognition, as seen by his ability to reflect on the thinking process, provide logical arguments, conclude, and anticipate problem-solving results. This is the highest form of abstract thinking according to cognitive hierarchy theory. Based on (Den Otter et al., 2022), structural

awareness shows that students understand and apply knowledge and assess and evaluate their thinking process, a hallmark of advanced scientific thinking.

The results of the academic analysis of C students showed a thorough mastery of all four levels of abstract thinking: recognition, representation, structural abstraction, and structural awareness. This ability reflects that the learning received by student C supports higher-order cognitive development, both in terms of conceptual knowledge and metacognitive regulation. Such students are ideal examples of reflective and independent learners, which are very much in line with the profile of Pancasila learners and the learning needs of the 21st century.

The substantial improvement observed in the control group, particularly at the recognition and representation levels, suggests that conventional instruction remains effective for supporting lower-level abstraction when content exposure and practice are adequate. These gains likely reflect students' familiarity with symbolic representations and teacher explanations. However, differences between groups became more pronounced at higher abstraction levels, where the experimental group demonstrated stronger structural reasoning and reflective awareness, highlighting the added value of AR beyond foundational learning.

Description of students' abstract thinking ability D

From the results of students' abstract thinking ability in the control class, students in the moderate category were analyzed, as shown in Table 6.

Table 6. Results of Analysis of Abstract Thinking Ability of Student D

No.	Abstraction Level	Analysis
1	Recognition	Based on the interview results in Appendix C.11 with student D, it can be seen that student D can recall the previous material related to chemical bonds.
2	Representation	Based on the interview results, student D can express the results of his thinking into chemical symbols and chemical structures, such as making electron configurations and Lewis structures.
3	Structural Abstraction	Based on the results of the interview, students can solve easy category problems and cannot solve medium and difficult category problems.
4	Structural Awareness	Based on the interview results, student D can provide conclusions or reasons correctly on easy category questions; in the medium and difficult categories, student D cannot provide reasons for the decisions that have been made.

Table 6 shows that student D lacks understanding of the learning material, so he cannot solve these problems, both medium category problems and difficult category problems. Student D takes a long time to complete the abstraction

process when working on problems. Student D can recall previous material and can express the results of his thinking into chemical symbols and chemical structures, such as making electron configurations and Lewis structures. However, student D cannot develop new strategies or other ways of solving problems and organizing the structure of the problems faced in moderate and complex category problems, so he cannot understand and solve developing problems. Moreover, student D cannot provide arguments and reasons for the decisions made.

Academic Analysis of Student B Based on Abstract Thinking Level as follows:

1. Recognition Level

At this stage, D students show cognitive recall ability of the basic concepts of chemical bonding. This is important as a prerequisite for further understanding, especially on abstract materials such as electron configuration, electronegativity, and Lewis structure. According to (Pratiwi et al., 2023), introducing basic concepts is crucial in learning chemistry because it is the foundation of conceptual thinking and advanced problem-solving skills.

2. Level of Representation

Student D can translate verbal concepts into symbolic representations in the form of Lewis structures and electron configurations. This shows that students have representational abilities, although not necessarily followed by deep conceptual understanding. (Fitriani et al., 2022) emphasized that in chemistry, the ability to represent ideas through chemical symbols is crucial to build understanding of concepts that are microscopic and abstract.

3. Structural Abstraction Level

Student D was only able to solve easy category problems and failed in medium and difficult problems. This shows that his abstract thinking ability is still limited to routine patterns, not yet able to be used to solve problems that require complex analysis or flexible thinking.

According to (Frey et al., 2020), many students struggle with structural abstraction due to weak linkages between concepts and a lack of experience in solving challenging contextual problems.

4. Structural Awareness Level

Student D could only give logical reasons on easy problems, but failed to evaluate and reflect on decisions at the level of more complex problems. This indicates a lack of metacognitive skills, the ability of students to control and evaluate their thinking processes, which are essential in modern science learning. (Kootstra & Muysken, 2019) stated that structural awareness requires a thorough mastery of concepts and metacognitive skills to analyze and reflect on the thinking process in solving chemical problems.

This shows that Student D has shown abstract thinking skills at the level of recognition and representation but is not yet optimal at the level of structural abstraction and structural awareness. The inability to solve medium and difficult-level problems reflects Student D's lack of critical and reflective thinking skills, which should be developed through AR-assisted learning. This means that the ability to think abstractly in chemistry is not just a matter of remembering and

representing but also requires cognitive and metacognitive strategies that are explicitly developed through challenging and reflective learning approaches.

Based on the results of interviews on students' abstract thinking abilities, it is found that based on the levels of abstraction, each student has different abstract thinking abilities. However, there are some students who have similar abstract thinking abilities per level. Abstract thinking ability is needed to help train students in abstract thinking and solve chemical problems (Nihayah, 2021). Therefore, students need to develop their abstract thinking skills to easily and be able to solve problems in learning abstract chemistry material and as an effort to improve the quality and learning outcomes of students. Based on research conducted (Page et al., 2018), the discussion of the research results concluded that one of the factors that cause the success of a learning process and learning achievement is the abstract thinking ability of students. So, it takes media that can support students' abstract ability in the learning process, namely *Augmented Reality.*

The results of the interviews also conclude that the *Augmented Reality* media used attracts students so that students are eager to take part in learning. In addition, this *Augmented Reality* media displays material by visualizing it in 3D form so that it helps students in the process of understanding the material. Chemical bonding material that tends to be abstract becomes easier to understand, and learning is not monotonous because, in the media, it presents how a bond occurs, in contrast to the usual method of learning process. These levels of abstract thinking skills are important to be gradually developed in learning chemistry, especially on chemical bonds. Teachers must design learning strategies that allow students to move from simply recognizing concepts to deep and reflective understanding.

Based on the analysis of four students from the experimental and control classes representing the high and medium categories, an in-depth understanding of the variations in students' abstract thinking abilities based on four levels: recognition, representation, structural abstraction, and structural awareness was obtained.

Students in the **high** category, both from the experimental class (Student A) and the control class (Student C), showed strong mastery at all four levels. They can remember basic concepts, represent ideas in the form of chemical symbols and models, develop alternative problem-solving strategies, and show metacognitive reflection and evaluation independently. This aligns with the findings of (Fitriani et al., 2022) who emphasized the importance of metacognition and representational abilities in supporting abstract thinking in chemistry learning.

In contrast, students in the **moderate** category showed variations in ability at each level. Student B (experimental class) showed quite good ability at the level of recognition of structural abstraction but began to experience problems at the level of structural awareness. Student D (control class) only showed mastery at the initial level (recognition and representation) and had difficulty developing strategies or

reflecting on their thinking process on more complex problems. This supports (Teichert et al., 2017) statement that students with low concept mastery tend to fail at the reflective stage due to weak metacognitive abilities.

AR-based learning in the experimental class has positively impacted the development of students' abstract thinking skills, especially in students A and B. This indicates that technology such as AR can be an effective tool for developing higher-order thinking skills when accompanied by a pedagogical approach that is oriented toward problem-solving and reflection (Setyowati et al., 2020). It is important to acknowledge that spatial ability may act as a mediating factor in students' learning with AR-based environments. Previous studies indicate that learners with higher spatial skills may benefit more readily from three-dimensional visualizations. Although spatial ability was not directly measured in this study, qualitative findings suggest that some students encountered difficulties in interpreting spatial representations despite access to AR media. This highlights the importance of instructional scaffolding and suggests that future research should consider spatial ability as a potential moderating variable.

No participant attrition occurred during the intervention period, and all students completed both pretest and posttest assessments. Data screening indicated no extreme outliers that required removal. Minor missing responses in open-ended items were addressed through standard scoring procedures and did not affect overall statistical trends.

The result of this research is limited by the scope of the study which was conducted at one Madrasah Aliyah Negeri in Pekanbaru. Other cultural and curricular contexts may influence the applicability of the results. Other variables such as the level of the teacher's experience and the classroom management skills of the teacher, and the prior exposure of the students to the technology may have impacted the results. While instructional fidelity was observed through the use of the same lesson plans and learning objectives, the differing levels of teacher agency and the various levels of student mobile technology exposure may have impacted the learning experience in different ways. The quality of devices students used and the level of technology used prior may have impacted the extent to which AR features were utilized, demonstrating the importance for future applications to have clearly defined implementation strategies.

Regarding sustainability, the AR intervention demonstrated practical feasibility within regular classroom instruction; however, long-term implementation requires institutional support, teacher training, and alignment with curriculum objectives. Future research should examine the sustainability of AR integration over extended periods and its scalability across diverse school contexts.

4. Conclusion

Based on the results of quantitative data analysis, the use of Augmented Reality (AR) learning media significantly improves students' abstract thinking skills in understanding the concept of chemical bonds. This is evidenced by a significant increase in Posttest Score, Average Increase in Ability and Equalization of Improvement, Increase in Each Level of Abstract Thinking, Effectiveness of AR seen from N-Gain Results, and Relevance of AR with Abstract Chemical Bonding Material AR interactive visualization is proven to assist students in building conceptual understanding and essential higher order thinking in chemistry. Thus, it can be concluded that using Augmented Reality media is very effective in improving students' abstract thinking skills, both significantly and evenly, especially in learning abstract chemical concepts such as chemical bonding. This media is worth recommending as an innovative technology-based learning strategy for chemistry learning in the digital era. Overall, students' abstract thinking ability is strongly influenced by the depth of conceptual understanding, representational skills, flexibility in problem-solving, and metacognitive abilities. Therefore, chemistry learning should not only focus on knowledge transfer but also encourage the formation of conceptual and reflective thinking structures.

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