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An Investigation into whether Applying Augmented Reality (AR) in Teaching Chemistry Enhances Chemical Cognitive Ability

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Abstract. Chemical cognitive ability is a fundamental aspect of effective chemistry education, facilitating students' understanding of essential concepts such as substance structure, chemical transformations, and atomic bonding processes. Augmented reality (AR) technology has emerged as a promising tool in science education, offering immersive learning experiences that enhance students' comprehension of chemical phenomena. This study explored the utilization of AR applications, specifically QuimiAR, in the designing of six simulation videos focusing on chemical bonding processes. These videos were integrated into a teaching method centered around the topic "Chemical Bonding" and implemented in a secondary school classroom in Hanoi, Vietnam, comprising 32 students. Following the AR-enhanced teaching session, students' chemistry cognitive ability was evaluated using three methods: standardized tests assessing five criteria of chemistry cognitive ability according to the Vietnamese educational curriculum; surveys gauging students' interest and knowledge acquisition using AR; and in-depth interviews. The results indicate that AR usage significantly increased students' engagement in learning, enhanced their understanding of substance composition and chemical bonding processes, and improved their ability to apply knowledge to solve learning challenges. This research provides practical guidance for educators in leveraging the advantages of QuimiAR software to design simulations focusing on chemical bonding, thereby fostering students' cognitive ability in chemistry. By expanding the use of AR technology to create various chemical simulations, teachers

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can cultivate students' cognitive abilities in chemistry, promoting active learning and facilitating academic success.

Keywords: augmented reality (AR); chemistry cognitive ability; chemical science; teaching chemistry

1. Introduction

The ability to perceive refers to the mental capacity of an individual to process information, solve problems, and make decisions. In the context of chemistry education, cognitive ability plays a vital role in comprehending complex concepts and applying them to real-world scenarios. Numerous studies have highlighted the significance of cognitive ability in chemistry learning. The chemical cognitive ability, which involves understanding and interpreting the language and symbols of chemistry, is essential to help students comprehend the world around them and make informed decisions regarding health and environmental issues (Yunita, 2017). Chemical awareness, that is, learning about the natural world from a chemical perspective, and applying acquired knowledge and skills have been identified as necessary competencies for students in the General Chemistry Curriculum (Nha, 2018). In the scope of our study, we are interested in the concept of chemical cognitive ability. This refers to the individual's ability to be aware of basic knowledge about substance structure, chemical processes, chemical transformations, and some basic chemical reactions. Therefore, developing chemical cognitive abilities for students is crucial in chemistry education. Various methods can be employed to develop students' chemical cognitive abilities, aiming to promote active learning and critical thinking through hands-on activities, group discussions, and problem-solving tasks.

Traditional teaching methods in chemistry education often rely on lectures and rote memorization rather than fostering active learning and critical thinking skills, which may not develop students' cognitive abilities effectively. Consequently, students encounter difficulties in grasping and applying concepts related to atomic structure, including comprehension gaps, incorrect formula usage, reliance on teacher-centric instruction, and anxiety when tackling chemistry questions (Afrianis & Ningsih, 2022). Moreover, the abstract nature of atomic chemistry compounds these challenges, as students cannot directly observe atomic structures through conventional means (Wu & Yezierski, 2023).

At the secondary school level, limitations in teaching atomic structure and chemistry persist due to various factors. These include time constraints, a lack of emphasis on practical science application, insufficient collaboration between teachers and students, and inadequate laboratory facilities (Bani, 2020). Students often struggle with developing a nuanced understanding of atomic processes, particularly in critiquing models and comprehending complex concepts. To address these limitations, research has examined how students utilize resources to enhance their understanding of atomic processes (Kelly et al., 2021). Challenges persist in the teaching of atomic structure and chemistry at the secondary school level due to the dominance of symbolic representations, a lack of diverse representation methods, and the disconnection between some representations and textual explanations (Enero Upahi & Ramnarain, 2019). These limitations hinder students in their ability to fully grasp atomic concepts and hinder their overall learning experience in chemistry education.

Augmented reality (AR) technology has emerged as a promising tool in science education, harboring the potential to enhance learning experiences. Numerous studies have demonstrated the positive impact of AR in science education, highlighting its effectiveness in improving learning performance and motivation. Rahmat et al. (2023) found that while teachers are still relatively unfamiliar with AR technology, they expressed positive perspectives on its potential in science education (Rahmat et al., 2023). Similarly, Abutayeh et al. (2022) emphasized the need for more research focusing on teachers' views and expectations regarding the use of AR in science and math education (Abutayeh et al., 2022). They found that using AR simulations on computers and smartphones has led to significant improvements in students' learning outcomes compared to traditional teaching methods. Simulations present visual images of particle behavior, which is not easily observable in real life. Thus, the purpose of this study is to investigate how AR can be utilized as a tool to create interest in learning and assist students in utilizing simulations to understand the formation of chemical bonds, thereby gaining a clearer understanding of the particle nature of matter and chemical transformations.

2. Literature Review

The integration of AR technology into science education brings forth a plethora of advantages that significantly influence students' motivation, engagement, and learning outcomes. Studies by Khan et al. (2019) and Fearn and Hook (2023) have illustrated that AR applications enhance learning motivation and stimulate student interest in science, especially at the undergraduate and primary levels. The immersive nature of AR experiences captures students' attention, rendering learning more enjoyable and effective. Particularly in science education, AR offers visual and interactive representations of abstract scientific concepts, enabling the comprehension of complex phenomena that are difficult to visualize in traditional learning settings (Guo et al., 2021). Moreover, research has indicated that incorporating AR enhances students' comprehension and retention of scientific information (Huang et al., 2019).

Innovative teaching methods promoting active learning are pivotal for enhancing students' cognitive abilities in chemistry. Technology-driven approaches, such as virtual experiments, enable learners to simulate intricate phenomena and grasp fundamental principles (Hoai & Thao, 2021). These experiments instill curiosity, creativity, and a passion for scientific exploration, fostering cognitive development among students. Additionally, the utilization of software to create 3D simulations in organic chemistry education aids students in mastering complex concepts (Hoai et al., 2023). AR technology also fosters the development of higher order thinking skills by engaging students in problem-solving and decision-making processes (Moro et al., 2020). These benefits include increased long-term-memory retention, enhanced content understanding, improved task performance, heightened motivation, and better collaboration across educational levels (Çetin & Türkan, 2021).

The interactive and immersive qualities of AR experiences have the capacity to captivate students' attention and enrich their learning enjoyment, as noted by Kirikkaya and Başgül (2019). AR applications present novel approaches for delving into scientific concepts, nurturing curiosity and intrinsic motivation (Damopolii et al., 2022). Through offering visual and interactive depictions of abstract scientific principles, AR assists students in comprehending and visualizing intricate phenomena, as demonstrated by Huang et al. (2019). Research has shown that AR enhances students' comprehension and retention of scientific information by allowing them to manipulate virtual objects and observe dynamic processes, thus facilitating more profound learning experiences (Rossano et al., 2020). AR involves students actively in hands-on and interactive experiences, fostering problem-solving skills and decision-making capabilities (Cai et al., 2022). Through the integration of real-world and virtual components, AR prompts students to authentically analyze and apply scientific knowledge. Furthermore, AR has the potential to bolster the development of spatial skills, which hold great importance in various scientific fields.

The increasing availability of AR technology on electronic devices, particularly smartphones, has led to its widespread integration into teaching and learning practices. AR is leveraged to create flexible virtual learning environments, offering students interactive and engaging educational experiences. Collaborative AR-enhanced learning environments have been investigated in numerous studies, revealing their positive impact on student engagement and motivation (Ahmed & Lataifeh, 2023). Collaboration in AR settings enables students to share ideas and actively participate in the learning process, fostering deeper understanding and knowledge construction (Dolmans et al., 2015; Lu et al., 2022).

Overall, collaborative AR-enhanced learning environments promote active engagement, knowledge sharing, and deeper understanding among students, thereby enhancing the learning process. However, the implementation of AR in science education faces challenges, including technical limitations such as the availability and cost of AR devices, which may hinder widespread adoption (Fearn & Hook, 2023). Moreover, successful integration of AR into the curriculum necessitates adequate teacher training and support (Koçak et al., 2019). Despite these obstacles, the potential benefits of AR in science education underscore its promise in enhancing teaching and learning experiences, emphasizing the need to address challenges to maximize its effectiveness.

AR technology has been widely utilized in teaching chemistry to enhance the learning experience. Studies have indicated that AR is primarily used in chemistry education for various purposes. AR technology has been employed to create a virtual chemistry laboratory for 11th Grade students, enhancing chemistry research projects through interactive virtual experiments using cloud-based technology (Nechypurenko et al., 2023a). Additionally, AR technology is utilized to teach organic compound reactions in chemistry, enhancing student engagement and understanding (da Costa Coelho et al., 2022). In high school chemistry education, AR technology allows students to conduct virtual experiments, observe reactions under a microscope, and comprehend chemical equilibrium states through interactive AR cards (Tarng et al., 2022). AR technology has also been utilized in chemistry education through the development of an accessible AR application, Chemistry Access, aimed at teaching atomic connections and compound formation to visually impaired students. Furthermore, AR technology has been used to create a virtual experiment to teach the principles of the Daniell cell in high school chemistry, improving academic achievement, particularly for low-performing students (Tarng et al., 2021).

Although there are numerous applications in education, studies have affirmed the positive impacts of AR technology in education. However, further research is needed to explore the specific advantages of AR in chemistry education, particularly the benefits of AR in enhancing chemical cognition in chemistry education. Therefore, this study aimed to address the following questions:

1. How is AR used in teaching chemistry?
2. How has AR technology supported the enhancement of students' chemistry perception skills?

3. Methodology

3.1 Study Overview

Figure 1 presents a flow diagram of the study overview.

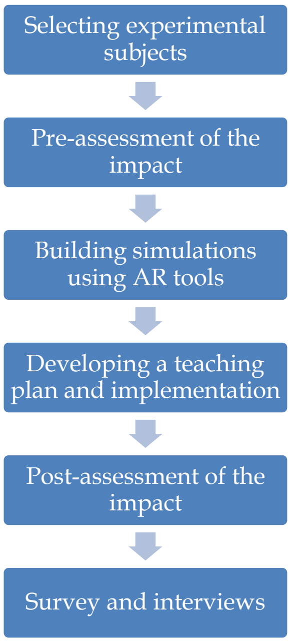

Figure 1: Study overview flow diagram

This experimental study was conducted in two classes in Hanoi, Vietnam with similar proficiency criteria. The classes were designated by the school's teachers. We randomly selected one of the two classes as the experimental group, and the remaining class served as the control group. The experimental group consisted of

32 students, including 15 male and 17 female students. The control group comprised 31 students, consisting of 17 male and 14 female students. Both classes were taught using the lesson plan designed by us, utilizing the flipped classroom method, with the experimental group using an AR application and the control group not using AR technology.

To assess students' abilities before the intervention, we constructed the first assessment test. The test comprised 10 objective multiple-choice questions related to the knowledge students had learned, including atomic structure and the periodic table of elements. The test was administered within a 15-minute timeframe by the participating teachers. The scores obtained by students in this test served as baseline scores for comparison with the results of the post-intervention test.

To conduct the experiment, we devised two teaching plans for both the experimental and control group. We employed the flipped classroom method for both groups, wherein the experimental group received additional simulations of molecular structures and chemical bond formation created by an AR application.

The post-experiment survey, which employed a Likert scale with six options, from 1 (*strongly disagree*) to 6 (*strongly agree*), focused on four issue groups: "Learning Attitude", "Satisfaction when Using AR Applications", "Knowledge Absorption", and "AR Utilization Ability". This survey was built upon the research of Hwang and Chang (2011) and references the studies of Chu et al. (2010) and Cai et al. (2014).

To conduct a qualitative assessment, we randomly selected 15 students. Pre-prepared cards with "Y" or "N" written on them were used for selection. Students with "Y" cards were chosen for interviews. In the study by Son (2024), both teachers and students acknowledged the positive role of AR technology in enhancing learning outcomes. Therefore, during the interviews, we asked students about three main issues: their interest in accessing and using AR in learning; the role of AR in knowledge acquisition; and the direction of AR usage in the study of other contents. The results of these research steps will be presented and analyzed in detail in the subsequent section of the study.

3.2 QuimiAR Application

QuimiAR is an AR application developed to help users learn chemistry engagingly and effectively (Figure 2). This application utilizes AR technology to create 3D models of chemical molecules, allowing users to interact with them directly. It is specifically designed to serve the purposes of research, teaching, and learning about atomic structure, molecular composition, and chemical bonds. QuimiAR does not require users to have programming or design knowledge. It is very easy to use, as users only need to select the molecule they want to observe from the application's database for observation.

Figure 2: Interface of the QuimiAR application

Regarding using the QuimiAR application directly in learning, the application can be downloaded from the App Store or Google Play Store. The interface of QuimiAR consists of two groups: covalent bonds and ionic bonds. Students select these groups and then choose the chemical molecules they want to observe.

For the use of pre-built 3D simulations, the research group uses the QuimiAR application to build some simulations of bond formation in certain molecules. The stages of simulating bond formation include:

- Describing the structure of the atoms that will form bonds, including valence electrons.
- Describing the process of bond formation, specifically the process of giving and receiving electrons to form ion bonds and the process of sharing electrons to form covalent bonds.
- Describing the molecular structure after bond formation.

A list of molecules along with links to the simulations is provided in Table 1.

Table 1: Simulation catalog

No.	Molecule	Link
1	Water	https://youtu.be/2WREbw5-IyI
2	Ozone	https://youtu.be/X4270aptUl8
3	Ethylene	https://youtu.be/XvzThTjHU4o
4	Sodium chloride	https://youtu.be/4dNRK5Qgouc
5	Mage oxide	https://youtu.be/oobWWtx4D44
6	Copper(II) chloride	https://youtu.be/LwZzAO-PwDU

3.3 Building a Lesson Plan Using AR to Develop Students' Cognitive Abilities

We constructed a lesson with the theme "Chemical Bonding" for teaching the 7th Grade students. This study encompassed the following aims:

1. Illustrating a representation of electron distribution within the atomic orbitals of select noble gases.
2. Elucidating the process of covalent bond formation based on the concept of electron sharing for achieving a full electron shell akin to noble gases.
3. Outlining the process of ionic bond formation according to the principle of electron transfer to attain a complete electron shell similar to noble gases.
4. Distinguishing various characteristics between ions and covalent compounds.

The flipped classroom method was utilized in the lesson, where experimental lessons were supplemented with simulations of chemical bonding and the QuimiAR application. Students also used additional devices such as computers, smartphones, tablets, etc. for learning.

The flipped classroom method involved three phases.

3.3.1 *Phase 1: online learning*

Students performed self-study at home through study materials and worksheets provided by the teacher. Students planned their self-study and completed worksheets according to the teacher's requirements. During this stage, students familiarized themselves with new information and prepared for classroom activities. They identified, clarified, or presented events, concepts, or chemical processes.

3.3.2 *Phase 2: face-to-face learning*

The teacher organized activities to implement the lesson in the classroom. Warm-up activities were conducted through guiding questions such as: Why do atoms "combine" with each other? and: What are the types of "combination" between atoms? Individual assessments of self-study results were carried out, where students reported self-study results using worksheets. The teacher answered students' questions and summarized the lesson content. Therefore, classroom time was dedicated to reviewing content from Phase 1, with teachers actively engaging students through group discussions, collaborative exercises, and assessments.

3.3.3 *Phase 3: online learning*

The teacher assigned tasks for students to reinforce and apply their knowledge by using the concept of chemical bonding to explain phenomena such as: in nature, table salt is in a solid state, difficult to melt, and difficult to evaporate, while sugar is easily soluble in water and ice melts at low temperatures, while water evaporates easily. Figure 3 below presents some images of the experimental process. Thus, teachers paved the way for deep learning, allowing students to independently process and reflect on information and apply their knowledge.

Figure 3: Photographs of the experimental process

3.4 Assessing Students' Chemical Cognitive Abilities

3.4.1 *Quantitative assessment*

Identifying components of chemical cognitive abilities. Chemical cognitive abilities consist of three components: chemical awareness; understanding the natural world from a chemical perspective; and applying learned knowledge and skills (Vietnam Ministry of Education and Training, 2018). Chemical cognitive abilities include five criteria:

- Criterion 1 (C1): Recognizing and stating the names of objects, events, concepts, or chemical processes.
- Criterion 2 (C2): Presenting events, characteristics, roles of objects, concepts, or chemical processes.
- Criterion 3 (C3): Describing objects using verbal, written, formulaic, schematic, diagrammatic, and tabular forms.
- Criterion 4 (C4): Comparing, classifying, and selecting objects, concepts, or chemical processes according to different criteria.
- Criterion 5 (C5): Explaining and reasoning about the relationships between objects, concepts, or chemical processes (structure – properties, cause-effect, etc.).

This study identified the chemical cognitive abilities that students need to achieve in studying chemical bonding. This included students' recognizing fundamental knowledge about substance structure, chemical processes, some basic chemical substances, and chemical transformations. Each criterion was quantified with four levels of the Thinking Levels Assessment Scale proposed by Boleslaw Niemierko to determine the level of thinking of chemical cognitive abilities (Level 1: poor; Level 2: average; Level 3: good; Level 4: excellent) (Gajek, 2019).

Building the test. To assess students' chemical cognitive abilities, the criteria were specified to align with the content taught. We conducted an assessment of students' chemistry cognitive abilities through evaluating their learning process both during online and in-person classes, along with assessments using quizzes, each consisting of 10 questions. The questions were presented in the form of objective multiple-choice questions, with the distribution of levels as follows: Level 1: recall/recognition (40%); Level 2: understanding (30%); Level 3: application lower level (20%); Level 4: application upper level (10%). All tests were conducted by students through Google Forms within a 15-minute time frame.

3.4.2 *Qualitative assessment*

We randomly selected 15 students from the experimental group with whom to conduct in-depth interviews after using the AR application to teach the Chemical Bonding unit. The interview questions focused on three main issues:

1. Understanding students' interests when accessing and using AR in learning.
2. Students' assessment of the role of AR in supporting their learning.
3. Direction for using AR applications in learning.

Depending on the level of collaboration among students, the scope of interview content can be expanded to gather a comprehensive understanding of students' experiences with AR technology and its impact on their learning.

4. Results

AR simulations of chemical bond formation provide visual representations, assisting students in understanding and visualizing the interaction of atoms when forming ion bonds and covalent bonds. This helps to form the concept of chemical bonding. As a result, students become interested in learning chemistry and develop cognitive ability in chemistry. The following assessment results confirm that students' chemical cognitive ability is enhanced after teachers use simulations of chemical bonding designed on the QuimiAR software for student learning.

4.1 Assessment of Chemical Cognitive Abilities through Test Results

Before the experiment, both groups were given Test 1 (pre-test). After the experiment, both groups were given Test 2 (post-test). The test results were statistically analyzed using SPSS software and are presented in Table 2.

Table 2 shows that, in the experimental group, the sig. (2-tailed) value is 0 ($t = 4.990$, $p = 0.000$). When the p-value is < 0.05, the null hypothesis of no difference is rejected. This means that the students' scores after the experiment, having used the AR tool in learning, are significantly higher than the scores before the experiment, indicating the impact of the experimental process.

Table 2: Results of the paired samples *t*-test

No.	Student group		Paired differences					t	df	Sig. (2-tailed)
			Mean	Standard deviation (SD)	Std. error mean	95% confidence interval of the difference				
						Lower	Upper			
1	Experimental	Score (post-test) – score (pre-test)	.91	1.03	.18161	.5358	1.2766	4.990	31	.000
2	Control	Score (post-test) – score (pre-test)	.26	1.46	.26220	-.2774	.7935	.984	30	.333

4.2 Post-Experiment Survey Results

We used Google Forms to design the questionnaire. The data collection process was conducted in the experimental class after the lesson under the guidance and supervision of the teacher, ensuring the reliability of the responses. The survey tool consisted of four groups of issues: 1) "Learning Attitude"; 2) "Satisfaction with Software Usage"; 3) "Knowledge Absorption"; and 4) "AR Utilization Capability". Thirty questions were designed to survey students on the four groups of issues, with the thirty-two students from the experimental class participating in the survey immediately after completing the experimental lesson. The collected data were processed using SPSS 22.0 software. The analysis of the Cronbach alpha reliability of the four groups of issues is summarized in Table 3.

Table 3: Summary of the Cronbach alpha values of the issue groups

Variable	Number of items	Cronbach alpha
Learning Attitude	7	0.989
Satisfaction with Software Usage	14	0.994
Knowledge Absorption	5	0.982
AR Utilization Capability	4	0.975
Overall	**30**	**0.997**

The results show that the Cronbach alpha value of the questionnaire is 0.997, indicating the high reliability of the questionnaire. The Cronbach alpha coefficient of each issue is greater than 0.70, demonstrating that each issue group is consistent and internally reliable. The average scores for each issue group are summarized in the chart in Figure 4. The results indicate that the "AR Utilization Capability" group has the highest average value, while the "Learning Attitude" group has the lowest average value.

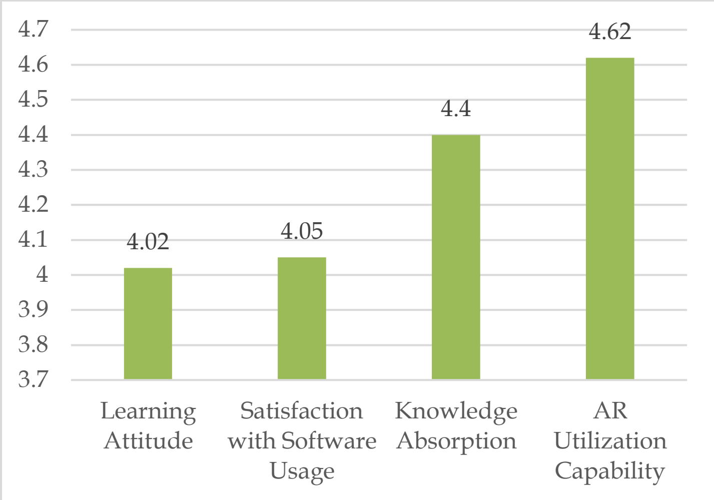

Figure 4: Average scores of the issue groups

The descriptive statistics for each of the issue groups are presented in tables 4 to 7 and subsequently discussed.

Table 4: Descriptive statistics for the "Learning Attitude" group

No.	Item	Mean	Std. deviation
1.1	I find the content chemically linking is very useful	4.19	1.57
1.2	The natural science subject is very interesting	3.76	1.39
1.3	The content related to chemistry is meaningful	4.47	1.16
1.4	I find the content outside the textbook very interesting	4.12	1.41
1.5	I will search for more information related to chemistry on the Internet	3.59	1.21
1.6	I will seek support from the Internet, teachers, and friends whenever I encounter difficulties	3.75	1.29
1.7	I think the natural science subject is essential for everyone	4.28	1.51
Level: *strongly disagree* = 1; *disagree* = 2; *slightly disagree* = 3; *slightly agree* = 4; *agree* = 5; *strongly agree* = 6			

The statistics show that the item "I find the content outside the textbook very interesting" received the highest rating (M = 4.47, SD = 1.16). This reflects that the students found the simulations created from the AR application interesting, which simulations are not found in textbooks or other usual learning materials. Additionally, the low standard deviation value indicates high consistency in students' responses. Conversely, the mean value for "I will search for more information related to chemistry on the Internet" was the lowest (M = 3.75, SD = 1.29).

Table 5: Descriptive statistics for the "Satisfaction with Software Usage" group

No.	Item	Mean	Std. deviation
2.1	AR software is very interesting	4.09	1.30
2.2	AR software helps me explore new knowledge	3.91	1.44
2.3	Using AR software allows me to see the microscopic world	4.69	1.23
2.4	I enjoy studying chemistry more when using AR software	4.87	1.10
2.5	AR is very interesting because it's like a game	3.66	1.41
2.6	I hope many other subjects also use AR	4.06	1.29
2.7	I hope to continue using AR in studying chemistry	4.12	1.58
2.8	I will introduce AR to others	3.97	1.43
2.9	I am interested in other learning tools based on AR	3.66	1.43
2.10	AR is very suitable when studying "Atomic Structure, Chemical Bonding"	3.75	1.29
2.11	AR allows collaborative learning	3.53	1.22
2.12	The design of the software is beautiful and attractive	4.53	1.27
2.13	AR software is easy to use	3.84	1.46
2.14	I think using AR software to explore the microscopic world is essential	4.00	1.41
Level: *strongly disagree* = 1; *disagree* = 2; *slightly disagree* = 3; *slightly agree* = 4; *agree* = 5; *strongly agree* = 6			

The summary results indicate that the three highest rated items are: "I enjoy studying chemistry more when using AR software" (M = 4.87, SD = 1.10); "Using AR software allows me to see the microscopic world" (M = 4.69, SD = 1.23); and "The design of the software is beautiful and attractive" (M = 4.53, SD = 1.27). This suggests that students are more engaged in studying chemistry with the use of AR applications, considering AR applications are very suitable for learning content related to the microscopic world that is not visible to the naked eye. Numerous studies have demonstrated that natural science is a highly practical subject, with many experiments and practical activities stimulating learning interest. However, content related to the microscopic world, such as atomic structure and chemical bonding, cannot be observed with the naked eye, and simulations built with AR applications can overcome this limitation. Conversely, the factor "AR allows collaborative learning" received the lowest rating (M = 3.53). Although group activities are suitable for classroom teaching, with AR applications and the devices to operate them being easy to use, and most students being able to use the applications, activities can be carried out individually, without much emphasis on group learning.

Table 6: Descriptive statistics for the "Knowledge Absorption" group

No.	Item	Mean	Std. deviation
3.1	I believe that AR makes study materials more accessible	4.28	1.61
3.2	I think using AR learning tools, like this game, is very helpful for studying chemistry	4.12	1.36
3.3	AR tools are more effective than any tools I have used before	3.69	1.33
3.4	AR helps me understand the essence of chemistry better	4.94	1.11
3.5	AR provides me with more space for creativity and learning	4.72	1.33
Level: *strongly disagree* = 1; *disagree* = 2; *slightly disagree* = 3; *slightly agree* = 4; *agree* = 5; *strongly agree* = 6			

The statistics reveal that the item "AR helps me understand the essence of chemistry better" has the highest average value (M = 4.94, SD = 1.11). Understanding the essence of the subject is crucial in chemistry, as it enables students to explain various related properties and deduce additional knowledge. Meanwhile, the factor "AR tools are more effective than any tools I have used before" has the lowest average value (M = 3.69, SD = 1.33).

Table 7: Descriptive statistics for the "AR Utilization Capability" group

No.	Item	Mean	Std. deviation
4.1	AR is easy to use	4.81	1.12
4.2	AR doesn't require much time and effort	4.09	1.17
4.3	AR operates in an easy-to-understand manner	4.72	1.33
4.4	I learned how to operate AR in a very short time	4.62	1.34
Level: *strongly disagree* = 1; *disagree* = 2; *slightly disagree* = 3; *slightly agree* = 4; *agree* = 5; *strongly agree* = 6			

The summarized results show that the average scores of the items for this construct are quite high, indicating that the students have a good understanding of technology. Installing and using applications on smart devices is easy for them. Among the items in the "AR Utilization Capability" group, "AR is easy to use" has the highest average value (M = 4.81, SD = 1.12). This can be attributed to the combination of students' good IT skills and the simplicity of using the AR application.

4.3 Interview Results

We conducted interviews immediately after completion of the experimental lesson, with 15 students randomly selected as interview participants by drawing lots from the experimental group. To ensure anonymity, we encoded the participating students from S1 to S15. The interviews were conducted by teachers, who asked questions, with some students volunteering or being designated to answer. Responses were recorded for synthesis and analysis. The overall results show that most of the students had a positive evaluation of using AR in their studies.

Regarding the ability of AR to generate interest in learning, S4 stated: "*It's like playing a video game; it's very interesting and easy to observe the formation of chemical bonds.*" Four out of five students confirmed that they were very excited about AR software. It helped them to experience "immersion" and made them feel like the main character in a virtual space. It also enhanced the fun factor, impressed the lesson, and made learning more enjoyable. This finding aligns with numerous research findings indicating that students feel excited and interested when using AR (Holley & Hobbs, 2019; Rasulova, 2022). However, S2 mentioned not being particularly enthusiastic about these simulations due to the difficulty of installation and inconvenience of operating them on a phone, which reduced interest in AR.

Concerning the ability to absorb lessons, the use of AR in education has been found to be effective in enhancing learning achievement, particularly appealing to the younger generation (Ghobadi et al., 2022). S1 remarked: "*I easily understand how covalent bonds and ions are formed after watching the simulation.*" Some student opinions affirmed the effectiveness of 3D simulations in describing the formation of chemical bonds: "*Electron transfer is very clear*" (S8); "*Using shared electrons is visually appealing*" (S11); "*So, the molecular structure of the compounds after bonding is like that; I never thought of it that way*" (S14); "*Understanding covalent bonding is easy when watching simulations of atoms sharing electrons*" (S7); and "*The simulation helped me understand the theoretical content in the textbook easily*" (S3). However, some students expressed doubts: "*How do we know the number of electrons involved in bonds?*" (S1); and "*The simulation only describes the knowledge in the textbook*" (S6).

Regarding the use of AR applications in other subjects, opinions suggested that AR should be used more for other subjects (S1, S4, S14); STEM subjects are very suitable for AR (S11); chemistry, physics, and biology content related to the micro-world are suitable for AR (S12); and historical sites that students cannot visit in person should also use AR (S15). S11, S10, and S7 expressed concerns that excessive use of AR could harm their eyes, simulation devices are expensive, and that there are limited molecules or chemicals in the available software. Other concerns included there being a lack of diverse experimental tools and that simulations could become boring if observed too frequently. Other studies have also indicated that AR can be used in various subjects by, for example, illustrating anatomy content in biology (Guerrero et al., 2018), or visiting historical landmarks and cultural heritage sites through virtual space (Argiolas et al., 2022).

Overall, despite some concerns, most students interviewed had a positive evaluation of using AR technology in education. AR simulations helped them to become more interested and absorb lessons more easily. In the future, AR technology is likely to continue to be widely used in various subjects and fields of study.

5. Discussion

This paper explores the use of technological devices and applications as tools to stimulate learning interest and develop cognitive abilities for students. We argue that traditional teaching technologies are primarily used as a means of delivering information. In contrast, AR technology allows students to interact with learning content, fostering interest and developing deeper cognitive abilities and understanding of chemical concepts. Our arguments are entirely consistent with the assessment results of the participating students' chemical cognitive abilities through pre- and post-impact assessments in the experimental and control group. The average score of students in the experimental group using AR increased by 0.91 points (t = 4.990, p = 0.000), indicating that the difference in scores between the two assessments (before and after) was due to the impact of using AR in learning. This result also aligns with studies by Taber and Garcia-Franco (2010), which asserted that traditional teaching methods in chemistry education may not effectively develop students' cognitive abilities.

A survey instrument with four issue groups was used for the experimental group students to evaluate their chemical cognitive abilities after using AR in learning. Descriptive statistics for the "Learning Attitude" group show that the item "I find the content outside the textbook very interesting" received the highest rating (M = 4.47, SD = 1.16). This reflects that students are fascinated by simulations created by AR applications, which are not visible in textbooks or other usual learning materials. Additionally, the low standard deviation value indicates high similarity in students' responses. The average result of the "AR Utilization Capability" group confirms that using AR is very simple and easy for students. This is demonstrated by the students' response to the item "AR is easy to use", which had the highest average value (M = 4.81, SD = 1.12) (Table 7).

Survey results from the "Knowledge Absorption" group indicate that using AR has a positive effect on students' learning. Students believe that AR is suitable for learning content in the micro-world that is not visible to the naked eye, such as cleavage and bond formation, electron sharing, or donation, the basis of chemical transformations. The results in Table 6 show that the item "AR helps me understand the essence of chemistry better" had the highest average value (M = 4.94, SD = 1.11). Therefore, when students understand the essence of the problem, this will help them explain many related properties as well as infer other knowledge. Moreover, students can observe the detailed process of chemical bond formation through AR applications. This evaluation result is consistent with the results of interviews with students after the experimental learning. Participating students affirmed: "*I easily understand covalent bonding when watching simulations of atoms sharing electrons*" (S7); and "*The simulation helped me understand the theoretical content in the textbook easily*" (S6). From our perspective, explaining properties and inferring knowledge are fundamental elements in building chemical cognitive abilities. Our viewpoint also aligns with that of Radloff and Guzey (2016), ascertaining the importance of cognitive abilities for students pursuing careers in science, technology, engineering, and mathematics.

Survey results from the "Satisfaction with Software Usage" group affirm that students are more interested in learning when using AR applications, believing that AR applications are suitable for learning content in the micro-world that is not visible to the naked eye (Table 5). The item "I find the content outside the textbook very interesting" had the highest average value (M = 4.47, SD = 1.16), reflecting that students are interested in simulations created by AR applications. Conversely, the item "AR allows collaborative learning" was not highly rated (M = 3.53). This affirms that AR applications are easy to use and that the devices are not complicated. Therefore, individuals can use them, without much concern for group learning.

Survey results on the use of AR applications in teaching the "chemical bonding" part of natural science show that AR applications stimulated the students' learning interest. They helped the students to learn the chemistry part easily and understand it better and are especially suitable for learning content in the micro-world that is not visible to the naked eye. The interactive nature and ease of use of AR applications also helped the students access and use this software conveniently.

Using AR in high school chemistry education enhances students' chemical awareness and interest in learning through interactive, visual, and engaging experiences, an observation also consistent with the study by Abualrob et al. (2023). AR allows students to manipulate virtual chemical structures and observe chemical reactions in real time, making abstract concepts tangible. Visualizations of complex phenomena, such as molecular structures and bonding interactions, aid in comprehension. The interactive nature of AR, often incorporating gamification elements and simulations, fosters curiosity and active participation. This has also been confirmed by Nechypurenko et al. (2023b), that using AR in high school chemistry enhances cognitive awareness and interest in chemistry by enabling interactive virtual experiments, ensuring safety, promoting hands-on learning, and improving understanding of complex topics through chemical imagery. Additionally, AR adapts to individual learning styles, providing personalized learning experiences that resonate with students. By contextualizing chemical concepts within real-world applications, AR illustrates their relevance and practical implications, increasing student appreciation for the subject.

Overall, we suggest that using computers, smartphones, and AR applications as cognitive tools can be an effective way to promote cognitive abilities and a deeper understanding of abstract concepts in natural science education. This method overcomes the limitations of traditional teaching methods. When using AR in teaching, interacting with content in meaningful ways allows students to build better personal knowledge and develop a deeper understanding of complex concepts such as substance concepts, chemical transformations, and chemical bonds. Our conclusions about using AR in natural science education are fully consistent with Bork et al.'s (2020) study on the nature of AR. The interactive and immersive nature of AR allows students to explore and manipulate virtual objects, leading to a more profound understanding of complex scientific concepts.

The study also discusses the importance of giving students control over the learning process when using support technologies. This can be achieved by allowing students to choose the tools they want to use and to decide how they want to use them. The opportunity to choose learning support tools empowers students to self-learn, self-research, and problem-solve. The application of AR in teaching, besides positively impacting learning outcomes, also helps enhance students' learning motivation.

6. Conclusion

This study investigated the use of AR in teaching natural science subjects through the theme of "Chemical Bonding". Three methods were used to assess students' chemical cognitive abilities when using AR technology in teaching: tests, surveys, and interviews. All three methods confirmed that using AR in teaching natural science enhanced students' chemical cognitive abilities. The interactive and immersive nature of AR allows students to easily explore scientific concepts. Through virtual space, students can observe atomic and molecular models as well as the movement of electrons forming chemical bonds. This will help increase students' learning interest, actively engage them in learning activities, and positively impact their cognition and learning motivation. AR creates a connection between knowledge and the learning environment, providing students with opportunities to interact with content in new, realistic, understandable, rich, and engaging ways. It thereby fosters cognitive thinking and promotes deeper understanding. Despite the potential benefits, the implementation of AR in science education also poses challenges. Technical limitations, such as the availability and cost of AR devices, may hinder widespread adoption. Additionally, the need for teacher training and support to integrate AR into the curriculum has been identified as an important factor for successful implementation.

AR offers visual and interactive depictions of conceptual scientific ideas, aiding learners in comprehending and picturing intricate phenomena. This enhances educational engagement, establishing the groundwork for the advancement of cognitive proficiency in the field of chemistry. Consequently, students develop natural inquiry abilities from a chemical perspective and the ability to apply learned knowledge and skills both in academia and real-life scenarios. Based on available software applications, students can construct AR simulations of atoms, molecules, and chemical compounds while studying substance structures and chemical transformations. Through this, understanding and applying AR for studying chemistry and other natural sciences with abstract, hard-to-observe concepts in real environments are facilitated. Issues related to nature and abstract science will be addressed.

In summary, the paper highlights the positive impact of AR technology in teaching, including enhancing students' learning activities, improving learning outcomes, increasing participation interest and learning motivation, and developing chemical cognitive abilities. However, further research is needed to address challenges related to AR implementation and to explore its potential in various scientific fields and educational contexts.

7. Limitations

This study tested only a relatively small number of students. Therefore, full generalization of the findings regarding the role of AR applications in education cannot be guaranteed. Currently, there are many AR applications, but this research used only QuimiAR, preventing comparison with other AR applications. Additionally, the study did not address the digital literacy of teachers and students in Vietnam regarding the use of AR technology. Therefore, more comprehensive research is needed to maximize the application of AR in education.

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