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Research Article

Integrating Augmented Reality in Chemistry Education: The Impact of the Augmented Reality Chemistry Student Investigation (AR-CSI) Module on Content Knowledge and 21st Century Skills

Nor Syatilla Haerany Abd Ghani[1,2], Tien Tien Lee[2,3]*, Jianfen Wang[2,4], Rusmansyah[5]

1 Department of Chemistry, Kedah Matriculation College, 06010 Changlun, Kedah, Malaysia
2 Department of Chemistry, Faculty of Science and Mathematics, Universiti Pendidikan Sultan Idris, 35900 Tanjong Malim, Perak, Malaysia
3 STEM Nurturing Center, Faculty of Science and Mathematics, Universiti Pendidikan Sultan Idris, 35900 Tanjong Malim, Perak, Malaysia
4 Department of Chemistry, Heng Shui University, 053000 Heng Shui, Hebei, China
5 Department of Chemistry Education, Faculty of Teacher Training and Education, Universitas Lambung Mangkurat, 70123 Banjarmasin, Indonesia
* Corresponding author: lee.tt@fsmt.upsi.edu.my

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ABSTRACT

Chemistry is often viewed as a challenging subject, and the main difficulty for students in learning chemistry is the presence of many abstract concepts. One of the important topics in chemistry that requires a deep understanding of concepts and extensive visualisation is chemical bonding. Thus, modern technology has created opportunities for students to overcome visualisation problems. Integrating modules with Augmented Reality (AR) can effectively enhance academic achievement and foster 21st century skills. The Augmented Reality Chemistry Student Investigation (AR-CSI) Module was designed to help students understand chemical bonding by integrating AR technology. A non-equivalent pretest-posttest control group design was employed to examine the effects of the AR-CSI Module on students' understanding of chemical bonding and the enhancement of 21st century skills. A total of 60 18-year-old students from one of the matriculation colleges in Malaysia were involved in the control and treatment groups. The instruments used comprised an achievement test and the Malaysian Twenty-First Century Skills Instrument (M-21CSI) questionnaire. Results revealed a significant difference in the understanding of chemical bonding between the control and treatment groups [$t(58) = -14.718$, $p < 0.001$]. Additionally, the treatment group showed a significant difference in the four clusters of 21st century skills scores compared to the control group [$F(4,55) = 149.645$, $p<.001$]. In conclusion, the findings indicated that the AR-CSI Module can enhance students' comprehension of chemical bonding and foster their 21st century skills. Incorporating an AR-based module into chemistry learning may serve as an effective pedagogical method to bridge the gap between theoretical knowledge and practical comprehension, thereby preparing students more effectively for the demands of a technology-driven and skills-oriented global environment.

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1. INTRODUCTION

In the 21st century, science and technology have become integral to nearly every aspect of modern life, including work, communication, daily living, and education. The modern world demands that education be approached from multiple angles. 21st century learners experience a changing educational landscape, using technology and online resources while developing skills like critical thinking and adaptability to succeed in a fast-evolving world. The emphasis of the 21st century classroom is on a collaborative and creative approach to learning. Research shows that 21st century skills help students stay current with the fast pace of digital technology and gain a broader base of knowledge and learning than in the past. These skills encompass collaboration and teamwork, creativity and imagination, critical thinking and problem-solving, flexibility and adaptability, global and cultural awareness, information literacy, leadership, civic literacy and citizenship, oral and written communication, social responsibility and ethics, technological literacy, and initiative (Kettler et al., 2019). To achieve this, the competencies individuals need must be drastically changed by integrating Science, Technology, Engineering, and Mathematics (STEM) literacies in their learning experiences (Jackson et al., 2021).

Governments worldwide are concentrating on improving the STEM abilities of their citizens (Tytler, 2020). UNESCO study lists Asian countries such as Malaysia, China, Korea, and India among the top ten producers of STEM graduates, establishing them as leaders in innovation and 21st century competitiveness. In order to achieve the creation of a Malaysian society that is open-minded and creative, the curriculum planned by the Malaysian Ministry of Education needs to equip the students with strong intellectual, spiritual, physical, and emotional readiness. STEM education plays a role in providing opportunities for students to experience learning in real career environments. The importance of integrating STEM into the science education curriculum needs to be realised when there are higher career demands compared to other fields. However, many students perceive STEM subjects as difficult, which may hinder their academic advancement and future career prospects (Mystakidis et al., 2022). STEM fields, encompassing science, technology, engineering, and mathematics, are intricately interconnected, and chemistry plays a crucial role in connecting them all.

Chemistry is often referred to as the core of science, connecting with other scientific fields (Capkinoglu et al., 2019; Kausar et al., 2022). Chemistry is part of the curriculum that helps students develop intellectually by encouraging them to inquire about nature and how it changes (Sugrah et al., 2023). Additionally, chemistry education can provide students with various unique opportunities to view the world from a "chemical" perspective and to help them learn natural concepts. The relevance of chemistry in life is a necessity for the growth of a country's technology, which cannot be disputed anymore. Scientifically, chemistry education encompasses all human efforts to explore, interpret, and control the natural world (Uwague, 2019). One of the main objectives of chemistry education is to prepare students for life beyond the classroom and apply the knowledge outside the classroom context (Kibga et al., 2021). Chemistry education is important as it can drive the country's growth and development. However, one of the main challenges students face in learning chemistry is the presence of numerous abstract concepts (Tala et al., 2022; Turel & Sanal, 2018), which often results in a reliance on rote memorisation rather than the development of a deep conceptual understanding. The abstract nature of chemical concepts was a common challenge for the students.

Chemistry involves understanding and connecting the sub-microscopic, macroscopic, and symbolic levels of representation (Petillion & McNeil, 2020). It is a scientific discipline consisting of many concepts, facts, and symbols, making it challenging to understand at all levels of study. Students who lack comprehension of chemical concepts will view chemistry as a challenging subject. Understanding chemistry allows students to comprehend the events occurring in their surroundings and offers them chances to link these occurrences with other facets of everyday life. Chemistry plays an important role in all fields of science and technology. Therefore, students need to have a high level of understanding of the chemistry subject. There are many factors contributing to students' perception of chemistry as a difficult subject. One of the main reasons is that students find many abstract chemistry concepts (Rahmawati et al., 2022; Üce & Ceyhan, 2019; Zephrinus & Phoebe, 2015). Furthermore, another challenge in learning chemistry is misconceptions in understanding chemical concepts. Misconceptions arise when students struggle to understand abstract concepts such as chemical bonding, and they have difficulty grasping and understanding the involved concepts (Nahum et al., 2010; Turel & Sanal, 2018). Gaining a deep understanding of chemical phenomena is not an easy task. Studies show that the development of students' understanding of chemical concepts is similar among all students (Rott & Marohn, 2017). The main difficulty in chemistry is due to students' differing views on phenomena at the micro and macro levels that often contradict their understanding. Students who rely on memorisation may be able to answer low-level cognitive chemistry questions, but they may struggle with questions that require higher cognitive skills. One of the important topics in chemistry that requires a deep understanding of concepts is chemical bonding.

Chemical bonding is a topic that differs from students' daily experiences. Students cannot visualise atoms, atomic structures, and how atoms and their bonds interact with each other. Therefore, students face difficulty in understanding the concepts involved in this topic of chemical bonding and have a significant potential for misconceptions due to visualisation problems with chemical bonds. Chemical bonding is a fundamental concept in chemistry education. To enhance understanding of other topics, such as chemical reactions, physical and chemical changes of substances, students need to solidify their understanding of chemical bonding first. Misconceptions often occur in the topic of chemical bonding because students perceive it as abstract and vastly different from their everyday life experiences. This statement is consistent with research conducted by Lay and Osman (2018), which suggests that science subjects are abstract and require deep understanding and visualisation skills.

The concept of abstract learning is closely related to the concept of visualisation because learning chemistry involves microscopic matters (Kuit & Osman, 2021; Nahum et al., 2010). The visual difficulty of students hinders the utilisation and development of learning concepts (Carrie et al., 2021). Topics like chemical bonding require imaginative abilities to envision molecular shapes, determine bond angles between atoms, and necessitate drawing in three-dimensional (3D) representations. Chemical bonding is considered difficult because the concept of bonding requires students to visualise atoms or ions and the bonding process (Hasanah et al., 2024; Stroumpouli & Tsaparlis, 2022). This statement is supported by Fitriyah et al. (2021), who stated that chemical bonding is inherently abstract with complex microscopic concepts. One of the difficulties for chemistry students is to connect the macroscopic world they can see with the sub-microscopic world (Tümay, 2016). Because the concept of chemical bonding requires visualisation skills to understand the geometrical shapes of molecules, there is a great potential for misconceptions among students (Sen & Yilmaz, 2017). Muljana et al. (2020) emphasise that these difficulties can be better understood if the concepts can be made tangible and easily remembered and understood by students. To overcome the problems in learning chemistry, the goal is to provide a medium that can display chemical bond structures in three dimensions (Sahin & Yilmaz, 2020). In addition, modern technology has provided opportunities for students to reduce visualisation problems using simulations or models.

Teaching methods using two-dimensional molecule images are less effective in enhancing students' conceptual knowledge and spatial visualisation skills (Kuit & Osman, 2021). Therefore, interventions involving 3-D models in physical or virtual form have been proposed to improve student performance (Ubesie et al., 2016). The effectiveness of the teaching and learning process depends on the creativity of educators and the adaptability to students' needs (Okorie et al., 2019). According to Hong and Woo (2006), three-dimensional model representations presented digitally on a computer screen are easier to visualise than physical models. This finding is also supported by Teplá et al. (2022), who claimed that the impact of instructional methods based on the use of 3D models can increase students' academic achievements. Nechypurenko et al. (2018) claimed that students can better visualise atomic, molecular, and crystal structures when taught using three-dimensional digital models. Various particle-based models have been developed and used as visualisation tools. Therefore, the integration of the latest multimedia in education, such as Augmented Reality (AR) technology, can help enhance visualisation and deepen understanding of chemistry.

One of the digital technologies involving a combination of vision and touch is AR. AR is one of the latest technologies with the potential to have a positive impact on teaching and learning (Cao & Yu, 2023). Past studies have revealed that AR provides many advantages, particularly in the field of education (Fadzil & Noor, 2023; Farzeeha et al., 2023; Gargrish et al., 2021). Among the advantages of AR is that it enables students to have different and effective learning experiences. Fatemah et al. (2020) and Brown et al. (2020) have created multiple interactive applications that utilise virtual reality technology, such as StereoChem (Swamy et al., 2018) and augmented reality with MoleculAR. These applications offer a new experience and a good impact for users. Lee and Hsu (2021) also showed the effectiveness of AR-assisted learning using the "Makeup AR" approach, which improved learning outcomes, self-efficacy, and reduced cognitive loads. Additionally, Wu et al. (2018) provided additional evidence supporting the efficacy of AR-based learning systems, indicating markedly superior learning achievements compared to conventional learning approaches. Findings suggest that students in properly designed virtual environments can exert less cognitive effort to obtain a better learning experience and knowledge (Garzón et al., 2019; Li et al., 2021). AR technology can be a positive innovation in the education field, serving as an interactive teaching tool to help students visualise (Jeong et al., 2019). Furthermore, students gain a deep understanding of the chemistry subject being studied through AR. In addition, students can engage in more effective interactive visualisations with AR.

AR can be easily accessed via smartphones by simply pointing the smartphone towards a marker, and the system will add the necessary information about the image to the screen (Calle-Bustos et al., 2017). Mobile applications are technologies developed specifically for use on mobile devices such as smartphones and tablets (Murat et al., 2020). In 21st century learning, mobile technologies have been widely adopted by teachers to enhance effectiveness in achieving learning objectives. Many researchers have discovered that incorporating AR into chemistry education significantly improves students' understanding of chemistry content and concepts (Romainor et al., 2020). In this study, the AR-CSI Module was developed as a learning aid for the topic of chemical bonding, integrating AR technology to help students visualise molecular geometries and molecular polarity. Complex information provided to students is simplified by technology and the use of instructional materials such as modules provided with animations or technology that can support abstract chemical concepts. This aligns with the research conducted by Singhal et al. (2012), indicating that students' comprehension of chemistry improves as they develop a better understanding of the spatial relationships between molecules and their correlation with the Valence Shell Electron Pair Repulsion (VSEPR) Theory when AR is integrated into the learning process.

Among the emerging technologies, AR has been recognised as a technology that can assist students to understand, evaluate, and recall information without exhausting them. AR has become quite popular among students by enhancing students' memory, spatial ability, learning, and critical thinking (Manishaa & Gargrish, 2023). Using AR in real-world learning activities can strengthen students' spatial cognition expression, their ability to operate experiments, and encourage collaborative learning among students (Shore et al., 2023). Previous research has demonstrated the use of AR technology in various chemistry topics, such as three-dimensional molecular visualisation (Baharuddin & Karpudewan, 2023), molecular geometry (Rahmawati & Kamaludin, 2024), general chemistry concepts (Khairani & Prodjosantoso, 2023), and acid–base topics (Khairunnisa et al., 2025). Findings from previous studies suggest that the application of AR technology effectively enhances students' conceptual understanding of chemistry. Utilising AR as an educational resource is highly appropriate for students to explore the concepts of chemical bonding, as it provides a visual representation of molecular structures.

Integrating AR-based learning resources can greatly enhance student engagement and enthusiasm for studying chemistry (Whatoni & Sutrisno, 2022). Educators need to develop engaging learning materials to captivate students' interest (Ziden et al., 2022). The relevance of AR in an academic context is supported by the fact that it can be used without expensive technology. At the same time, AR applications enable students to conduct self-directed learning, saving teachers time from repeatedly explaining concepts. Thus, the special features of AR make it suitable for use as a learning tool, especially for activities involving interactivity and 3D visualisation abilities. Previous studies have shown the integration of 21st century skills, particularly in the aspects of digital literacy, critical thinking, creativity, collaboration, and communication, with chemistry concepts (Abualrob et al., 2023; Dewi et al., 2022). Most of these studies focus on the development of 21st century skills, but not all components of these skills have been researched comprehensively. Most research emphasises a few components of 21st century skills, such as digital literacy, collaboration, communication, and creativity, while other components, such as critical thinking and creativity, have received less attention. Therefore, there is a need for a study that integrates all components of 21st century skills. Hence, this research was conducted to evaluate the effectiveness of the AR-CSI Module in enhancing students' understanding of chemical bonding and strengthening their 21st century skills. Nevertheless, limited research has examined the use of AR in teaching the highly abstract topic of chemical bonding, especially concerning the development of students' 21st century skills.

Therefore, a modular self-learning system approach with interactive and engaging AR technology integration was developed, and the effects on the content knowledge and 21st century skills were investigated. This study was also conducted to address the identified research gap by developing and evaluating the effectiveness of the AR-CSI Module in enhancing students' understanding of chemical bonding and fostering their 21st-century skills. The findings of this study are expected to contribute to the existing body of literature on the integration of AR technology in chemistry education and to reinforce pedagogical practices that emphasise 21st century skills at the matriculation level. Hence, the research aims to answer whether there is a significant difference in the mean score of the achievement posttest between the control and treatment groups. The second research question that needs to be answered is whether there is a significant difference in the mean score of 21st century skills posttest between the control and treatment groups in terms of digital literacy, inventive thinking, effective communication, and high productivity.

2. METHODOLOGY

2.1. Sample

This non-equivalent group pretest-posttest quasi-experimental design involved a total of 60 18-year-old students from one of the matriculation colleges in Northern Malaysia. This study employed a quasi-experimental design because the student groupings were predetermined by the institution rather than randomly assigned. According to Creswell and Creswell (2018), quasi-experimental designs are appropriate when randomisation is not possible, but a pretest can be used to establish group equivalence before the intervention. The selected matriculation college was chosen because the students face difficulties in mastering abstract concepts such as chemical bonding, and the institution has sufficient technological infrastructure to implement AR technology effectively (Ghani & Lee, 2022). The 60 students were divided into control and treatment groups, with 30 students in each group. Both groups were taught by chemistry lecturers who have more than 10 years of experience in teaching chemistry.

2.2. Instruments

The instruments used in this study comprised an achievement test and the Malaysian Twenty-First Century Skills Instrument (M-21CSI) questionnaire (Soh et al., 2012). The achievement test consisted of 20 objective questions and three structured questions. The distribution of objective items in achievement tests based on the level of Bloom's Taxonomy is presented in Table 1. The distribution of subjective items in the achievement tests based on the level of Bloom's Taxonomy is presented in Table 2. The questions were adapted from past years' questions of the Matriculation Program Semester Examination, Matriculation Division of the Ministry of Education, Malaysia. Two equivalent sets of achievement tests were provided (pretest and posttest), with the items in the tests similar in terms of the level of Bloom's Taxonomy. All these questions need to be answered within two hours. The achievement test was administered in the form of a pretest and posttest before and after the intervention. Pretest results were utilised to assess students' existing knowledge before interventions. Posttest results were employed to evaluate the effectiveness of the interventions in improving students' understanding of chemical bonding. Five experts examined the items to maintain their content validity. Next, the content validity index (CVI) was calculated, resulting in a value of 1.00. A pilot study was conducted to assess the reliability of the test using the test-retest method, yielding a reliability coefficient of 0.604 (average) (Hair et al., 2010).

Table 1. Distribution of objective items in achievement tests

Item	Level of Bloom's Taxonomy	Total Item
3	Remembering	1
1, 7, 15	Understanding	3
5, 8, 10, 13, 19	Applying	5
2, 6, 9, 16, 17	Analysing	5
4, 11, 12, 14, 18, 20	Evaluating	6
-	Creating	0

Table 2. Distribution of subjective items in achievement tests

Item	Level of Bloom's Taxonomy	Total Item
1(b)(ii)	Remembering	1
1(b)(iii)	Understanding	1
1(a), 1(b)(i), 2(a)	Applying	3
2(b)	Analysing	1
3	Evaluating	1
-	Creating	0

The Malaysian 21st Century Skills Instrument (M-21CSI) questionnaire was used to measure students' 21st century skills in terms of digital literacy, inventive thinking, effective communication, and high productivity. The questionnaire was adapted from Soh et al. (2012). Students provided feedback on all items by indicating their opinions on a scale of 1 (Strongly Disagree, SD), 2 (Disagree, D), 3 (Agree, A), and 4 (Strongly Agree, SA). The validity of M-21CSI was checked by three experts, and the reliability was examined by an internal reliability coefficient of 0.916. The distribution of items is presented in Table 3.

Table 3. Distribution of items in M-21CSI

Cluster	Distribution of Items	Total Item
Digital Literacy	1-5	5
Inventive Thinking	6-11	6
Effective Communication	12-17	6
High Productivity	18-23	6

2.3. Procedure of the Study

The AR-CSI Module was developed for implementation among students in the two-semester (SDS) matriculation program for the treatment group. Before the intervention, a meeting was held with the chemistry lecturers involved. These lecturers were given a briefing session to manage the AR-CSI Module and carry out the designed activities. Data for this study were collected using two main instruments, namely an achievement test and the Malaysian Twenty-First Century Skills Instrument (M-21CSI) questionnaire (Soh et al., 2012). An achievement pretest and the M-21CSI questionnaire were administered to both groups to assess their preliminary knowledge of chemical bonding concepts and 21st century skills before the intervention. The students assembled for 60-minute sessions three times a week for 10 weeks. The students require a duration of 10 weeks to allow sufficient time for them to explore the abstract concepts of chemical bonding themselves, which aligns with the Constructivist 5E Learning Model. The students in the treatment group learned the chemical bonding topic using the AR-CSI Module along with the AR-CSI Mobile Application, while the control group was instructed via a conventional teaching method using a chemistry tutorial book. After the intervention, an achievement posttest and M-21CSI questionnaire were administered to the students from both the control and treatment groups. Subsequently, answer scripts for the achievement pre- and posttest were assessed based on the provided scoring scheme.

2.4. Data Analysis

The collected data were analysed using inferential statistics to determine the effects of the AR-CSI Module on students' understanding of chemical bonding and the enhancement of 21st century skills. Table 4 presents the research questions, hypotheses, and the data analysis methods used.

Table 4. Research questions, hypotheses, and data analysis methods

Research Question	Hypotheses	Data Analysis Method
RQ1: Is there a significant difference in the mean score of the achievement posttest between the control and treatment groups?	H_{01}: There is no significant difference in students' achievement between the control and treatment groups after the intervention.	Independent Samples t-Test
RQ2: Is there a significant difference in the mean score of 21st century skills posttest between the control and treatment groups in terms of digital literacy, inventive thinking, effective communication, and high productivity?	H_{02}: There is no significant difference in the mean score of 21st century skills posttest between the control and treatment groups in terms of digital literacy, inventive thinking, effective communication, and high productivity.	A Multivariate Analysis of Variance (MANOVA)

3. RESULTS AND DISCUSSION

3.1. Students' Understanding of the Chemical Bonding Concepts

A normality test was conducted to assess the distribution of posttest results for both groups before performing inferential statistical analyses. Since the sample size is small, a Shapiro-Wilk test was performed and did not show evidence of non-normality for both control (W = 0.93, p-value = 0.123) and treatment groups (W = 0.97, p-value = 0.555). Hence, an independent-samples t-test was implemented to test the hypothesis. The results of the independent-samples t-test are shown in Table 5.

Table 5. Comparison of posttest mean scores between the control and treatment groups

Group	N	Mean	Standard Deviation	Minimum	Maximum	t	df	Sig.
Control	30	33.67	7.54	19	46	14.72	36.66	< .001
Treatment	30	55.23	2.76	49	60			

Results from Table 5 show that there is a significant difference in the mean score of the achievement posttest between the control and treatment groups [$t(36.66) = 14.72$, $p < .001$]. The mean score of the posttest for the treatment group (M = 55.23, SD = 2.76) surpassed the control group (M

= 33.67, SD =7.54). Hence, H_{01} is rejected. This finding shows that students who learned the topic of chemical bonding using the AR-CSI Module achieved higher levels of achievement compared to those in the control group who learned the same topic using a conventional method. Chemical bonding is an abstract topic, quite distant from the everyday experiences of students. They cannot see an atom, its structure, or its interactions with other atoms. If these concepts can be made into real and easily imagined by students, the problem can be better understood. In pursuit of this goal, there are already chemistry handbooks with colourful images and laboratory exercises in schools. However, not all issues can be understood by reading chemistry books or conducting experiments in laboratories, especially regarding atomic structure and chemical bonding. The concept of chemical bonding requires visualisation for better student comprehension. To enhance understanding of chemical bonding concepts, materials must depict molecular structures in visual forms. Therefore, there is a need for new instructional media and learning modules to enhance the understanding of concepts of chemical bonding (Praptiwi et al., 2020). The AR-CSI Module is a printed tutorial module that contains learning materials such as exercises, activities, and quizzes. It is integrated with AR technology via the AR-CSI Mobile Application to assist students in visualising molecular geometry in the chemical bonding topic (Figure 1). The use of AR technology in designing teaching and learning materials assisted students in understanding abstract chemistry concepts and promoting active learning (Badilla-Quintana et al., 2020; Qassem et al., 2016; Wong et al., 2021).

Figure 1. AR technology enables students to visualise molecular shapes in 3D

Generally, the conventional method of classroom teaching, or face-to-face learning, involves the teacher presenting lessons while standing in front of the students. Conversely, the participants pay attention, take notes, and maintain a passive role throughout the entire lesson (Tan et al., 2022). To overcome this, the AR-CSI Module created an interactive and engaging learning environment by implementing the Constructivist 5E Learning Model. The AR-CSI Module comprises four units: Unit 1: Explain Valence Shell Electron Pair Repulsion Theory (VSEPR), Unit 2: Draw the basic molecular shapes: linear, trigonal planar, tetrahedral, trigonal bipyramidal, and octahedral, Unit 3: Predict and explain the shapes of molecules and bond angles in a given species, and Unit 4: Explain bond polarity, dipole moment, and deduce the polarity of molecules based on the shapes and resultant dipole moment. Each activity in the AR-CSI Module follows each phase in the Constructivist 5E Learning Model sequentially. Activity 1 (Engage) in each unit of the AR-CSI Module begins with a game that can capture students' interest and subsequently encourage their exploration into the next activity. There are four digital investigation games in the engagement phase of each unit: (1) Maze of Mystery Molecules, (2) Escape Room: Pursuing Happiness, (3) Mystery Unpleasant Molecules, and (4) The Maze Runner: World of Polarity. Through Activity 2 (Explore), students build conceptual understanding based on hands-on activities by conducting investigations. Activity 3 (Explain) aims to help students develop explanations and further ideas through reflection on the investigations they have conducted. Next, Activity 4 (Elaborate) involves students expanding their conceptual understanding by applying the concepts in new situations. Finally, Activity 5 (Evaluate) is used to assess students' progress, encouraging them to evaluate their understanding and abilities. Each learning stage featured in the

AR-CSI Module is complemented by engaging activities that emphasise the principles of 21st century education.

The findings revealed that the use of the AR-CSI Module significantly enhanced students' understanding of chemistry abstract concepts. The results are in line with the Cognitive Theory of Multimedia Learning (Mayer, 2009), which emphasises that individuals learn more effectively through a combination of text and visuals than through text alone. These findings are supported by the study of Rahman et al. (2024), which showed that interactive multimedia (AR) environments can enhance students' understanding of abstract chemistry concepts. Similarly, the systematic review by Riza et al. (2023) demonstrated that the use of multimedia in chemistry subjects can increase students' interest and achievement. Hence, these studies provide strong evidence that multimedia-based approaches, such as AR, are effective in improving students' understanding of chemistry.

3.2. Students' Mastery of 21st Century Skills

To perform inferential statistical analyses, the assumption of normality needs to be obeyed. A Shapiro-Wilk test was performed since the sample size is small. The results show evidence of normality for both control (W = 0.96, p-value = 0.357) and treatment groups (W = 0.89, p-value = 0.600). Hence, Multivariate Analysis of Variance (MANOVA) was implemented to test the hypothesis. The results of the multivariate test are shown in Table 6. Table 6 shows that F(4,55) = 149.645, Wilks' Lambda = 0.084, $p<.001$, $\eta^2 = 0.916$. The results show a significant difference in the mean score of the 21st century skills posttest between the control and treatment groups with a large effect size (Cohen, 1992). A post-hoc test was conducted to determine which 21st century skills showed a significant difference between the groups (Table 7).

Table 6. Multivariate test for the 21st century skills posttest

Effect		Value	F	Hypothesis df	Error df	Sig.	Partial Eta Squared
Intercept	Pillai's Trace	0.998	7391.530	4.000	55.000	<.001	0.998
	Wilks' Lambda	0.002	7391.530	4.000	55.000	<.001	0.998
	Hotelling's Trace	537.566	7391.530	4.000	55.000	<.001	0.998
	Roy's Largest Root	537.566	7391.530	4.000	55.000	<.001	0.998
Groups	Pillai's Trace	0.916	149.645	4.000	55.000	<.001	0.916
	Wilks' Lambda	0.084	149.645	4.000	55.000	<.001	0.916
	Hotelling's Trace	10.883	149.645	4.000	55.000	<.001	0.916
	Roy's Largest Root	10.883	149.645	4.000	55.000	<.001	0.916

Table 7. Test of between-subject effects for the 21st century skills posttest

Source	Dependent Variable	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Corrected Model	Digital Literacy	144.150[a]	1	144.150	109.961	<.001	0.655
	Inventive Thinking	770.417[b]	1	770.417	390.028	<.001	0.871
	Effective Communication	756.150[c]	1	756.150	505.068	<.001	0.897
	High Productivity	355.267[d]	1	355.267	310.635	<.001	0.843
Intercept	Digital Literacy	20056.817	1	20056.817	15299.808	<.001	0.996
	Inventive Thinking	21622.017	1	21622.017	10946.264	<.001	0.995
	Effective Communication	21698.017	1	21698.017	14493.109	<.001	0.996
	High Productivity	19874.400	1	19874.400	17377.616	<.001	0.997
Groups	Digital Literacy	144.150	1	144.150	109.961	<.001	0.655
	Inventive Thinking	770.417	1	770.417	390.028	<.001	0.871
	Effective Communication	756.150	1	756.150	505.068	<.001	0.897
	High Productivity	355.267	1	355.267	310.635	<.001	0.843
Error	Digital Literacy	76.033	58	1.311			
	Inventive Thinking	114.567	58	1.975			
	Effective Communication	86.833	58	1.497			
	High Productivity	66.333	58	1.144			
Total	Digital Literacy	20277.000	60				
	Inventive Thinking	22507.000	60				
	Effective Communication	22541.000	60				
	High Productivity	20296.000	60				
Corrected Total	Digital Literacy	220.183	59				
	Inventive Thinking	884.983	59				
	Effective Communication	842.983	59				
	High Productivity	421.600	59				

Due to the presence of four dependent variables, a Bonferroni adjustment was made, resulting in a new significant level of 0.0125. Table 7 shows that all the clusters of 21st century skills show a significant difference, F(1,58) = 109.961, $p<.001$, $\eta^2 = 0.655$ for digital literacy; F(1,58) = 390.028,

$p<.001$, $\eta^2 = 0.871$ for inventive thinking; $F(1,58) = 505.068$, $p<.001$, $\eta^2 = 0.897$ for effective communication; $F(1,58) = 310.635$, $p<.001$, $\eta^2 = 0.843$ for high productivity. These results have proven that H_{02} is rejected. There is a significant difference in the mean score of 21st century skills posttest between the control and treatment groups in terms of digital literacy, inventive thinking, effective communication, and high productivity. The mean scores and standard deviations for all the clusters of 21st century skills are presented in Table 8.

Table 8. Mean scores and standard deviations for the 21st century skills posttest

Clusters	Groups	Mean	Standard Deviation
Digital Literacy	Control	16.73	1.57
	Treatment	19.83	0.38
Inventive Thinking	Control	15.40	1.22
	Treatment	22.57	1.57
Effective Communication	Control	15.47	0.63
	Treatment	22.57	1.61
High Productivity	Control	15.77	1.17
	Treatment	20.63	0.96

The findings showed a significant difference in the mean posttest scores of 21st century skills between the control and treatment groups. The treatment group that used the AR-CSI Module obtained higher scores in 21st century skills, which include digital literacy (M = 19.83, SD = 0.38), inventive thinking (M = 22.57, SD = 1.57), effective communication (M = 22.57, SD = 1.61), and high productivity (M = 20.63, SD = 0.96), compared to the control group for digital literacy (M = 16.73, SD = 1.57), inventive thinking (M = 15.40, SD = 1.22), effective communication (M = 15.47, SD = 0.63), and high productivity (M = 15.77, SD = 1.17). The posttest results revealed that students in the treatment group performed better than students in the control group. The most significant improvements were observed in inventive thinking and effective communication, indicating that the use of the AR-CSI Module in this study successfully fostered students' critical thinking and collaborative engagement. These results are consistent with the findings of Nousheen et al. (2024), who reported that digital interactive learning enhances students' performance in chemistry and develops their 21st century skills. Similarly, Saidin et al. (2024) found that AR improves students' critical and inventive thinking skills. In addition, Serrano-Ausejo and Mårell-Olsson (2024) highlighted that immersive technologies can support students' spatial abilities in chemistry as well as their 21st century skills. The AR-CSI Module was developed by implementing mobile-based learning, resulting in the creation of the AR-CSI Mobile Application. Mobile-based learning provides convenient access to various learning resources via applications and the internet. Students can download e-books, educational materials, and videos online (Ashiq et al., 2023). Mobile-based learning enables students to access learning materials and resources at any time and from anywhere (Aurum & Surjono, 2021). An important element of mobile-based learning is its capacity to stimulate critical thinking abilities in students, thereby promoting self-directed learning (Aurum & Surjono, 2021). Mobile-based learning provides a more captivating, accessible, and customized approach to education, perfectly suited to meet the evolving demands of the digital era (Tong et al., 2023).

The content of the AR-CSI Module emphasises the four 21st century skill clusters of enGauge: digital-age literacy, inventive thinking, effective communication, and high productivity. Digital era literacy refers to the ability to use digital technology, communication tools, or networks to access, manage, integrate, evaluate, and create information in a knowledge-based society (Setha et al., 2023; Spante et al., 2018). In the AR-CSI Module, students can enhance their digital era literacy through the Digital Investigation Game in the engage phase. These games stimulate students' curiosity and encourage them to carry out exploration in the next phase. Students construct new knowledge based on their existing knowledge. They need to explore the learning to make connections with their existing knowledge. The second cluster included in the AR-CSI Module is inventive thinking. Inventive thinking is a cognitive process that utilises creative and critical thinking in problem-solving to develop innovative or unique solutions (Samad et al., 2023). The activities in the AR-CSI Module place a strong emphasis on engaging students in hands-on problem solving to develop their inventive thinking. Through activities prepared in this module, students can enhance their understanding by seeking out new knowledge and finding solutions on their own. The findings indicated that this approach was effective in enhancing students' inventive thinking skills, as students were able to provide many solutions with suitable justifications.

The next cluster involved in this module is effective communication. Collaborative learning fosters communication, teamwork, and peer-to-peer knowledge sharing, enriching the learning experience and promoting a deeper understanding of chemical bonding principles. Afterwards, students are encouraged to build their effective communicative skills through collaborative learning by sharing the solutions they have found with both their peers and teachers. Communication is considered effective when students can convey messages according to the situation and context they face (McGunagle & Zizka, 2020; Mustapha & Jamaludin, 2021). Meanwhile, communication is less effective if the audience cannot understand the content of the message conveyed by the speaker. This sharing process allows for valuable input and comments to be received, which in turn facilitates the opportunity for students to adjust based on the feedback received. The last 21st century skill cluster integrated into the AR-CSI Module is high productivity. It reflects the ability to perform well in various aspects of life and work by efficiently utilising resources, achieving desired outcomes with quality and innovation, collaborating effectively with others, and adapting to change (Mustapha & Jamaludin, 2021). Each activity in this module is structured from concrete and easy concepts, followed by abstract and complex concepts. Through the AR-CSI Module, activities are initiated with easier tasks and then progress to more complex ones. For example, Activity 1 in Unit 1 involves drawing Lewis structures and determining the number of lone pairs and bonding pairs of electrons. Subsequently, Activity 2 involves drawing basic molecular shapes. Then, Activity 3 involves scientific discussions and further, more complex activities. At the final stage, students are required to perform self-assessment by formulating conclusions regarding all the activities they have engaged in throughout the learning journey. The application of the chemistry learning investigation approach with the integration of 21st century learning, such as 4C skills (Collaboration, Communication, Critical and Creative thinking), enhances students' learning experience.

4. CONCLUSION

This study explored the impact of the AR-CSI Module on students' comprehension of chemical bonding and the development of 21st century skills. The results indicated that the AR-CSI Module boosted students' chemistry knowledge and improved their four clusters of 21st century skills. However, this study has limitations in that it only tested four clusters of 21st century skills: digital age literacy, inventive thinking, effective communication, and high productivity. Soft skills were not included. Future studies can be conducted by involving all clusters of 21st century skills. Furthermore, additional research on this approach should be undertaken and applied to various chemistry topics to benefit students. This study adds to the literature by integrating AR and the constructivist learning approach in teaching chemical bonding and chemical concepts while fostering 21st century skills among students.

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CONFLICT OF INTEREST
The authors declare no conflicts of interest.

AUTHOR CONTRIBUTION
Nor Syatilla Haerany Abd Ghani: Conceptualisation, Designing and developing the module and the mobile application, Methodology, Data curation, Writing original draft. Tien Tien Lee: Conceptualisation, Methodology, Supervision, Writing, Reviewing and Editing. Jianfen Wang: Reviewing and Editing. Rusmansyah: Reviewing and Editing.

DATA AVAILABILITY
The authors confirm that the data supporting the findings of this study are available within the article.

DECLARATION OF GENERATIVE AI
Not applicable.

ETHICS
Not applicable.

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