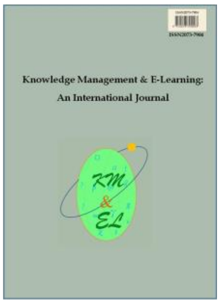
Enhancing students' critical thinking and visualisation skills through mobile augmented reality

Nor Farhah Saidin
Universiti Pendidikan Sultan Idris, Tanjung Malim, Perak, Malaysia
Noor Dayana Abd Halim
Noraffandy Yahaya
Universiti Teknologi Malaysia, Skudai, Johor, Malaysia
Nurul Nadwa Zulkifli
Universiti Putra Malaysia Bintulu Sarawak Campus, Malaysia
Universiti Putra Malaysia, Serdang Selangor, Malaysia



Knowledge Management & E-Learning: An International Journal (KM&EL)
ISSN 2073-7904

Recommended citation:
Saidin, N. F., Halim, N. D. A., Yahaya, N., & Zulkifli, N. N. (2024). Enhancing students' critical thinking and visualisation skills through mobile augmented reality. *Knowledge Management & E-Learning, 16*(1), 1–41. https://doi.org/10.34105/j.kmel.2024.16.001

Knowledge Management & E-Learning, 16(1), 1–41

Enhancing students' critical thinking and visualisation skills through mobile augmented reality

Nor Farhah Saidin*

Department of Computer Sciences and Digital Technology
Faculty of Computing and Meta-Technology
Universiti Pendidikan Sultan Idris, Tanjung Malim, Perak, Malaysia
E-mail: nfarhah_saidin@meta.upsi.edu.my

Noor Dayana Abd Halim*

School of Education
Faculty of Social Sciences and Humanities
Universiti Teknologi Malaysia, Skudai, Johor, Malaysia
E-mail: noordayana@utm.my

Noraffandy Yahaya

School of Education
Faculty of Social Sciences and Humanities
Universiti Teknologi Malaysia, Skudai, Johor, Malaysia
E-mail: p-afandy@utm.my

Nurul Nadwa Zulkifli

Department of Science and Technology
Faculty of Humanities, Management and Science
Universiti Putra Malaysia Bintulu Sarawak Campus, Malaysia
Institute for Mathematical Research
Universiti Putra Malaysia, Serdang Selangor, Malaysia
E-mail: nurulnadwa@upm.edu.my

*Corresponding author

Abstract: Augmented Reality (AR) has emerged in our educational paradigm as a new tool to accelerate change in the teaching and learning process. This technology can improve students' visualisation skills, which helps them understand abstract concepts, especially in Chemistry. Furthermore, visualisation skills help improve students' critical thinking. This study was conducted with 16 secondary students. Before and after the intervention, students were required to complete a Purdue Spatial Visualisation Test to measure their visualisation skills. During four weeks of intervention, students explored the content using a mobile augmented reality application for learning chemical bonds (called CBOND) and completed critical thinking tasks each week. This study employed data mining using a decision tree to predict the path to improving students' visualisation and critical thinking skills in learning chemical bonds.

The results revealed that CBOND had a significant effect on students' visualisation and critical thinking development. Therefore, this study proved that augmented reality technology could help students to visualise abstract concepts, especially in Chemistry, and in turn, foster their higher level of critical thinking.

Keywords: Augmented reality; Visualisation skills; Critical thinking; Data mining; Chemistry

Biographical notes: Dr. Nor Farhah Saidin is a senior lecturer at the Faculty of Computing and Meta-Technology, Universiti Pendidikan Sultan Idris, Malaysia. She obtained a bachelor's degree in Computer Science, master's degree and Ph.D in Educational Technology from Universiti Teknologi Malaysia. She is involved in various researches related to her area of interests particularly in multimedia education, mobile learning, augmented reality, collaborative learning and others that related to educational technology. In terms of publication, she has authored various publication likes journal articles, chapter in books, proceeding papers and others.

Assoc. Prof. Dr. Noor Dayana Abd Halim was born in Kuala Lumpur, Malaysia in 1986. She received a Bachelor of Science and Technology in Education degree in Chemistry from Universiti Teknologi Malaysia in 2009, and a Ph.D. in Educational Technology from the same university in 2012. She has been a Senior Lecturer at School of Education, Faculty of Social Sciences and Humanities UTM since 2012 and was appointed as an Associate Professor in 2021. Her research interests include online learning, open and distance learning, augmented and virtual reality, multimedia learning, personalized learning, and any other topics related to technology in education. She is also a member of the Young Scientists Network Academy of Sciences Malaysia (YSN-ASM) and a professional member of the Malaysian Board of Technologists (MBOT). Additionally, she has written numerous articles and presented at national and international conferences and seminars in the area of technology in teaching and learning.

Prof. Noraffandy Yahaya received his Ph.D. in computer-based learning from the University of Leeds, U.K. He served as the Head of the Department of Educational Science, Mathematics, and Creative Multimedia for nine years, and in 2023, he was appointed as the Chair of the School of Education at the Faculty of Social Sciences and Humanities in Universiti Teknologi Malaysia. He has been an Associate Professor since 2013, and his research interests include multimedia in education, online learning, and ICT in education. He has supervised over 40 completed master's degree students and seven completed Ph.D. students in the field of educational technology, online learning, and ICT in education. He has also served as an External Examiner for doctoral dissertations at universities in Malaysia and Australia and as an Assessor for master's dissertations at a university in New Zealand. He has conducted studies on students' interaction in online learning environments, learning analytics, and massive open online courses. He has published over 80 articles in journals and conference proceedings in the research areas of online learning, ICT in education, and the use of technology in teaching and learning.

Nurul Nadwa Zulkifli was born in Sarawak, Malaysia in 1989. She earned a Bachelor of Science degree in Computer and Education, with a major in Mathematics, from Universiti Teknologi Malaysia in 2013. She also completed a Master of Education and a Ph.D. in Educational Technology from the same institution in 2014 and 2019, respectively. Currently, she is a Senior Lecturer at the Universiti Putra Malaysia Bintulu Sarawak Campus and a Research Associate at the Institute for Mathematical Research, Universiti Putra Malaysia, Malaysia. Her research interests include online learning, mobile learning, social media for learning, artificial intelligence for teaching and learning, blended learning, pedagogy, collaborative and cooperative learning.

1. Introduction

The advanced technology that emerged in education is now being explored to solve problems in the teaching and learning process. This is because the teaching method and the use of static textbooks alone are failing to engage students which have contributed to poor learning outcomes. Tsai (2020) reported that the respondents found it boring to hear the lecturer talking in front of them. Similarly, Gowda and Suma (2017) also agreed that the drawback of teacher-centred instructions was that students felt bored and reduced the rate of mind present in the classroom. The students also believed that integrating technology was important and would help them in their learning process (Borycki & Kushniruk, 2021). Therefore, educators have begun to seek technologies that have the potential to be integrated into education to help students learn actively and improve their understanding, especially in science-related subjects like Chemistry. Therefore, educators have begun to seek new potential technologies to be integrated into education in order to help students learn actively and improve their understanding, especially in the field of Chemistry.

Chemistry is the most common subject that contains many abstract concepts, creating difficulties for the students to visualise. Therefore, teachers integrate technologies with active learning strategies to help students effectively learn Chemistry. For example, a survey conducted by Ayob et al. (2019) shows that the implementation of technology in a blended learning approach while teaching Chemistry can improve students' achievement in this subject. Recently, AR has emerged as a visualisation tool. According to Shelton and Hedley (2002), AR has many advantages and has great potential to change the instructions and learning of complex concepts and content. Therefore, these advantages can be applied to the topic of chemical bonds to decrease students' misconceptions due to the inability of the students in visualisation because AR also allows detailed visualisation and object animation in which the students can view and interact with the 3D images during their learning (Gün & Atasoy, 2017; Shelton & Hedley, 2002). In addition, AR is displayed in different ways and view angles to improve students' understanding of the subjects. This is because AR is presented in different and efficient ways to make students understand the content better.

AR has been evolving over the years and has become portable and available in mobile devices as a result of rapid technological development. The concentration of AR and mobile devices provides an innovative experience and gives more exciting experiences for users to explore the physical world easily because it is handheld and portable, unlike PCs (Lin et al., 2013). AR is characterised as a live, direct or indirect, view of a physical, real-world environment in which the elements are augmented by computer-generated sensory input such as sound, video, graphics or GPS data. However, the latest technologies in AR have shifted to Mobile Augmented Reality (MAR), in which AR was used in mobile applications (Nincarean et al., 2013). Nincarean et al. (2013) and Kaźmierczak et al. (2021) also stated that MAR created a more meaningful learning experience and a majority of the participants from previous studies reported higher motivation, enjoyment and educational effects.

2. Background of the study

2.1. Difficulties in visualising the abstract concepts in chemistry

Chemistry is one of the elective science subjects and the core to the other parts of science which has received less interest from students. This is because they found it hard to understand. Chemistry is a science subject that will equip students with the knowledge that can help them in problem-solving, decision-making, and critical and scientific thinking. Many researchers (Botella et al., 2018; Levy Nahum et al., 2004; Özmen, 2004; Tan et al., 2001) believe students are weak in Chemistry and always fall into the misconception problem. According to Uzuntiryaki and Geban (2016), students have difficulties understanding most of the concepts in Chemistry and hold misconceptions which lead to the prevention of meaningful learning.

Levy Nahum et al. (2010) stated that the concepts associated with chemical structure and bonding, such as molecules, ions, hydrogen bonds and giant lattices, are abstract. This abstract concept will create difficulties that may lead to misconceptions due to the students' fundamental misunderstanding. For example, in chemical bonding, there is great potential for forming alternative conceptions as students try to derive meaning from what is said by the teacher or what is written in the textbooks because the concepts of this topic are abstract (Willingham, 2007). Besides, scientific concepts are complicated because many scientific ideas and models are too sophisticated to be taught in schools. Therefore, Hoban and Nielsen (2013) suggested that school curriculum should include representations of science such as animations and videos. Taber (2011) supported Kelly and Jones's (2008) recommendation as they reported that many students were able to correct their misconceptions after viewing either static molecular visualisations or animations (Fang & Guo, 2016).

Chemistry is a subject that involves talking about the problems in visualisation in science education. This is because Chemistry is a visual science subject in which visualisation plays a major role in daily practices (Wu & Shah, 2004). Chemical bonding is an example of a basic topic that contains an abstract concept that cannot be directly applied to everyday life. Therefore, students need help in understanding the chemical bonding concept (Lutviana et al., 2019; Uzuntiryaki & Geban, 2016). Many students are still confused in answering simple questions regarding the topics of chemical bonding (Bakar & Ayob, 2010). The common problem amongst students is that they need help to write the sequence of electrons for the ionic bond and covalent bond and create a mental diagram about the formation of the bond (Bakar & Ayob, 2010).

Moreover, Bakar and Ayob (2010) conclude that a few problems in the study of chemical bonding led to students' misconceptions. Some students cannot identify the type of bonding and still answer single and double bonds instead of the right answer which are covalent and ionic. Besides, students cannot identify the conditions of every chemical bond that forms between the elements. A similar finding was revealed by Dawati et al. (2019) in which most students do not understand that bonds occur in the electron transfer of sodium chloride from sodium to chloride. Students have difficulties drawing the diagram of the electron sequences for the ionic and covalent compounds, rendering the diagram to be dysfunctional. Another problem with chemical bonds amongst students is that they cannot draw the Lewis structure correctly. This is because they do not understand the concept and cannot visualise the abstract concept (Bakar & Ayob, 2010; Dawati et al., 2019).

Therefore, effective teaching strategies or new tools to enhance the teaching and learning qualities that can help in the visualisation of abstract concepts in chemical bonds should be developed and further implemented. According to Vavra et al. (2011), from the 65 articles on visualisation that were analysed, most of the studies were in Chemistry which emphasises that visualisation is essential when learning Chemistry.

Dawati et al. (2019) mentioned that students sometimes needed help to translate one representation to another because of their limited conceptual knowledge and poor visual-spatial skills. Vavra et al. (2011) stated that technology such as animations and other computer-based visualisations facilitate understanding, motivate student interest in learning and help them learn as an extra practice. Besides, visualisation skills can be improved with the help of technology, such as by mentally manipulating complex spatial dimensional and 3D figures (Tsai & Yen, 2014).

2.2. Technologies used to visualise abstract concepts in chemistry

Abstract concepts in science can be categorised into theoretical and descriptive concepts. Examples of descriptive concepts can be found with directly observable exemplars in Chemistry, such as chemical reactions. Theoretical concepts represent abstract concepts that cannot be viewed with the naked eye, such as protons, atoms, molecules, and others (Derman et al., 2019). Research has demonstrated the beneficial use of technology as a means for visualising abstract concepts. Visualisation technology provides a means to learn about visible phenomena that are too small, large, fast, or slow to see with the unaided eye (Cook et al., 2006; Dawati et al., 2019). For example, Al-Balushi et al. (2017) developed an animation to help students understand abstract concepts in Chemistry. According to them, this type of technology allows students to visualise the interactions amongst molecules and understand the related chemical concepts.

According to Gkitzia et al. (2020), many students have difficulties learning symbolic and molecular representations of chemistry. To promote the students' understanding of chemical representation, they introduced eChem, a computer-based visualising tool that allowed them to build molecular models and view multiple representations simultaneously. They also prove that technology can be used as a learning tool to help students understand chemistry. This is because multiple link representations that are represented by multimedia allow students to visualise the interactions amongst molecules and avoid misconceptions related to chemical concepts.

There is an abundance of available technology in education that aims to help students in visualisation, including simulation and animation. However, Prinz et al. (2005) highlight that technology such as simulation has limitations in that the resolution of the appearances is not consistent and the quality of the videos is also low, which forces the students to replay the simulation repeatedly to ensure understanding. Therefore, Falvo (2008) stressed that researchers must keep exploring the best visualisation technology to be integrated into the modern classroom to ensure an effective learning process. Lin and Wu (2021) also investigated the appropriate instruction sequence approach and different ways of using visualisations that could significantly increase students' conceptual understanding of chemistry. To overcome the limitations of simulation and animation where the resolution of the appearances is not consistent and the quality of the videos is also low, students are forced to replay the simulation repeatedly to ensure understanding, the technology like AR is better for be applied because it functions in real-time and more user friendly as it happened within the users' environment.

AR is a new technology that has emerged in education. AR has been extensively studied, yet there needs to be more paucity in the use of AR in education (Martin et al., 2018). The number of research has been consistently growing due to the effectiveness of this technology in recent years. AR has been used in many education fields, including Medicine, Chemistry, Mathematics, Physics, Geography, Biology, Astronomy, Language and History. Augmented reality provides an efficient way of representing a model that needs visualisation, with a higher ability to interact than other interfaces (Shen, 2019; Singhal et al., 2012). Singhal et al. (2012) provided support by demonstrating a seamless interaction between real and virtual environments and using a tangible interface metaphor for object manipulation.

AR is an innovation to improve the learning of three-dimensional shapes instead of using the traditional method in which teachers use wooden objects or any physical objects. When technology evolves in education, there is also an introduction to animation and simulation in learning three-dimensional shapes. Cerqueira and Kirner (2012) list several advantages of using AR techniques for educational purposes. For example, AR minimises the misconceptions that arise due to the inability of students to visualise concepts such as chemical bonds because AR allows detailed visualisation and object animation (Botella et al., 2018). AR allows macro or micro visualisation of objects and concepts that cannot be seen with the naked eye. AR displays objects and concepts in different ways and at different viewing angles, which helps students understand the subject better (Cerqueira & Kirner, 2012). This is the reason why AR can visualise better as compared to simulation or animation technology.

Medina et al. (2007) revealed that students in their study repeatedly mentioned during the activities and interviews that they liked how the AR showed the interactions inside a protein, which they had never seen before. These findings show that AR has a high potential in showing different types of representations, such as static 2D/3D images and 3D dynamic images (animations) to visualise interactions amongst amino acids and protein-building processes. In addition, most of the research conducted on AR to date shows that students are excited and interested to learn using AR. For example, research conducted by Rehman et al. (2019) provided positive feedback about their experience of the combination of virtual and real environments. Burton et al. (2011) also reported similar results, with the participants in their study excited about the potential of this technology for sharing information and learning about new concepts. This feedback is useful in determining the readiness of students to accept and use this new technology. AR also encourages students to become more active in the learning process due to the interactivity of its applications (Lamounier et al., 2010). Therefore, it encourages students to think critically and creatively, improving their experiences and understanding. Yang et al. (2015) used AR to develop visualisation mindtools which may help students to think critically.

Hence, AR can be used in learning Chemistry to resolve the misconception among students. Many processes, ideas and concepts can be better illustrated using real-world images d and graphics (Singhal et al., 2012). According to Gudyanga and Madambi (2014), visualising tools to minimise learners' misconceptions is a good initiative because it will create a visually stimulating teaching and learning environment rather than a conceptual environment so that students can understand the concept better.

Over the years, the Horizon Reports (2004-2011) have identified mobile devices as having the potential to transform education. Today, AR is being developed and designed to be integrated into mobile devices. The relevance of mobile learning is supported by the NMC Horizon Report: 2018 Higher Education Edition (Becker et al., 2018), which highlights that AR technology is still emerging in recent years. Research has consistently shown that mobile technology will have a significant impact on the future of education (Martin et al., 2011; Roslan et al., 2021). Specifically, Martin et al. (2011) identifies MAR as a highly promising technology in this field, providing users with ease and flexibility for unrestricted use in various locations (Höllerer & Feiner, 2004). The mobility of mobile devices is also a significant advantage over desktop PCs, as they can be used on the go, whenever and wherever the user desires (Crompton et al., 2016).

Inferences deduced from the literature show that MAR can be used in visualisation and simultaneously create easiness for the students to use it anywhere and everywhere other than helping students to learn in a fun way. According to Stanger-Hall et al. (2011), visualisation can improve existing knowledge and understanding and may develop cognitively active learning and critical thinking skills. Harrell (2004) indicated that argument visualisation is being used to help students construct diagrams that will gradually improve students' critical thinking abilities. Similar results were shown by Shatri and Buza (2017) as they found that visualisation as a teaching and learning form exerts a positive influence in increasing and developing students' critical thinking ability. A majority of prior studies have underlined that the positive effect of visualisation may enhance students' critical thinking skills.

2.3. Development of critical thinking in learning with visualisation tools

Previous researchers have mentioned that visualisation or images formed are a part of the critical thinking process. Gardner and Hatch (1989) said that visual is one of the multiple intelligences that students should possess to be efficient critical thinkers. Critical thinking is an important attribute for success in the 21st century. Critical thinking is defined as higher-order thinking or level 3-6 of Bloom's Taxonomy of Cognition (Stanger-Hall et al., 2011). Critical thinking is crucial to be learned and applied by students because this skill is needed to enhance other skills that may be useful in a person's daily life and the future.

Critical thinking is consistently emphasised, such as in the Program for International Student Assessment (PISA) in the assessment of science, math and reading (Rosen & Tager, 2013; Çoban et al., 2022). Reports from PISA and Trend in International Mathematics and Science Study (TIMMS) by OECD (2013) established that Malaysian students score below the global average compared to other Asian countries. According to Suhadi et al. (2016), the main cause of this problem is that Malaysian students are unable to master thinking skills. Therefore, to ensure that Malaysia is not far behind other countries, the transformation of the learning strategies to foster students' critical thinking should take place. AR content is aligned with a learning goal.

Various initiatives are implemented to enhance the development of critical thinking skills among students (Zulkifli et al., 2020). According to Zakaria et al. (2014), the element of higher-order thinking skills (HOTS) is now the focus in the learning of Science, Technology, Engineering and Mathematics (STEM). For example, positive results were found in the STEM area and in training special skills such as spatial awareness (Buchner & Jeghiazaryan, 2020). This can be observed from questions in the Form 3 Assessment (PT3) that have required students to think critically to find the answers. According to

Santrock (2008), thinking has several functions, such as reasoning, forming concepts, critical and creative and problem-solving. However, nowadays, in the challenging world, it is required for an individual to possess critical thinking skills that consist of components that require high-level intellectual and rational skills such as reflection, argument, understanding and evaluation (Jiménez-Aleixandre & Puig, 2012).

The Malaysian Education Blueprint (Ministry of Education Malaysia, 2013) outlines a new teaching approach that is more student-centred than the previous teacher-centred approach in enhancing critical thinking skills among students. Suhadi et al. (2016) also mentioned that technology has the potential to be a medium for the implementation of this recommendation when it comes to educational transformation. June et al. (2014) deduces that the integration of video and interactive activities in class may help to stimulate interactions and develop critical thinking amongst students. Students will become more responsive and develop self-confidence during discussions. This proves the importance of educational technology in supporting students' learning.

2.4. Relationship between critical thinking and visualisation

According to Kogut (1996), suitable strategies must be applied to improve critical thinking. The strategies listed by Kogut (1996) are asking questions frequently and directly to the students individually, using examples and illustrations, promoting discussion among students in class group assignments and effective use of feedback to encourage critical thinking and exemplification. The strategies mentioned that illustration is one of the strategies for developing students' critical thinking skills. This is supported by Gardner's (1992) statement stating that visual is one of the multiple intelligences students should possess to be efficient critical thinkers. Visualisation can also be used to improve existing knowledge and understanding and may develop active learning and critical thinking skills (Stanger-Hall et al., 2011). Some studies that present visualisation tools like e-maps, graphic organisers, web-based simulation, and others use specific tasks to develop the student's critical thinking. Most of these studies show positive outcomes in developing critical thinking using visualisation tools.

Specific teaching or learning strategies must be applied to ensure that the learning process using visualisation tools is effective. Collaborative learning is a suitable example of strategies that can help in enhancing students' critical thinking. Despite these strategies, visualisation may also help improve students' critical thinking. According to Han (2010), critical thinking can be applied in teaching computer visualisation and communication. Critical thinking is an essential skill that students must master in order to produce independent thinkers (Khan et al., 2022). Educators have become more interested in teaching "thinking skills" instead of teaching content or information in recent years. Certain strategies have to be applied to help improve critical thinking. It is proven that critical thinking can be improved using visualisation as research shows that 3D visualisation can improve students' critical thinking skills in university as students can analyse information from various available sources.

Shatri and Buza (2017) reported similar findings as they found that visualisation increases communication, increases critical thinking, and provides an analytical approach to solving various problems. An experiment was constructed for visualisation and deduced that visualisation is fundamental for developing and increasing critical thinking. The results taken from this research highlight the positive effect of visualisation in the teaching and learning process in developing students' critical thinking and overall performance. The results also show that visualisation motivates students to learn by improving their collaboration and critical thinking approaches.

Learning with visualisation also may consequently improve students' achievement. Istiqomah et al. (2020) stated that implementing the somatic, auditory, visualisation, and intellectual (SAVI) learning approach improves students' attention towards mathematics lessons. Erbas and Demirer (2019) used AR as a visualisation tool in learning biology. AR activities have proven to improve students' academic achievement and motivation in a biology course. Consequently, it was found that the student's motivation in the experimental group increased more than that of the students in the control group. The teacher and the students stated that AR activities might increase their achievement scores and motivation.

Based on the discussion above, this study developed a mobile augmented reality application to support the learning of chemical bonds (called CBOND) and investigate the effects of CBOND on student learning. The research questions of the study include:

RQ1: What are the effects of CBOND on students' visualisation skills?

RQ2: What are the effects of CBOND on students' critical thinking skills?

RQ3: What are the students' critical thinking paths to obtain high-level visualisation skills?

3. Method

3.1. Participants

In this study, 16 Form 4 (16 years old) students who were taking Chemistry in a secondary school were chosen to learn using CBOND for four weeks. Certain criteria were taken into account in selecting the sample. The first was that the selected school should have students who were already exposed to the latest learning technology, such as online learning, mobile learning and others. Only for research question three, which intends to observe details on the critical thinking skills development process amongst students when learning using CBOND, the sample needed was 4 students. In this part, the critical thinking task was analysed in detail. The level of critical thinking involved in this research was assessed and discussed thoroughly and the two students who scored the highest and the lowest in the critical thinking task were selected. This was to determine the pattern of their level of critical thinking in detail for each week, whether it increased, decreased, or remained stagnant.

3.2. Instruments

The students were required to complete a Purdue Spatial Visualisation Test (PSVT) in week 1 (pre-test) and week 6 (post-test) to measure their visualisation skills before and after learning the CBOND intervention. During the intervention, each student was asked to perform four critical thinking tasks after completing the weekly learning activities. The intervention is illustrated in Fig. 1 below. This study recorded the PSVT test and the Critical thinking task in written form.

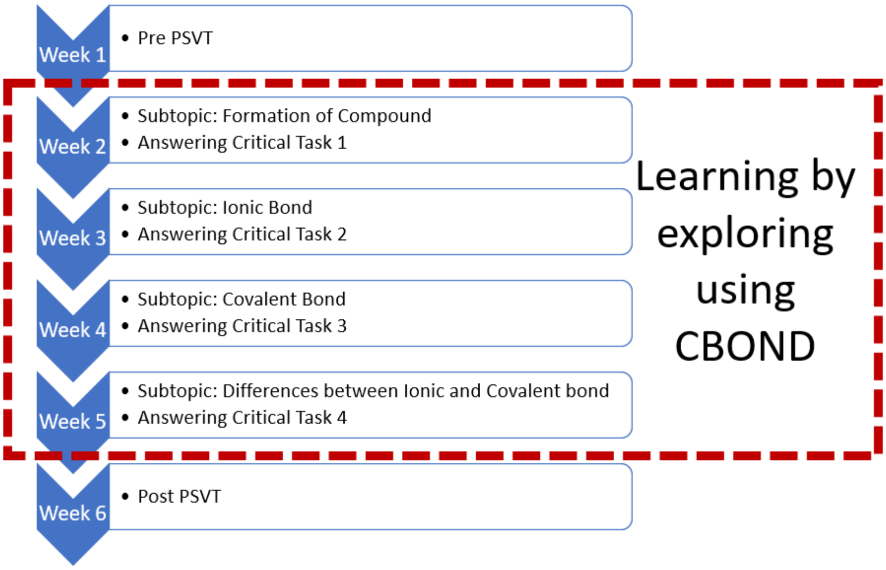


Fig. 1. Research procedure during the intervention

All participants were involved in the 4-week of teaching and learning using CBOND. Several activities required students to explore the CBOND application using the markers provided, as shown in Fig. 1. Besides the CBOND was integrated with simulation and audio to explain the concept.

3.2.1. CBOND – a mobile augmented reality application for learning chemical bond

The learning theories used as guidelines in designing CBOND for learning chemical bonds were the cognitive theory of multimedia learning (Mayer, 2005) and the principles for designing visualisation tools in Chemistry (Wu & Shah, 2004). CTML was used as the guideline to produce effective multimedia learning and the principles for designing visualisation tools in Chemistry (Wu & Shah, 2004) were used because it is focused on visualising the object specifically in Chemistry. In the implementation of CBOND in the classroom, a pre-test was conducted before students used CBOND and a post-test was conducted after students used CBOND. The test consisted of two tests which were the Purdue Spatial Visualisation Test (PSVT) to measure visualisation skills and the Chemical Bond Test to measure the students' knowledge and achievement. Before exploring CBOND, the students and teacher explained how to use the CBOND and the mini-book provided. The students were divided into four groups of four. The exploration using CBOND, and the class activity were conducted concurrently.

The software used to develop the CBOND is Unity, consisting of Unity3D Packages used to develop applications in MAR. The software is suitable for developing applications on multiple platforms such as PC, MAC, Android, and iOS. CBOND needed a visible marker to make the MAR display in 3D visual. This marker was provided on specific pages of the mini-book. This ensures that the student's learning process is systematic and follows the syllabus outlined in KSSM. Two pages were developed in the

CBOND Application: the 'Main' page and the 'Instructions' page. Another button included was the camera, which was utilised to scan the marker.

The mini-book was provided with the CBOND application. The mini-book acted as the guideline to ensure that the student's learning was systematic throughout the lesson. The flow of the content in the mini-book adhered to the KSSM syllabus set by the government. This may avoid confusion during the exploration process using CBOND. Several markers (refer to Fig. 2) were provided in the mini-book used during their learning using CBOND. Marker is needed when using CBOND because it is detected by the camera in order to display the virtual objects on the screen. Different markers displayed different representations on the screen. Therefore, the markers for each element and compound in chemical bonds were provided in the CBOND mini-book.

Fig. 2. The example of markers in CBOND for students' exploration

In the first week of treatment (Week 3), the teacher explained the whole process and the student's individual and team roles. The students were divided into groups of four and the groups were assigned based on their pre-test performance. Each week, the teacher started the class by introducing the subtopic to the students. The teacher gave the task and facilitated the learning process using CBOND. The exploration was guided by the mini-book provided for each group. In each session during the exploration using CBOND, students had the time to explore CBOND within the subtopic to manipulate and explore on their own freely.

Using the variety of markers, students are able to explore the formation of ionic bonds (Fig. 3) and covalent bonds (Fig. 4) during the teaching and learning process. This is an example of exploring activities amongst students using the CBOND.

Respective to Fig. 3, students are able to visualise how the Sodium (Na) transfers its one electron to Chlorine (CI) to become an octet. For covalent bonds (Fig. 4), students are able to see how the sharing of electrons occurred between two molecules of Chlorine (CI).

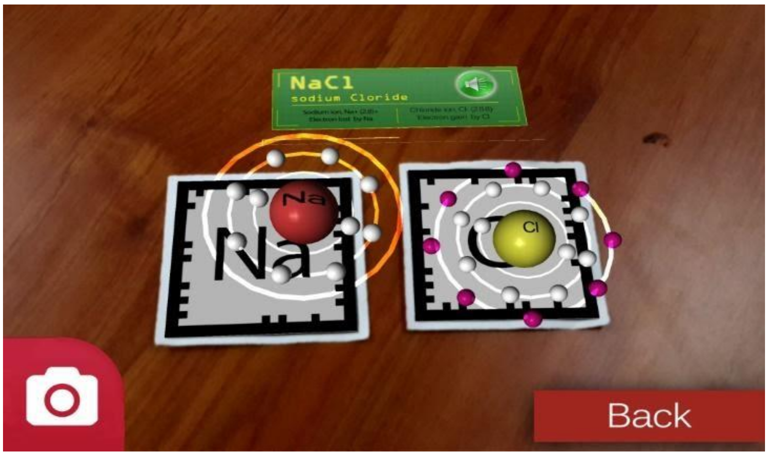


Fig. 3. Example of ionic bond formation (NaCI)

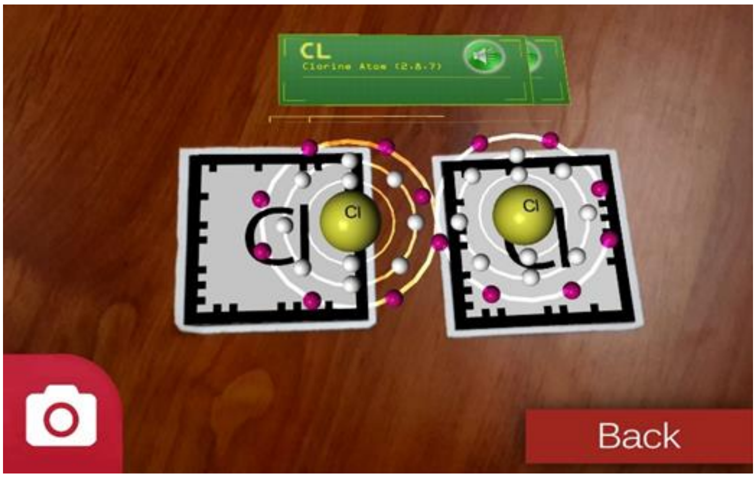


Fig. 4. Example of covalent bond formation (CI2)

3.2.2. Purdue spatial visualisation test (PSVT)

Mental rotation is defined by Sorby (2007) as a whole object that is being transformed while mental transformation involves the transformation of a part of the object. Two tests are conducted to investigate the level of visualisation skills of the students. The Purdue Spatial Visualisation Test (PSVT) includes PSVT: R for rotation and PSVT:D for development. According to Oliver-Hoyo and Babilonia-Rosa (2017), the most common test used in Chemistry education studies involves rotations like ROT or PSVT: R. This test was performed before and after they experienced learning using CBOND during the treatment phase. This is because the literature shows that MAR has great potential in visualisations. This opportunity is taken to maximise the advantages of MAR in visualisation in learning Chemistry because the abstract concepts in Chemistry require visualisation skills.

The visualisation test conducted during the pre-test and post-test was the PSVT test. PSVT: R was used to measure the ability of the students to rotate the mental image, while

PSVT:D was used to measure the ability of the students to develop the mental image. PSVT: R and PSVT:D consisted of 30 questions and the test were recorded as the findings of PSVT test. These questions were used before and after the treatment to determine the differences in the test scores after the students completed learning using CBOND. The test was conducted for 40 minutes before and after the treatment process of the research. PSVT was used because this test was common and was usually used to examine visualisation in Chemistry education (Wu & Shah, 2004).

3.2.3. Critical thinking tasks

The critical thinking task was conducted during the treatment process of the research. The critical thinking task was included after the students used the developed CBOND. The questions of the critical thinking task on chemical bonding were selected based on Bloom's Taxonomy from the collection of SPM questions. According to Bissell and Lemons (2006), the first basic category in the first two levels of Bloom's Taxonomy did not require critical thinking skills. This was also agreed by Crowe et al. (2017) as they mentioned that the first two levels did not require critical thinking and the level of critical thinking becomes higher from Level 3 to Level 6 in Bloom Taxonomy. This opinion is also supported by Swart et al. (2010), who mentioned that the critical thinking skills in Bloom's Taxonomy covered the level of applying, analysing, evaluating, and creating. Therefore, the selection of questions will be emphasised from Level 3 to Level 6.

The original version of Bloom's Taxonomy was developed by Benjamin Bloom (1956). However, Cochran et al. (2007) highlighted that Bloom's taxonomy should be updated to make it relevant to 21st-century practices. Therefore, the nouns were changed to verbs, while the two sequences of the two top levels in the original version of Bloom's Taxonomy by Benjamin Bloom (1956) were swapped in the revised version of Bloom's Taxonomy by Anderson and Krathwohl (2001). Therefore, the selected questions referred to the revised version of Bloom's Taxonomy by Anderson and Krathwohl (2001).

The Critical Thinking Task questions were designed based on Bloom's Taxonomy by Anderson and Krathwohl (2001). Therefore, the critical thinking task covered questions from Level 3 to Level 6, which were applying, analysing, evaluating, and creating. There were four questions for each Critical Thinking Task that were given to the students every week, covering Level 3, Level 4, Level 5, and Level 6 of Bloom's Taxonomy. The topics include the formation of compounds (Task 1), ionic bonds (Task 2), covalent bonds (Task 3) and differences between ionic and covalent bonds (Task 4). Each task consists of questions from each level of Understanding, Remembering, Applying, Analysing, Evaluating and Creating in revised Bloom's Taxonomy. Table 1 shows the example questions for each level of critical thinking.

Table 1 shows an example of critical thinking task questions. The alphabet shown as A, D and (d) in the table is the only example that can be anything related to the scope.

3.3. Data analysis

At this phase, all the data gathered from the PSVT test, and the four critical thinking tasks were collected to analyse. The details of each process or method conducted during this phase are discussed below.

Table 1
Example of question

<table>
<tr><th>Level</th><th>Example of critical thinking question</th></tr>
<tr><td>Level 1 (Understanding)</td><td>What is the type of bond for compound A?</td></tr>
<tr><td>Level 2 (Remembering)</td><td>List the properties of compound A?</td></tr>
<tr><td>Level 3 (Applying)</td><td>Next, please help Ali identify the name of the element and classify each element into two elements which are metal elements or non-metal elements by putting a cross (X) on the table below. Illustrate the electron arrangement of the covalent compounds.
<table>
<tr><th>Element</th><th>Name of the element</th></tr>
<tr><td>A</td><td></td></tr>
<tr><td>B</td><td></td></tr>
<tr><td>C</td><td></td></tr>
<tr><td>D</td><td></td></tr>
<tr><td>E</td><td></td></tr>
<tr><td>F</td><td></td></tr>
</table></td></tr>
<tr><td>Level 4 (Analysing)</td><td>Differentiate the differences between atom A and atom D in terms of their tendency to donate electrons.</td></tr>
<tr><td>Level 5 (Evaluating)</td><td>Explain and justify your answer to question (d).</td></tr>
<tr><td>Level 6 (Creating)</td><td>Write other examples of metal and non-metal elements that are not included in the table above and give the reason for your answer. Next, illustrate each of the elements that you stated. All answers must be filled in the table below.
<table>
<tr><th>Other examples</th><th>Metal</th><th>Non-Metal</th></tr>
<tr><td>Reasons:</td><td></td><td></td></tr>
<tr><td>Illustration:</td><td></td><td></td></tr>
</table></td></tr>
</table>

3.3.1. The effect of CBOND on students' visualisation skills

The visualisation test conducted during the pre-test and post-test was the PSVT test. This test was divided into PSVT:R and PSVT:D. PSVT:R was for rotation while PSVT:D was for development. PSVT:R was used to measure the ability of the students to rotate the mental image, while PSVT:D was used to measure the ability of the students to develop the mental image. PSVT:R and PSVT:D consisted of 30 questions. These questions were used before and after the treatment to determine the differences in the test scores after the students completed learning using CBOND. The test was conducted for 40 minutes before and after the treatment process of the research. PSVT was used because this test was common and was usually used to examine visualisation in Chemistry Education (Wu & Shah, 2004).

Based on the previous reliability reported by previous research, the reliability of the PSVT:R test was 0.771 and PSVT:D was 0.800 (Nordin & Saud, 2007) and PSVT:R test was 0.792 and PSVT:D was 0.783 (Rahman & Eliya, 2010). Table 2 shows the levels of visualisation based on students' scores, as suggested by Nordin and Saud (2007).

Table 2
The Levels of visualisation based on scores

Score	Level of visualisation
81-100	Excellent
61-80	Very good
41-60	Good
0-40	Weak

A simpler version by Rahman and Eliya (2010) was selected to measure the students' visualisation skills and prevent students from feeling bored when answering the question. According to Rahman and Eliya (2010), the value of the reliability of the instrument was high. The reliability will be low if the α value of the instruments is below 0.6 (Abu & Tasir, 2000). This is parallel with Cronbach's alpha scale by George and Mallery (2003). Ghazali (2016) said that the instruments are valid when higher reliability is attained. A higher reliability translated into a lower existence. A reliability test of the PSVT also has been conducted within the sample in this study. The results showed that PSVT:D has an α value of .872, PSVT:R has an α value of .737 and PSVT as a test has an α value of .898. This showed that the PSVT test is reliable to use.

3.3.2. The effect of CBOND on students' critical thinking skill

The content analysis was conducted to determine the effect of learning using CBOND on students' critical thinking skills. As mentioned before, the revised version of Bloom's Taxonomy proposed by Anderson and Krathwohl (2001) was used to design the questions for weekly critical thinking tasks. Table 3 illustrates the critical thinking levels and the example of students' ability to answer the questions. According to Anderson and Krathwohl (2001), levels 3 to 6 (Applying, Analysing, Evaluating and Creating) are the levels that students need to think critically when answering the questions. The critical thinking levels were measured based on students' scores for each type of question.

3.3.3. Prediction path of students' critical thinking to obtain high-level visualisation skills

The prediction model was developed by using a data mining technique named decision tree modelling by using a Random Tree classifier by WEKA software. The data used to develop the predictive model includes the students' scores in critical thinking level (Level 3 to 6) for all tasks and the post-test scores for visualisation level (PSVT). The accuracy of the generated classification tree results is 95%.

4. Results and discussions

4.1. The effect of CBOND on students' visualisation skills

Descriptive and inferential analysis was conducted to study the effect of CBOND on students' visualisation skills.

Table 3
Critical thinking levels in Bloom's Taxonomy and the student's ability to answer the questions

Critical thinking level		The student's ability to answer the questions
High critical thinking skills	Level 6 (Creating)	1. Recall or remember 2. Explain the information that has been stated 3. Apply it 4. Distinguish between different parts of the answer. 5. Justify 6. Create a new point of view.
Low critical thinking skills	Level 5 (Evaluating)	1. Recall or remember 2. Explain the information that has been stated 3. Apply it 4. Distinguish between different parts of the answer. 5. Justify
	Level 4 (Analysing)	1. Recall or remember 2. Explain the information that has been stated 3. Apply it 4. Distinguish between different parts of the answer.
	Level 3 (Applying)	1. Recall or remember 2. Explain the information that has been stated 3. Apply it
	Level 2 (Understanding)	1. Recall or remember 2. Explain the information that has been stated
	Level 1 (Remembering)	1. Recall or remember

4.1.1. Descriptive analysis

Table 4 shows the descriptive analysis obtained from the pre- and post-PSVT tests. PSVT test was given to students before and after the treatment, which is learning using CBOND. The scores before and after the treatment and the levels of visualisation for each student were recorded. The students were categorised based on their scores (Nordin & Saud, 2007) (refer to Table 4). Next, the bar graph in Fig. 5 compares each student's pre- and post-PSVT test scores.

4.1.2. Inferential analysis

Inferential analysis was conducted to determine the effect of learning using CBOND on students' visualisation skills. This inferential analysis was conducted to compare the means between the two variable groups which were pre-PSVT and post-PSVT. Wilcoxon Signed-Ranks Test was performed to compare the mean scores between both tests to determine the effects of CBOND on students' visualisation skills. The non-parametric test was performed as an alternative to the parametric test because the number of samples was insufficient to conduct the parametric test. Therefore, the following hypotheses were tested:

> ***H_0:*** There is no significant difference between the mean of the pre-PSVT test scores and the post-PSVT test scores.

H_1: There is a significant difference between the mean of the pre-PSVT test scores and the post-PSVT test scores.

Table 4
Scores (in %) of the students for pre- and post-PSVT tests and levels of visualisation skill

Students	Pre-test		Post-test	
	Score	Categorisation	Score	Categorisation
S1	27	Weak	40	Weak
S2	40	Weak	70	Good
S3	27	Weak	50	Good
S4	37	Weak	50	Good
S5	37	Weak	53	Good
S6	47	Good	60	Good
S7	63	Very good	80	Very good
S8	50	Good	63	Very good
S9	33	Weak	53	Good
S10	40	Weak	53	Good
S11	53	Good	60	Good
S12	40	Weak	57	Good
S13	27	Weak	27	Weak
S14	47	Good	57	Good
S15	47	Good	53	Good
S16	10	Weak	23	Weak
Mean	41.20		50.80	
Standard deviation	2.761		3.243	

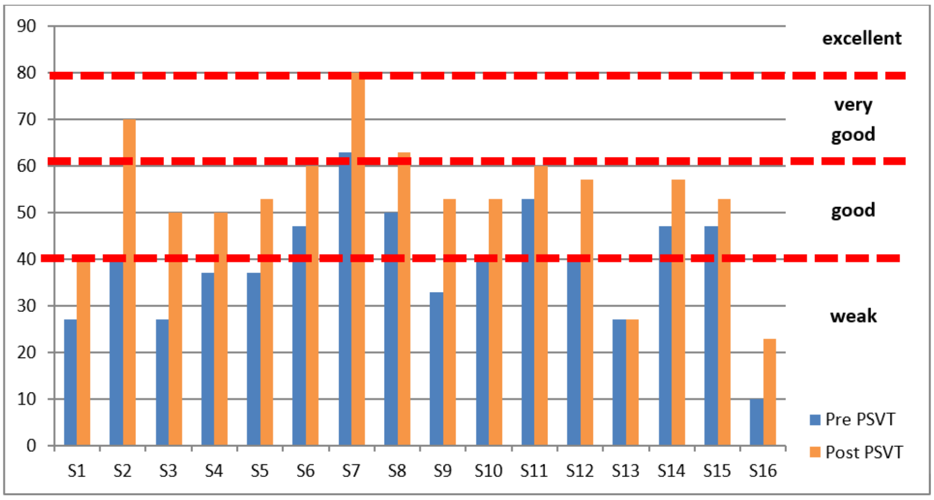


Fig. 5. Comparison of pre- and post-PSVT test scores

From the findings, none of the students scored lower than their pre-PSVT test scores in the post-PSVT. 14 students scored very high in their post-PSVT test as compared to their pre-PSVT test and 2 students scored the same in both pre- and post-PSVT tests. The significant value is .001, which was lower than the value of alpha of .05, and thus, Ho was rejected. This means that the pre-PSVT test scores had a significant difference from the post-PSVT test scores ($z = –3.313$, $p < .001$). This result shows that CBOND has a significant effect on improving the visualisation skills of students.

As mentioned in the literature review, augmented reality applications can facilitate students' spatial visualisation skills in education (Yuen et al., 2011). The findings supported the idea of students' improvement after learning using MAR based on a study done by Omar et al. (2019) in which the students in the experimental group displayed a greater level of visualisation skills in terms of mental rotation skills compared to students in the control group after learning in an orthographic projection classroom. The findings from this study are also in line with findings from Eh Phon et al. (2019a) which revealed that augmented reality could potentially enhance students' spatial visualisation ability. They found that an AR tool can help students visualise abstract science concepts such as the galaxy system (Eh Phon et al., 2019b). This can be attributed to AR applications facilitating abstract concepts' concretisation and improving students' understanding of the concepts and processes (Shelton & Hedley, 2002).

Therefore, CBOND helped them visualise the atoms or the formation of molecules that humans were unable to see with the naked eye. Wojciechowski and Cellary (2013) also stated that AR helped students visualise abstract concepts, especially when teaching objects and phenomena that are impossible to see with the naked eye. In addition, the AR environment implemented in CBOND allows the learning content to be presented meaningfully and improves practical skills. In this research, the principles by CTML (Mayer, 2005) and Principles for designing a visualising tool on Chemistry (Wu & Shah, 2004) were highlighted as they said that signalling principles or linked inferential is important. This is because a chemical bond involves the process of sharing, donating or receiving valence electrons. Students must have this basic conceptual understanding to understand more complicated content in other subtopics or topics. Therefore, the highlight or signalling may help them visualise the abstract concept of the atoms/molecules that were formed. This is supported by Cheng and Tsai (2013) in which an AR environment improves visualisation skills, practical skills, and conceptual understanding.

Roca-González et al. (2017) also found similar results. Their study shows that the visualisation skill scores of students in the experimental group trained with AR increased compared to the control group which had no significant effect. This is because when students are being trained to visualise, it will improve their visualisation skills. In research done by Gün and Atasoy (2017), there were positive responses from the students as most said that the 3D presentation by AR helps to visualise better than the 2D presentation on a board or notebook.

Students need to understand what it looks like by imagining the phenomenon. Visualisation skills are required to ensure the students understand what is happening between the atoms. This is because the formation is invisible to the human eye. Students need their visualisation skills to understand it well. Therefore, when students are asked difficult questions, they are able to answer the questions easily. CBOND is the tool that helps in visualising invisible things. Moreover, CBOND incorporates AR technology for learning chemical bonding to help students visualise abstract concepts.

Purdue Spatial Visualisation Test (PSVT) was used in this research to measure the students' visualisation skills and mental ability to visualise the outcomes. CBOND incorporated AR technology to prepare for the Chemical Bond Test; thus, AR helps students to visualise abstract concepts. These simultaneously will train the students and improve their ability to visualise. Although there are many available tests, the PSVT was found to be the most suitable for secondary students. The PSVT test concept was also similar when students did the rotation test since students had to visualise what would happen after the visual was rotated. In CBOND, students had to visualise the formation of the atoms. Both the PSVT test and the visualisation of CBOND are related.

4.2. The effect of CBOND on students' critical thinking

The critical thinking task was conducted weekly (week 1 until week 4) which consisted of critical thinking questions from Bloom's Taxonomy levels of applying, analysing, evaluating and creating. The tasks were designed differently according to the different sub-topics and were designed following the Malaysian National Curriculum which is called Standard Based Curriculum for Secondary Schools (KSSM) for chemical bonds topic.

4.2.1. Descriptive analysis

Table 5 reports that the mean score for Critical Thinking Task 1 was 72.75, and the standard deviation was 10.73. The mean score for Critical Thinking Task 2 was 73.625, and the standard deviation was 8.95. The mean scores for Critical Thinking Tasks 3 and 4 were 45.375 and 51.75, respectively, while the standard deviation for Critical Thinking Task 3 was 16.617 and Critical Thinking Task 4 was 9.875.

Table 5
Scores (in %) of critical thinking tasks for each student

Students	CT 1 score	CT 2 score	CT 3 score	CT 4 score
S1	68	72	56	50
S2	88	92	50	56
S3	84	72	76	60
S4	76	70	32	48
S5	70	80	50	32
S6	74	64	44	56
S7	84	68	40	56
S8	72	74	38	56
S9	60	64	50	60
S10	78	84	64	64
S11	66	76	34	52
S12	68	80	20	40
S13	58	72	24	30
S14	72	76	76	68
S15	92	80	42	38
S16	54	54	30	12
Mean	72.75	73.625	45.375	51.75
Standard deviation	10.73	8.95	16.6168	9.875

Note. CT = Critical thinking task.

The table also shows that the mean score increased from critical thinking task 1 to critical thinking task 2 by about .875. However, the score dropped in critical thinking task 3. The decreased score from critical thinking 2 was approximately 28.25, and critical thinking 4 showed an increment of a mean score of approximately 6.375. There were three students (S2 and S10) who achieved scores above the mean scores for all the critical thinking tasks. Two students (S13 and S16) scored below the mean score.

From Table 5, seven students scored better than the mean score, while nine scored lower than the mean score for CT1. The number increased in CT2, showing that eight students scored higher than the mean score for CT2. For CT3, the number of students who scored higher than the mean score was seven and the number of students who scored lower than the mean score was nine. However, the students scored higher than the mean score in CT4; nine students scored higher than the mean score and seven scored lower than the mean score.

Two students scored higher than the mean score for all the critical thinking tasks (S2 and S10) (refer to Table 5). Two students scored below the mean score for all the tasks (S13 and S16). The findings show no substantial differences in the number of students who scored higher or lower than the mean score, but most students scored well, with half scoring higher than the mean score for at least 2 of the critical thinking tasks. There were only two students who scored lower than the mean score for all the tasks. This finding also shows that in CT4, the number of students who scored more than the mean score was 9 which was greater than the number of students who scored lower than the mean score. However, it has to be pointed out that CT4 was the hardest task as the design of question CT4 consists of a higher level of questions as compared to CT1, CT2 or CT3.

As compared to the mean score, most students scored better in CT2 than in CT1. Most students' scores decreased in CT3 and increased again in CT4. CT4 scores obtained by the students were not as good as CT1 and CT2, but better than the scores in CT3. One of the reasons the scores decreased in CT3 was that the type of question asked in CT3 was experimental. This type of question requires the students to identify what elements were involved in the experiment and describe the characteristics of the elements and compounds involved. This is evidenced by Johnson (2002), who revealed that students have difficulties understanding what happens during the chemical reaction process in experiments. Besides that, students claimed that they had difficulties linking the chemical changes during experiments and with chemical reactions (Eilks et al., 2007). This is supported by Kurt and Ayas (2012), who agreed that the reaction rate involving chemical reactions is difficult to understand and apply in real life. However, it is different from CT1, CT and CT4 where the questions were more direct as they used analogies and real-life examples. These tasks tested the students based on what they had learned and understood when learning the topic. Students rarely made mistakes when answering these questions because they knew what they needed to answer.

The difficulty level of the syllabus can also affect students' critical thinking scores. In CT3 and CT4, the questions were more challenging towards the end of the syllabus. In CT4, students' mean score was better than CT3 but lower than CT1 and CT2 due to the question difficulty level factor. This is because CT4 questions were difficult as they covered the last part of the chemical bond topic. Students need to think more critically to apply what they learn to answer the questions. For example, questions in CT4 asked about the differences between both types of bonds rather than straightforward questions. S2 and S10 agreed on this as they indicated that CT1 and CT2 were easier compared to CT3 and CT4. As discussed earlier, the sequence of the content of the mini-book and CBOND referred to the KSSM syllabus. Therefore, the tasks were organised according to the difficulty level, from easy to hard. Hence, from Week 1 to Week 4, the difficulties of CT1-CT4 differed in terms of difficulty level. Therefore, this explains why the students' mean scores of CT3 and CT4 were lower than CT1 or CT2. This is important to consider the syllabus, which is another reason why the theory of cognitive theory of media learning (CTML) was taken into account by considering the students' cognitive load.

4.3. Analysis of each level of critical thinking

Furthermore, the process of developing critical thinking for each level of student learning using CBOND was also investigated. For this purpose, only four levels (applying, analysing, evaluating, creating) categorised by Anderson and Krathwohl (2001) which involved critical thinking when answering questions were chosen to be intensely analysed. Table 6 shows the analysis of students' answers to the weekly critical thinking tasks (CT1-CT4). The student's critical thinking skills were categorised as high if they scored higher than the mean score and categorised as low if they scored below the mean score. Below is the discussion of students' critical thinking process for each level.

4.3.1. Applying level

Fig. 6 illustrates the total number of students who scored above the mean score and lower than the mean score for applying level. Applying is the third level in the revised version of Bloom's Taxonomy which is the lowest level that needs critical thinking skills. For this level, the students needed to answer questions that required them to recall or remember the information and apply it in a new way. For example, the students must illustrate the answer in the critical thinking task. Most students scored higher than the mean score at the applying level, as shown in Fig. 6.

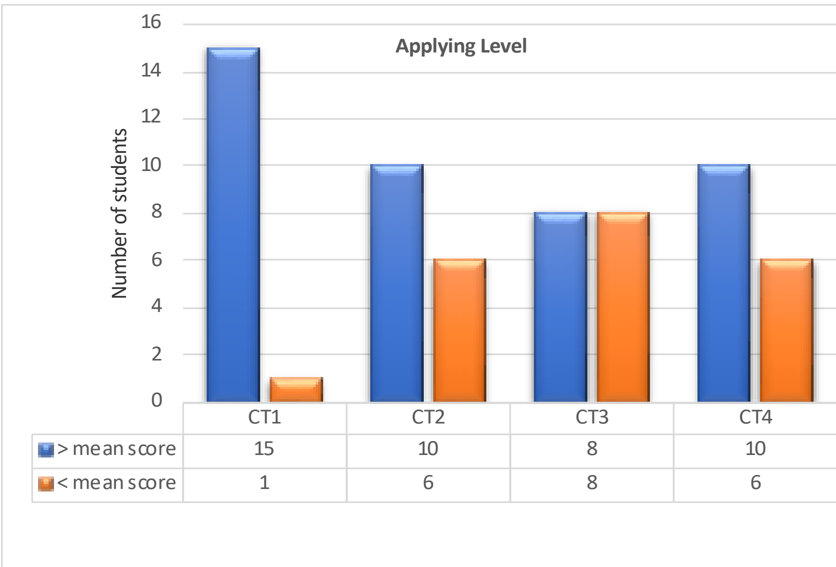


Fig. 6. Number of students' mean scores in applying level for the weekly critical thinking task

In CT1, only one student scored below the mean score (S1), while the other students obtained higher than the mean score. At the applying level (see Table 6), there were six students (S4, S7, S8, S9, S10, S14) in CT2, eight students (S1, S4, S6, S7, S11, S12, S13, S14) in CT3 and six students (S1, S4, S5, S8, S13, S16) in CT4 who scored below the mean score. Students mostly scored high in the applying level except in CT3, where the total number of students who scored higher and lower than the mean score was the same. The mean score value for CT3 also was the lowest compared to other Critical Thinking tasks.

Table 6
Analysis of the student's critical thinking task score (%) in the weekly critical thinking tasks

Students	Applying				Analysing				Evaluating				Creating			
	CT 1	CT 2	CT 3	CT 4	CT 1	CT 2	CT 3	CT 4	CT 1	CT 2	CT 3	CT 4	CT 1	CT 2	CT 3	CT 4
S1	92	100	67	50	100	100	50	20	50	0	17	50	36	88	86	63
S2	100	100	75	80	100	100	50	60	50	67	17	38	100	100	57	50
S3	100	100	83	80	100	100	83	20	67	67	50	63	71	38	86	63
S4	100	70	50	60	100	100	17	40	33	50	33	38	71	63	29	50
S5	100	100	75	40	75	100	50	40	33	100	17	50	71	38	57	0
S6	100	100	67	80	92	83	33	60	67	100	17	38	43	0	57	50
S7	100	60	67	80	100	75	50	20	67	67	0	63	71	69	43	50
S8	100	70	83	60	100	67	33	20	33	50	25	75	57	100	14	50
S9	100	60	83	80	100	50	50	40	0	100	8	63	43	50	57	50
S10	100	80	83	80	75	100	83	40	67	50	33	75	71	100	57	50
S11	100	100	67	80	75	100	50	20	17	100	8	100	71	25	14	0
S12	100	100	50	80	100	83	17	40	0	50	0	50	71	88	14	0
S13	100	100	67	60	75	100	33	20	0	50	0	44	57	50	0	0
S14	100	60	67	80	83	100	100	40	33	50	83	88	71	88	57	50
S15	100	100	83	80	100	100	50	40	67	50	25	44	100	75	14	0
S16	100	90	75	40	83	100	33	20	0	50	17	0	36	0	0	0
Mean	100	87	71	69	91	91	45	33	39	68	21	53	66	62	36	35

Note. CT = Critical thinking task

This revealed that students understand how to illustrate the atoms or molecules required by the critical thinking task questions. This is because most of the questions for the application level asked the students to make illustrations. Therefore, CBOND helps students in visualising atoms or molecules. This shows that CBOND also helps to improve students' understanding of the importance of basic concepts. This is because if the students fail to answer questions at the applying level, the tendency not to be able to answer questions at the upper level of critical thinking is high. In brief, the students can answer most questions at the applying level which required them to do illustrations as CBOND helped them improve their understanding by visualising atoms or molecules during the treatment. The principles in CTML (Mayer, 2005) and principles for designing visualising tools on Chemistry (Wu & Shah, 2004) helped in the representation of CBOND visualisation such as the consideration of spatial contiguity principle in CTML (Mayer, 2005) whereby words and pictures of visual were displayed simultaneously. This is because people learn better when corresponding words and pictures are presented near rather than far from each other on the page or screen.

4.3.2. Analysing level

Analysing level is the fourth level in the revised version of Bloom's Taxonomy. Students need to have extra skills compared to applying which the students need to distinguish different parts of the answers. Students needed to compare or distinguish what type of chemical bonds were involved in the questions. A similar result was obtained at the analysing level, in which most students scored higher scores than the mean score for the analysing level. Fig. 7 shows the number of students' mean scores in analysing level for each critical thinking task.

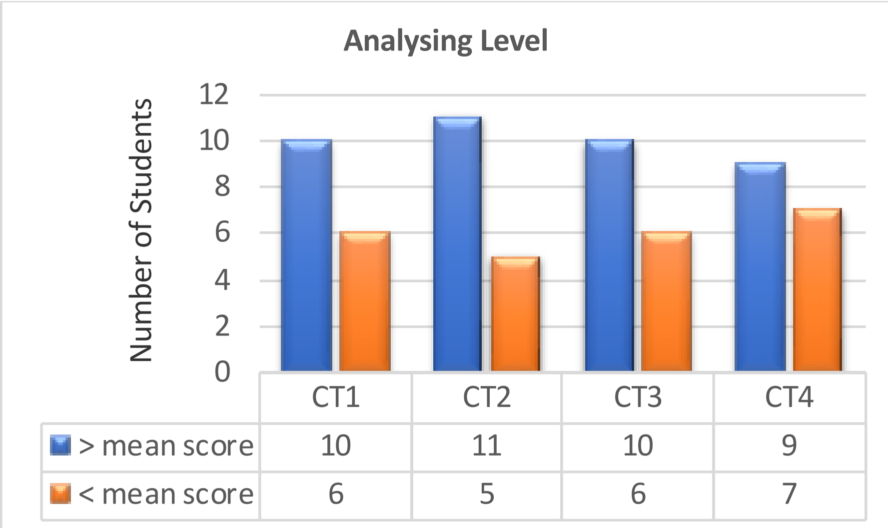


Fig. 7. Number of students' mean scores in analysing level for the weekly critical thinking task

Referring to Fig. 7, there were six students (S5, S11, S12, S13, S14, S16) in CT1, five students (S6, S7, S8, S9, S12) in CT2, six students (S4, S6, S8, S12, S13, S16) in CT3 and seven students (S1, S3, S7, S8, S11, S13, S16) in CT4 who scored below the mean score in the analysing level. Students mostly scored high at the analysing level. This level required students to differentiate the two types of bonds which were ionic and covalent. Therefore, when most students scored higher than the mean score, it shows that most of them were able to analyse the differences between the bonds. Students can differentiate the properties of each type of bond, how the bond was formed and what group of elements was involved in the formation of covalent bonds or ionic bonds. The chemical bond topic introduces the basic topic related to chemical bonds before the students learn more about it in the next topic. Students must know the reason for the formation of a compound. The students must know what atoms belong to what group or period. This is because the ionic bond is formed between a metal and a non-metal while a covalent bond is formed between two non-metal atoms. When the students can differentiate this, they will know what formation bond will be formed.

4.3.3. Evaluating level

The evaluating level is the fifth level in the revised version of Bloom's Taxonomy. At the evaluating level, students have to explain and justify their answers. In the assigned critical thinking task, students must justify the answers completely to attain full marks. For example, in the Critical Thinking Task, students have to justify why they chose ionic bond or covalent bond as the answer. Poor evaluating skills may contribute to marks. In contrast with applying and analysing levels, most students' evaluated level scores were below the mean scores. Fig. 8 presents the number of students' mean scores in evaluating level for each critical thinking task.

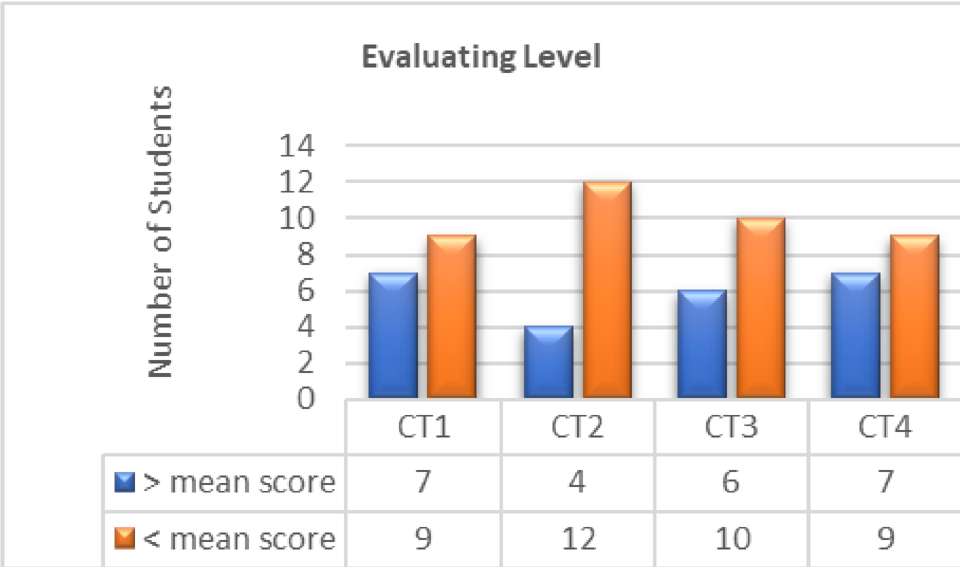


Fig. 8. Number of students' mean scores in evaluating level for the weekly critical thinking task

Fig. 8 shows that students CT3 scored very low in the evaluating level, where the mean score for the students was only 21 (refer to Table 6). The mean score value was the lowest as compared to all mean scores in all tasks. This may be due to the type of questions in CT3 which is the experimental type. The students were not able to evaluate their answers, especially when the questions were experiment-related. There were only 7 students (S1, S2, S3, S6, S7, S10, S15) in CT1, 4 students (S5, S6, S9, S11) in CT2 and 6 students (S3, S4, S8, S10, S14, S15) in CT3 and 7 students (S3, S7, S8, S9, S10, S11, S14) in CT4 who scored above the mean score. This demonstrates that most students have low skills at the evaluating level and are poor at evaluating their answers, especially when the questions are based on experiments. Students failed to score full marks because the students were not able to justify how the compound was formed.

However, many students could have performed better at the evaluating level which may also affect their creating skills. This may be attributed to the fact that students need to write justifications for their answers which contradicted Efe and Efe (2011). The findings reveal that students who were taught with the help of computer simulations made statistically significant improvements in their test scores at all levels of Bloom's taxonomy. However, in a study by Febrina et al. (2019), the evaluating level was the highest level included in the textbook compared to other levels. This is because evaluating is the main part of critical thinking that can generate and attract students to use all their mental processes optimally. Referring to the first Bloom's Taxonomy in 1956 by Dr Benjamin Bloom, the evaluating level was the highest in Bloom's Taxonomy. This indicates that the evaluating level was one of the highest levels of critical thinking.

4.3.4. Creating level

Creating level is the highest level in the revised Bloom's Taxonomy. To achieve this level, students need to create a new product or point of view. In this Critical Thinking Task, students have to create a new molecule based on their knowledge of chemical bonds. They also need to explain how the molecules or compounds were formed. Fig. 9 illustrates the number of students' mean scores in creating a level for each critical thinking task.

Fig. 9. Number of students' mean scores in evaluating level for the weekly critical thinking task

CT4 reported the lowest mean score in the creating level was 35 and was followed by CT3 36, CT2 62 and CT1 66 (refer to Table 6). This is because the creating level in the CT4 was hard. There were six students (S1, S6, S8, S9, S13, S14) in CT1, seven students (S3, S5, S6, S9, S11, S13, S16) in CT2 and seven students (S4, S8, S11, S12, S13, S15, S16) in CT3 and six students (S3, S5, S6, S9, S11, S13, S16) who scored below the mean scores.

At the creating level, the questions required students to think of other molecules or atoms similar to what was asked in the questions. Students needed to understand what they had learned to provide new examples. Besides that, the students needed to evaluate their answers at the creating level, for which the students needed to give reasons for their answers. Therefore, the score of each critical thinking task for the creating level shows that the mean score decreased from CT1 to CT4. However, the number of students who scored higher than the mean score for each task was greater than the students who scored lower than the mean score. This shows that the students' creating skills were good because most students scored higher than the mean score. Students also scored well when answering questions at the creating level. Creating level is the highest level in the revised Bloom's Taxonomy. Similar findings can be observed in Crowe et al. (2017) in which they found that the criteria requiring the most complex thinking skills show the most dramatic improvement in results. There was a significant increase in students' ability to interpret data and design their hypotheses which are the required skills for analysing and creating Bloom's levels.

To sum up, most students were able to think critically when answering the tasks. This shows that the students improved their critical thinking skills, especially the lowest level of critical thinking. This shows that CBOND helped in improving students' understanding of chemical bonds and their critical thinking skills. Students were mostly able to answer questions well in applying, analysing, and creating levels but not in the evaluating level. Previous studies have also reported that the use of technology can help students develop thinking and interpretation skills, resulting in them developing higher-order thinking skills (Efe & Efe, 2011). The findings demonstrated that CBOND also helped improve students' understanding of basic concepts, which is important because if the students fail to answer questions at the applying level, the tendency of students to not answer questions in the upper level of critical thinking becomes higher. This is supported by Talanquer (2018), who said that it is difficult for students to understand the relationship between topics in Chemistry, where students need to have a basic understanding and need to relate ideas to the topic. Moreover, learning the concepts in Chemistry depends on students' understanding of the fundamental ideas at the analysis level which presents students with materials (or asks them to locate materials), then asks questions or presents problems with answers that require them to differentiate or organise some parts appropriately.

4.3.5. Findings from two high-performing students in critical thinking development

Of all 16 students, S2 and S10 were observed to have scored higher marks than the mean score for most critical thinking tasks, especially at the creating level, which was the highest level in Bloom Taxonomy. Table 7 demonstrated that S2 scored high for most critical thinking levels (applying, analysing, creating) except in the evaluating level in CT3 and CT4 tasks. This may be due to the question's difficulty and the need for more skills in evaluation. From S2 answers' in CT3 and CT4 at the evaluating level, S2 did not provide enough information for the answer. As a result, S2 did not score full marks for the evaluating level. However, S2 scored higher than the mean score in the creating level, which was the highest level of critical thinking.

Table 7
S2's score for each critical thinking level in the critical thinking task

	CT1	CT2	CT3	CT4
Applying	100, High	100, High	75, High	80, High
Analysing	100, High	100, High	50, High	60, High
Evaluating	50, High	100, High	17, Low	38, Low
Creating	100, High	100, High	57, High	50, High

Note. High = above the mean score, Low = below the mean score

A similar scenario was reported by S10, who also scored higher than the mean score at the creating level. In contrast, S10 obtained low scores in the applying and evaluating levels in CT2 and the analysing level in CT1. Students needed to differentiate between two atoms in terms of their tendency to donate or accept electrons, but S10 only stated the answers without differentiating the atom. Therefore, S10 cannot obtain full marks for the analysing level of CT1. Overall, the S10's critical thinking skill achievement was considered high because S10 scored high for each critical thinking level.

Table 8
S10's score for each critical thinking level in the critical thinking task

	CT1	CT2	CT3	CT4
Applying	100, High	80, Low	83, High	80, High
Analysing	75, Low	100, High	83, High	40, High
Evaluating	67, High	50, Low	33, High	75, High
Creating	71, High	100, High	57, High	50, High

Note. High = above the mean score, Low = below the mean score

S13 and S16 were also chosen as they were weak in answering the questions in the higher levels of critical thinking for all tasks (refer to Table 6) which is elaborated on in the next section.

4.3.6. Findings for two low-performing students in critical thinking development

In contrast to S2 and S10, another significant finding was observed for S13 and S16 (refer to Table 9 and Table 10) as S13 and S16 scored low for most of the CT tasks. The students could not answer higher-level questions that were analysing, evaluating, and creating. Applying level was the only level that both students could answer. Referring to the answers of S13 and S16 on all the tasks, the results show the students know how to draw or state the type of bond, but when evaluating the answers, they failed to give the correct answers. These results deduce that both students understood the basics of the topic but needed to gain the necessary skills for analysing when there are many atoms involved. The students also lack the evaluating and creating skills needed to develop a strong understanding of the differences between the bonds and atoms. When the students do not fully understand the topics, the students are unable to provide the appropriate explanation or example for the questions.

Table 9
S13's score for each critical thinking level in the critical thinking task

	CT1	CT2	CT3	CT4
Applying	100, High	100, High	67, Low	60, Low
Analysing	75, Low	100, High	33, Low	20, Low
Evaluating	0, Low	50, Low	0, Low	44, Low
Creating	57, Low	50, Low	0, Low	0, Low

Note. High = above the mean score, Low = below the mean score

S2 and S10 scored higher marks than the mean score for most levels in the critical thinking tasks. Out of four tasks, S2 scored one task lower than the mean scores for evaluating in CT3 and evaluating in CT4. S10 obtained low scores in the applying and analysing levels in CT1 and evaluating levels in CT2. This shows that these two students experienced difficulties in answering evaluating questions. Overall, S2 and S10's critical thinking skill achievement can be considered high because the students mostly scored high for the entire critical thinking task. S2 and S10 demonstrated good level visualisation skills. From S2 answers' in CT3 and CT4 on evaluating level part of questions, S2 did not provide sufficient information for the answer. As a result, S2 did not score full marks for the evaluating level. However, S2 was able to score higher than the mean score in the creating level which was the highest level of critical thinking.

Table 10
S16's score for each critical thinking level in the critical thinking task

	CT1	CT2	CT3	CT4
Applying	100, High	90, High	75, High	40, Low
Analysing	85, Low	100, High	33, Low	20, Low
Evaluating	0, Low	50, Low	17, Low	0, Low
Creating	36, Low	0, Low	0, Low	0, Low

Note. High = above the mean score, Low = below the mean score

Other than improving the student's visualisation like CBOND did, other dimensions like scaffolding are also needed to spark students' ability to think critically and provide complete answers when the students answer questions that need to be evaluated. Besides, the students need more practice, especially in experiment questions. This is because most of them could not answer well when the questions were twisted. S10 obtained low scores in the applying and evaluating levels in CT2 and analysing levels in CT1. Students need to differentiate between the two atoms in their tendency to donate or accept an electron, but S10 only states the answers without differentiating the atoms. Therefore, S10 could not obtain full marks for the analysing level in CT1. Overall, the student S10's critical thinking skill achievement can be considered high because S10 mostly scored high for each critical thinking level.

S13 and S16 scored low for most of the tasks. The students were mostly unable to answer the higher levels which were analysing, evaluating, and creating. Applying level was the only level that both students could answer well. This is because CBOND that was applied in their learning helped improve their understanding and their applying skills. This is because most of the applying level in the topic needed them to draw which was related to the CBOND used. However, this is a good sign as the weaker studies are now able to improve their applying skills and basic understanding of the topics. Both S13 and S16 students were students with weak visualisation levels. A higher level of critical thinking skills like evaluating needs time to improve. Although S13 and S16 scored lower than the mean scores for evaluating and creating levels of critical thinking, the improvement in the applying and analysing should be considered because it will then help the students to improve other higher levels.

Based on S13 and S16's answers on all the tasks, the results showed the students know how to draw or state the type of bond. However, when it comes to evaluating the answers, both students failed to give the correct answers. In conclusion, the answers revealed that students understood the basics of the topic but lacked skills on how to analyse when there are many atoms involved. Besides, the students also lack the evaluating and creating skills needed to fully understand the differences between the bonds and atoms. More learning time is needed with CBOND to help them improve their analysing and creating skills. When the students do not fully understand the topics, the students cannot provide the appropriate explanation or example for the questions. This is why both students cannot answer the evaluating and creating level questions well.

In conclusion, CBOND helped in improving the development of critical thinking skills among the students. This can be deduced from the findings as most students scored higher than the mean scores for applying, analysing, and creating levels. Students were found to have low evaluating skills, as most scored lower than the mean scores. The positive development of the student's critical thinking was considered a great achievement because most students can answer the higher level of critical thinking which was the creating level. Therefore, critical thinking skills should be improved from time to time.

4.4. The prediction path of students' critical thinking level to obtain high-level visualisation skills

For the last research question, the path of students' critical thinking level to obtain high-level visualisation skills was developed using a data mining technique which is a decision tree modelling using a Random Tree classifier by WEKA software. Fig. 10 shows the decision tree analysis of students with different levels of visualisation and critical thinking.

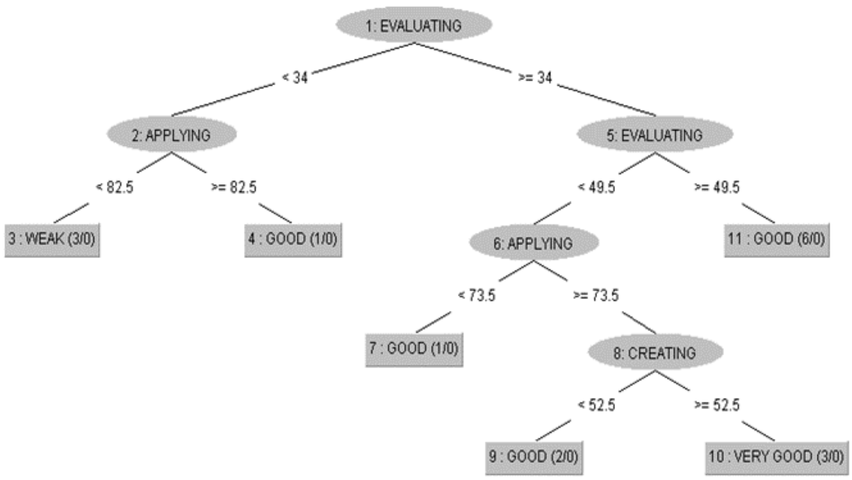


Fig. 10. Decision tree analysis for students with different levels of visualization and critical thinking task

Fig. 10 illustrates the model derived from several pathways to achieve the very good, good and weak visualisation levels. A total of 11 nodes (rectangle and oval shapes) were derived from the model and the three leaf nodes (rectangle) were good, weak, very good) indicated the students' level of visualisation. The bracket beside (X, X) of the visualisation level indicated the number of students' classification, followed by how many students were incorrectly classified. From the output, no students were incorrectly classified. The number of learning paths derived from the model is shown in Table 9. There were three visualisation levels which were very good, good, and weak.

In Table 11, there were three visualisation levels involved for the sample, which were very good, good, and weak. There was one learning path for very good, four for good and one for weak. The detailed information on each path was shown in the table, which consisted of additional information on the number of students on each path and the path involved.

A total of three students had a very good level of visualisation, one student had a good level for the first path, six students for the second path, one student for the third path and two students with a good level of visualisation for the fourth path. Last but not least, three students had a weak level of visualisation. The students with weak visualisation level may improve to good or very good visualisation levels. There is one path for the students to improve to a very good visualisation level and four paths for the students to improve to a good visualisation level. In order for the students to improve from weak to very good visualisation level, the students have to score at least 34 marks or higher for evaluating questions, at least or greater than 73.5 marks for applying questions and at least or greater than 52.5 marks for creating questions.

Table 11
Details of the path for each visualisation level

Level of visualisation	Number of paths	Number of students	Path	The decision tree prediction
Very good	1	3 (S2, S7, S8)	Evaluating → Applying → Creating	The decision tree predicts that the learning pathway for students with very good visualisation level is as: • Students that score equal to or more than 34 marks for evaluating level. • Students that score equal to or more than 73.5 marks for applying level. • Students that score equal or more than 52.5 marks for creating level.
Good	1	1 (S12)	Evaluating → Applying	The decision tree predicts that the learning pathway for students with good visualisation level is as: • Students that score less than 34 marks for evaluating level. • Students that score equal or more 82.5 marks for applying level.
	2	6(S3, S5, S6, S10, S11, S14)	Evaluating → Evaluating →	The decision tree predicts that the learning pathway for students with good visualisation level is as: • Students that score equal to or more than 34 marks for evaluating level. • Students that score equal to or more than 49.5 marks for evaluating level.
	3	1(S4)	Evaluating → Evaluating → Applying	The decision tree predicts that the learning pathway for students with good visualisation level is as: • Students that score equal to or more than 34 marks for evaluating level. • Students that score less than 49.5 marks for evaluating level. • Students that score less than 73.5 marks for applying level.
	4	2 (S9, S15)	Evaluating → Evaluating → Applying → Creating	The decision tree predicts that the learning pathway for students with good visualisation level is as: • Students that score equal to or more than 34 marks for evaluating level. • Students that score less than 49.5 marks for evaluating level. • Students that score less than equal or more than 73.5 marks for applying level. • Students that score less than equal or more than 52.5 marks for creating level.
Weak	1	3(S1, S13, S16)	Evaluating → Applying	The decision tree predicts that the learning pathway for students with weak visualisation level is as: • Students that score less than 34 marks for evaluating level. • Students that score less than 82.5 marks for applying level.

Four paths can be used as guidelines for teachers to improve from weak to good visualisation level. The first path was if the students' score was below 34 marks in the evaluating level; thus, the applying level of the students must be at least or greater than 82.5 marks for students to shift from weak to good visualisation level. The second path that can be followed for the students to improve to a good visualisation level is that the students have to score at least 49.5 marks or higher for the evaluating level. For the third path, if the students score at least 34 marks or higher but lower than 49.5 marks for evaluating the type of questions, the students can achieve a good visualisation level but if the students' applying level is below 73.5 marks, students may only progress to the good visualisation level. If the students can score at least 73.5 marks or higher in the applying level, the students may improve to a very good visualisation level if the students score at least 52.5 marks or higher in the creating level but if the students score below, the students will only improve to the good visualisation level.

For students with a good visualisation level and want to improve to a very good level of visualisation, there is one path to be followed whereby the students have to score at least 34 marks or higher for evaluating level type of questions, at least 73.5 marks or higher for applying level type of questions and at least 52.5 marks or higher for the creating level type of questions. The decision tree also shows that the evaluating level is on the top of the tree structure which indicates that the evaluating level has a strong relationship with visualisation skills. Besides, it also shows that the creating level is the critical thinking level that will determine the students to possess either good or very good visualisation level.

In conclusion, the evaluating level is the level that exerted the most significant influence on students' visualisation skills. In addition, for students to achieve a very good visualisation level, they should score well in the highest level of skills in Bloom's taxonomy which is the creating level. Fig. 11 was drawn to illustrate the predicted paths for students to improve visualisation skills and critical thinking levels. Several paths can be used as guidelines for students with weak or good visualisation skills to improve the students' visualisation skills and critical thinking level.

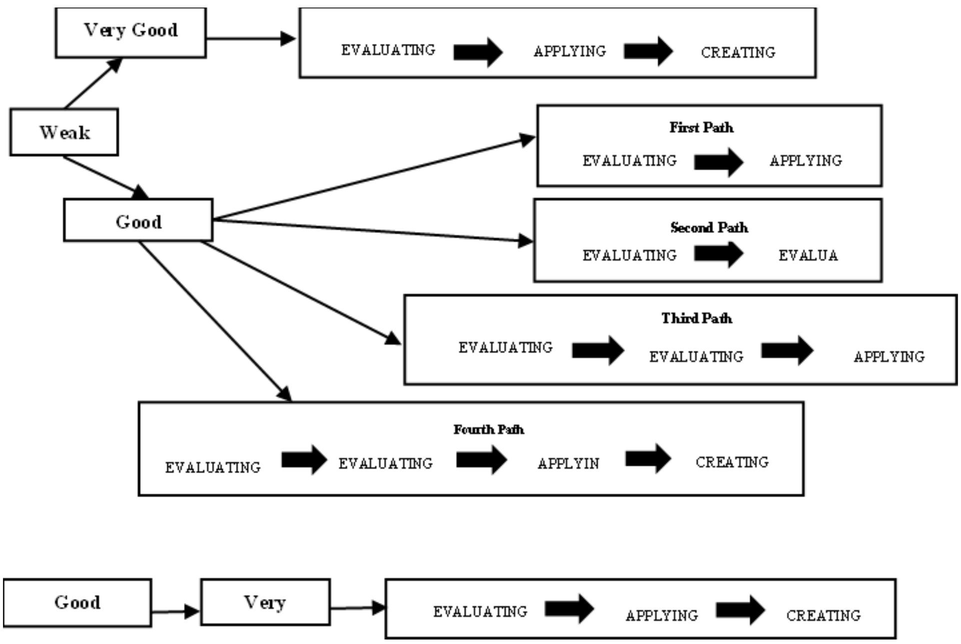


Fig. 11. Predicted paths for students to improve visualisation skills and critical thinking level

The model obtained a few paths to achieve very good, good, and weak levels of visualisation. A total of 11 nodes (rectangle and oval shapes) from the model and 3-leaf nodes (rectangle) were good, weak, very good), indicating the students' levels of visualisation. In the parentheses next to (X, X), the level of visualisation is the number of students classified in the level followed by how many students are incorrectly classified. The findings show that there were no students were incorrectly classified. The total number of the learning paths derived from the predictive model showed three visualisation levels: very good, good and weak. There was one learning path for very good, four learning paths for good and 1 learning path for weak. There were three students (S2, S7 and S8) who had very good visualisation levels with one prediction path. 14 students had good visualisation levels with four different paths. The first path consisted of only one student (S12), the second path consisted of six students (S3, S5, S6, S10, S11 and S14), the third path consisted of one student (S4), and the fourth path consisted of two students (S9 and S15). Only one path was derived for this category with three students (S1, S13, and S16) for weak visualisation levels. All six predictive paths in Table 9 showed that the students could improve the visualisation level to very good.

For students who intend to improve from weak to very good visualisation level, the students had to score at least 34 marks or higher at the evaluating level, at least 73.5 marks or higher at the applying level and at least 52.5 marks or higher at the creating level. For students to improve from weak to good visualisation levels, four paths need to be followed. The first path was that the students needed to score below 34 marks at the evaluating level, causing the applying level to be at least 82.5 or higher marks. The second path that the students can follow to improve their visualisation level to good is that they have to score at least 49.5 marks or higher at the evaluating level.

Next, if the students' applying level score was below 73.5 marks, the students can only improve to good visualisation. If the students can score at least or greater than 73.5 marks at the applying level, and at least and greater than 52.5 marks at the creating level, the students tend to improve to a very good visualisation level. If the students scored lower than 52.5 marks at the creating level, the students would only improve to the good visualisation level. Apart from that, the students with good visualisation level can improve to a very good visualisation level if they follow one path that they need to score at least 34 marks or higher at the evaluating level, at least 73.5 marks or higher at the applying level, at least 52.5 marks or higher at creating level. For the students with a good visualisation level who intend to improve to a very good visualisation level, there is one path to be followed. The students have to score at least 34 marks or higher at the evaluating level, at least 73.5 marks or higher at the applying level and at least 52.5 marks or higher at the creating level.

The findings showed that students had different learning methods and preferences depending on their abilities (Strijbos et al., 2004). The findings on the prediction path for students with weak, good, and very good visualisation levels can be improved together with their critical thinking skills. These prediction paths could be one of the references to improve students' visualisation and critical thinking skills when using CBOND or specifically AR technology to learn chemical bonds or other subjects requiring visualisation. Although AR has proven to have a positive effect on students' learning (Akçayır & Akçayır, 2017; Aziz et al., 2012; Chen et al., 2017), the framework or references should still be referred to because learning with AR without any guidance will not exert much impact to students' learning.

CBOND or any AR cannot improve visualisation and critical thinking alone. Proper development and principles must be applied to ensure that the AR environment can create meaningful learning (Saidin et al., 2019). Besides that, these prediction paths and findings can help other researchers or teachers when using AR as a tool to improve the students' learning, critical thinking, and visualisation skills. In addition, the decision tree (Fig. 11) also revealed that the evaluating level is the top of the tree structure. This indicates that evaluating is the critical thinking level strongly related to visualisation skills. This also shows that creating is the critical thinking level that will determine whether students have good or very good visualisation.

In short, the evaluating level is the critical thinking level that influences the students' visualisation skills the most. In order for students to achieve a very good visualisation level, they should score well at the creating level as it is at the highest level in the revised Bloom's Taxonomy (Anderson & Krathwohl, 2001). The predicted paths are beneficial for students or teachers to understand what kind of critical thinking skills need to be improved to enhance visualisation skills. This will then improve students' understanding of the topic of chemical bonds or other topics or subjects that require students to have good visualisation skills. For better illustration, Fig. 11 simplified the predicted paths for students to improve visualisation skills and critical thinking proficiency.

5. Conclusion

In conclusion, CBOND which implements AR technology was developed to investigate its effects on students' visualisation skills and critical thinking levels. Prediction paths for students to improve visualisation skills and critical thinking levels were also identified. The paths were found to help improve students' visualisation and critical thinking skills depending on their visualisation skills differences.

The developed CBOND showed a positive impact on students' visualisation skills. This was because most students' visualisation levels improved towards the end of the treatment. Other than that, for the weekly task on critical thinking, the students were found to score higher than the mean score for at least two out of four tasks given. The students were found to have difficulties in scoring the questions involving experimental questions. However, if looking at details about the students' critical thinking development, the students were found to have difficulties scoring the questions at the evaluating level, but the students could score well at the creating level. This showed how useful CBOND is in helping to improve the student's critical thinking skills. The predicted path was developed to help learners improve their visualisation skills. Learners could follow the appropriate path that fits their context to obtain a high visualisation level.

This study gave implications in educational practices to teachers or trainers. The positive findings showed teachers the AR potential in their teaching. Teachers can simplify their teaching techniques by applying more fun technology and practising active participation. Besides, the framework to improve students' visualisation and critical thinking skills also could be a guideline to teachers, trainers, or researchers when they want to improve visualisation and critical thinking skills. They can follow the path in the framework depending on the student's level of visualisation skills. The collaborative learning strategies (adapted from Lee et al. 2004) can be referred to make the collaboration of students during the learning more efficient. Besides, the use of AR technology will help students to understand and teach in conveying the lessons. Instead of teaching using static visuals, a teacher now can try using AR technology that is more fun in class. Other than that, this research also identified the relationship amongst the variables in the research, which shows the important variables to improve other variables. This can also be the teacher's guideline if they want to teach chemical bond topics using AR in class. Besides, using the critical thinking task that referred to the level of Bloom's Taxonomy enhances the student's critical thinking and gives the teachers many benefits when they want to teach chemical bonds.

Author Statement

The authors declare that there is no conflict of interest.

Acknowledgements

The authors would like to thank Universiti Teknologi Malaysia and Ministry of Higher Education Malaysia for their support in making this project possible. This work was supported by the Research University Grant (Q.J130000.2531.16H59) initiated by Universiti Teknologi Malaysia and Ministry of Higher Education. Additionally, the authors express gratitude to Mybrain15 for the scholarship support that has significantly contributed to the successful completion of this endeavor.

ORCID

Nor Farhah Saidin https://orcid.org/0000-0003-3640-9724

Noor Dayana Abd Halim https://orcid.org/0000-0003-3707-767X

Noraffandy Yahaya https://orcid.org/0000-0002-7952-5461

Nurul Nadwa Zulkifli https://orcid.org/0000-0002-2232-3885

References

Abu, M. S., & Tasir, Z. (2000). *Pengenalan kepada analisis data berkomputer: SPSS 10.0 for windows*. Venton Publishing.

Akçayır, M., & Akçayır, G. (2017). Advantages and challenges associated with augmented reality for education: A systematic review of the literature. *Educational Research Review, 20*, 1–11. https://doi.org/10.1016/j.edurev.2016.11.002

Al-Balushi, S. M., Al-Musawi, A. S., Ambusaidi, A. K., & Al-Hajri, F. H. (2017). The effectiveness of interacting with scientific animations in Chemistry using mobile devices on grade 12 students' spatial ability and scientific reasoning skills. *Journal of Science Education and Technology, 26*(1), 70–81. https://doi.org/10.1007/s10956-016-9652-2

Anderson, L. W. & Krathwohl, D. R. (2001). *A taxonomy for learning, teaching, and assessing: A revision of Bloom's taxonomy of educational objectives*. Longman.

Ayob, N. F. S., Halim, N. D. A., Zulkifli, N. N., Zaid, N. M., & Mokhtar, M. (2019). Overview of blended learning: The effect of station rotation model on students' achievement. *Journal of Critical Reviews, 7(6)*, 320–326. Retrieved from http://eprints.utm.my/92585/1/NoorDayanaAbd2020_OverviewofBlendedLearningtheEffect.pdf

Aziz, K. A., Aziz, N. A. A., Yusof, A. M., & Paul, A. (2012). Potential for providing augmented reality elements in special education via cloud computing. *Procedia Engineering, 41*, 333–339. https://doi.org/10.1016/j.proeng.2012.07.181

Bakar, M. N., & Ayob, N. A. (2010). Masalah pembelajaran mengenai topik ikatan kimia dalam konteks penyelesaian masalah di kalangan pelajar Tingkatan Empat. Retrieved from http://eprints.utm.my/11556/1/Masalah_Pembelajaran_Mengenai_Topik_Ikatan_Kimia_Dalam_Konteks_Penyelesaian_Masalah_Di_Kalangan_Pelajar_Tingkatan_Empat.pdf

Becker, S. A., Brown, M., Dahlstrom, E., Davis, A., DePaul, K., Diaz, V., & Pomerantz, J. (2018). *NMC horizon report: 2018 higher education edition*. EDUCAUSE. Retrieved from https://library.educause.edu/~/media/files/library/2018/8/2018horizonreport.pdf

Bissell, A. N., & Lemons, P. P. (2006). A new method for assessing critical thinking in the classroom. *BioScience, 56*(1), 66–72. https://doi.org/10.1641/0006-3568(2006)056[0066:ANMFAC]2.0.CO;2

Botella, F., Peñalver, A., & Borrás, F. (2018, September). Evaluating the usability and acceptance of an AR app in learning Chemistry for secondary education. In *Proceedings of the XIX International Conference on Human Computer Interaction (Interacción '18)*. https://doi.org/10.1145/3233824.3233838

Borycki, E. M., & Kushniruk, A. W. (2021). Editorial: Knowledge management and e-learning: Improving the safety of technologies and devices. *Knowledge Management & E-Learning, 13*(4), 390–394. https://doi.org/10.34105/j.kmel.2021.13.020

Buchner, J., & Jeghiazaryan, A. (2020, June). Work-in-progress – The ARI^{2}VE model for augmented reality books. In *Proceedings of the 2020 6th International Conference of the Immersive Learning Research Network (iLRN)* (pp 287–290). IEEE. https://doi.org/10.23919/iLRN47897.2020.9155110

Burton, E. P., Frazier, W., Annetta, L., Lamb, R., Cheng, R., & Chmiel, M. (2011). Modeling augmented reality games with preservice elementary and secondary science teachers. *Journal of Technology and Teacher Education, 19*(3), 303–329. Retrieved from https://www.learntechlib.org/primary/p/37136/

Cerqueira, C., & Kirner, C. (2012). Developing educational applications with a non-programming augmented reality authoring tool. In T. Amiel & B. Wilson (Eds.), *Proceedings of the EdMedia 2012 – World Conference on Educational Media and Technology* (pp. 2816–2825). Association for the Advancement of Computing in Education. Retrieved from https://www.learntechlib.org/primary/p/41166/

Chen, P., Liu, X., Cheng, W., & Huang, R. (2017). A review of using augmented reality in education from 2011 to 2016. In E. Popescu et al. (Eds.), *Innovations in Smart Learning* (pp. 13–18). Springer. https://doi.org/10.1007/978-981-10-2419-1_2

Cheng, K. H., & Tsai, C. C. (2013). Affordances of augmented reality in science learning: Suggestions for future research. *Journal of Science Education and Technology, 22*(4), 449–462. http://doi.org/10.1007/s10956-012-9405-9

Çoban, M., Akçay, N. O., & Çelik, İ. (2022). Using virtual reality technologies in STEM education: ICT pre-service teachers' perceptions. *Knowledge Management & E-Learning, 14*(3), 269–285. https://doi.org/10.34105/j.kmel.2022.14.015

Cochran, D., Conklin, J., & Modin, S. (2007). A new bloom: Transforming learning. *Learning & Leading with Technology, 34*(5), 22–25. Retrieved from https://files.eric.ed.gov/fulltext/EJ779824.pdf

Cook, M. P. (2006). Visual representations in science education: The influence of prior knowledge and cognitive load theory on instructional design principles. *Science Education, 90*(6), 1073–1091. https://doi.org/10.1002/sce.20164

Crompton, H., Burke, D., Gregory, K. H., & Gräbe, C. (2016). The use of mobile learning in science: A systematic review. *Journal of Science Education and Technology, 25*, 149–160. https://doi.org/10.1007/s10956-015-9597-x

Crowe, A., Dirks, C., & Wenderoth, M. P. (2017). Biology in bloom: Implementing Bloom's taxonomy to enhance student learning in biology. *CBE – Life Sciences Education*, *7*(4), 368–381. https://doi.org/10.1187/cbe.08-05-0024

Dawati, F. M., Yamtinah, S., Rahardjo, S. B., Ashadi, A., & Indriyanti, N. Y. (2019). Analysis of students' difficulties in chemical bonding based on computerized two-tier multiple choice (CTTMC) test. *Journal of Physics: Conference Series, 1157*(4): 042017. https://doi.org/10.1088/1742-6596/1157/4/042017

Derman, A., Koçak, N., & Eilks, I. (2019). Insights into components of prospective science teachers' mental models and their preferred visual representations of atoms. *Education Sciences, 9*(2): 154. https://doi.org/10.3390/educsci9020154

Efe, H. A., & Efe, R. (2011). Evaluating the effect of computer simulations on secondary biology instruction: An application of Bloom's taxonomy. *Scientific Research and Essays*, *6*(10), 2137–2146. https://doi.org/10.5897/SRE10.1025

Eh Phon, D. N., Abidin, A. F. Z., Ab Razak, M. F., Kasim, S., Basori, A. H., & Sutikno, T. (2019a). Augmented reality: Effect on conceptual change of scientific. *Bulletin of Electrical Engineering and Informatics, 8*(4), 1537–1544. https://doi.org/10.11591/eei.v8i4.1625

Eh Phon, D. N., Rahman, M. H. A., Utama, N. I., Ali, M. B., Halim, N. D. A., & Kasim, S. (2019b). The effect of augmented reality on spatial visualization ability of elementary school student. *International Journal on Advanced Science, Engineering and Information Technology*, *9*(2), 624–629. https://doi.org/10.18517/ijaseit.9.2.4971

Eilks, I., Moellering, J., & Valanides, N. (2007). Seventh-grade students' understanding of chemical reactions: Reflections from an action research interview study. *Eurasia Journal of Mathematics, Science and Technology Education, 3*(4), 271–286. https://doi.org/10.12973/ejmste/75408

Erbas, C., & Demirer, V. (2019). The effects of augmented reality on students' academic achievement and motivation in a biology course. *Journal of Computer Assisted Learning*, *35*(3), 450–458. https://doi.org/10.1111/jcal.12350

Falvo, D. (2008). Animations and simulations for teaching and learning molecular chemistry. *International Journal of Technology in Teaching and Learning*, *4*(1), 68–77. Retrieved from https://sicet.org/main/wp-content/uploads/2016/11/ijttl-08-01-4_1_5_Falvo.pdf

Fang, N., & Guo, Y. (2016). Interactive computer simulation and animation for improving student learning of particle kinetics. *Journal of Computer Assisted Learning, 32*(5), 443–455. https://doi.org/10.1111/jcal.12145

Febrina, F., Usman, B., & Muslem, A. (2019). Analysis of reading comprehension questions by using revised Bloom's Taxonomy on higher order thinking skill (HOTS). *English Education Journal, 10*(1), 1–15. Retrieved from https://jurnal.usk.ac.id/EEJ/article/view/13253/0

Gardner, H. (1992). *Multiple intelligences* (Vol. 5). Minnesota Center for Arts Education.

Gardner, H., & Hatch, T. (1989). Educational implications of the theory of multiple intelligences. *Educational Researcher, 18*(8), 4–10. https://doi.org/10.3102/0013189X018008004

Ghazali, N. H. M. (2016). A reliability and validity of an instrument to evaluate the school-based assessment system: A pilot study. *International Journal of Evaluation and Research in Education*, *5*(2), 148–157. http://doi.org/10.11591/ijere.v5i2.4533

Gkitzia, V., Salta, K., & Tzougraki, C. (2020). Students' competence in translating between different types of chemical representations. *Chemistry Education Research and Practice*, *21*, 307–330. https://doi.org/10.1039/c8rp00301g

Gudyanga, E., & Madambi, T. (2014). Pedagogics of chemical bonding in chemistry; Perspectives and potential for progress: The case of Zimbabwe secondary education. *International Journal of Secondary Education, 2*(1), 11–19. https://doi.org/10.11648/j.ijsedu.20140201.13

Gowda, R. S., & Suma, V. (2017, February). A comparative analysis of traditional education system vs. e-Learning. In *Proceedings of the 2017 International Conference on Innovative Mechanisms for Industry Applications (ICIMIA)* (pp. 567–571). IEEE.

Gün, E. T., & Atasoy, B. (2017). The effects of augmented reality on elementary school students' spatial ability and academic achievement. *Eğitim ve Bilim – Education and Science, 42*(191), 31–51. https://doi.org/10.15390/eb.2017.7140

Han, L. (2010, November). A case study of applying critical thinking in teaching and learning computer visualization and communication. In *Proceedings of the 2010 International Conference on Education and Management Technology* (pp. 183–187). IEEE. https://doi.org/10.1109/ICEMT.2010.5657674

Harrell, M. (2004). *The improvement of critical thinking skills in what philosophy is*. Carnegie Mellon University. Retrieved from https://www.cmu.edu/dietrich/philosophy/docs/tech-reports/158_Harrell.pdf

Hoban, G., & Nielsen, W. (2013). Learning science through creating a "Slowmation": A case study of preservice primary teachers. *International Journal of Science Education, 35*(1), 119–146. https://doi.org/10.1080/09500693.2012.670286

Höllerer, T., & Feiner, S. (2004). Mobile augmented reality. In H. Karimi & A. Hammad (Eds.), *Telegeoinformatics: Location-Based Computing and Services*. Taylor & Francis Books. Retrieved from http://web.cs.wpi.edu/~gogo/courses/imgd5100_2012f/papers/Hollerer_AR_2004.pdf

Istiqomah, A. N., Kurniawati, I., & Wulandari, A. N. (2020). The implementation of somatic, auditory, visualization, intellectually (SAVI) learning approach to improve students' attention toward mathematics learning. *Journal of Physics: Conference Series, 1563*(1): 012033. https://doi.org/10.1088/1742-6596/1563/1/012033

Jiménez-Aleixandre, M. P., & Puig, B. (2012). Argumentation, evidence evaluation and critical thinking. In B. J. Fraser, K. Tobin and C. J. McRobbie (Eds.), *Second International Handbook of Science Education* (pp. 1001–1015). Springer. https://doi.org/10.1007/978-1-4020-9041-7_66

Johnson, P. (2002). Children's understanding of substances, part 2: Explaining chemical change. *International Journal of Science Education, 24*(10), 1037–1054. https://doi.org/10.1080/09500690110095339

June, S., Yaacob, A., & Kheng, Y. K. (2014). Assessing the use of YouTube videos and interactive activities as a critical thinking stimulator for tertiary students: An action research. *International Education Studies, 7*(8), 56–67. http://doi.org/10.5539/ies.v7n8p56

Kaźmierczak, R., Szczepańska, A., Kowalczyk, C., Grunwald, G., & Janowski, A. (2021). Using AR technology in tourism based on the example of maritime educational trips – A conceptual model. *Sustainability, 13*(13): 7172. https://doi.org/10.3390/su13137172

Kelly, R. M., & Jones, L. L. (2008). Investigating students' ability to transfer ideas learned from molecular animations of the dissolution process. *Journal of Chemical Education, 85*(2), 303–309. https://doi.org/10.1021/ed085p303

Khan, N., Sarwar, A., Chen, T. B., & Khan, S. (2022). Connecting digital literacy in higher education to the 21st century workforce. *Knowledge Management & E-Learning, 14*(1), 46–61. https://doi.org/10.34105/j.kmel.2022.14.004

Kogut, L. S. (1996). Critical thinking in general chemistry. *Journal of Chemical Education,* *73*(3), 218–221. Retrieved from https://www.une.edu/sites/default/files/Critical-Thinking-in-General-Chemistry-Journal-of-Chemical-Education.pdf

Kurt, S., & Ayas, A. (2012). Improving students' understanding and explaining real life problems on concepts of reaction rate by using a four step constructivist approach. *Energy Education Science and Technology Part B: Social and Educational Studies*, *4*(2), 979–992. Retrieved from https://repository.bilkent.edu.tr/bitstreams/a6cadd9b-90d9-4601-a389-b12eee88dfe9/download

Lamounier, E., Bucioli, A., Cardoso, A., Andrade, A., & Soares, A. (2010, August). On the use of augmented reality techniques in learning and interpretation of cardiologic data. In *Proceedings of the 2010 Annual International Conference of the IEEE Engineering in Medicine and Biology* (pp. 610–613). IEEE. http://doi.org/10.1109/IEMBS.2010.5628019

Lee, I., Leem, J. H., Jin, S., Sung, E. M., Moon, K. A., & Seo, H. J. (2004, October). Analysis of collaborative learning behaviors and the roles of collaborative learning agent. In *Proceedings of the E-Learn 2004 World Conference on E-Learning in Corporate, Government, Healthcare, and Higher Education* (pp. 2748–2754). Association for the Advancement of Computing in Education. Retrieved from https://www.learntechlib.org/primary/p/11059/

Levy Nahum, T., Hofstein, A., Mamlok-Naaman, R., & Bar-Dov, Z. (2004). Can final examinations amplify students' misconceptions in Chemistry? *Chemistry Education Research and Practice*, *5*(3), 301–325. http://doi.org/10.1039/B4RP90029D

Levy Nahum, T., Mamlok-Naaman, R., Hofstein, A., & Taber, K. S. (2010). Teaching and learning the concept of chemical bonding. *Studies in Science Education*, *46*(2), 179–207. https://doi.org/10.1080/03057267.2010.504548

Lin, C. Y., & Wu, H. K. (2021). Effects of different ways of using visualizations on high school students' electrochemistry conceptual understanding and motivation towards chemistry learning. *Chemistry Education Research and Practice*, *22*(3), 786–801. https://doi.org/10.1039/d0rp00308e

Lin, T. J., Duh, H. B. L., Li, N., Wang, H. Y., & Tsai, C. C. (2013). An investigation of learners' collaborative knowledge construction performances and behavior patterns in an augmented reality simulation system. *Computers & Education*, *68*, 314–321. https://doi.org/10.1016/j.compedu.2013.05.011

Lutviana, E., Rahardjo, S. B., Susanti, E., Yamtinah, S., Mulyani, S., & Saputro, S. (2019). The computer-assisted testlet assessment instrument to measure students' learning difficulties in chemical bonding. *Journal of Physics: Conference Series*, *1156*: 012019. https://doi.org/10.1088/1742-6596/1156/1/012019

Martin, J., Bohuslava, J., & Igor, H. (2018, September). Augmented reality in education 4.0. In *Proceedings of the 2018 IEEE 13th International Scientific and Technical Conference on Computer Sciences and Information Technologies (CSIT)* (pp. 231–236). IEEE.

Martin, S., Diaz, G., Sancristobal, E., Gil, R., Castro, M., & Peire, J. (2011). New technology trends in education: Seven years of forecasts and convergence. *Computers & Education*, *57*(3), 1893–1906. https://doi.org/10.1016/j.compedu.2011.04.003

Mayer, R. E. (2005). Principles for reducing extraneous processing in multimedia learning: Coherence, signaling, redundancy, spatial contiguity, and temporal contiguity principles. In R. E. Mayer (Ed.), *The Cambridge Handbook of Multimedia Learning* (pp. 183–200). Cambridge University Press. https://doi.org/10.1017/CBO9780511816819.013

Medina, E., Chen, Y. C., & Weghorst, S. (2007, June). Understanding biochemistry with augmented reality. In C. Montgomerie & J. Seale (Eds.), *Proceedings of the ED-*

MEDIA 2007 – World Conference on Educational Multimedia, Hypermedia & Telecommunications (pp. 4235–4239). Association for the Advancement of Computing in Education. Retrieved from https://www.learntechlib.org/primary/p/25987/

Ministry of Education Malaysia. (2013). *Malaysia Education Blueprint 2013 – 2025 (Preschool to Post-Secondary Education)*. Ministry of Education Malaysia. Retrieved from https://planipolis.iiep.unesco.org/sites/default/files/ressources/malaysia_blueprint.pdf

Nincarean, D., Alia, M. B., Halim, N. D. A., & Rahman, M. H. A. (2013). Mobile augmented reality: The potential for education. *Procedia – Social and Behavioral Sciences, 103*, 657–664. https://doi.org/10.1016/j.sbspro.2013.10.385

Nordin, M. S., & Saud, M. S. B. (2007, November). Kajian awal terhadap kebolehan ruang pelajar-pelajar pengajian kejuruteraan di sekolah-sekolah menengah teknik. In Z. Tasir et al. (Eds.), *Proceedings of the 1st International Malaysian Educational Technology Convention (IMETC 2007)* (pp. 1105–1116). Persatuan Teknologi Pendidikan Malaysia.

OECD. (2013). *PISA 2012 assessment and analytical framework: Mathematics, reading, science, problem solving and financial literacy*. OECD Publishing. http://doi.org/10.1787/9789264190511-en

Oliver-Hoyo, M., & Babilonia-Rosa, M. A. (2017). Promotion of spatial skills in chemistry and biochemistry education at the college level. *Journal of Chemical Education, 94*(8), 996–1006. https://doi.org/10.1021/acs.jchemed.7b00094

Omar, M., Ali, D. F., Mokhtar, M., Zaid, N. M., Jambari, H., & Ibrahim, N. H. (2019). Effects of mobile augmented reality (MAR) towards students' visualization skills when learning orthographic projection. *International Journal of Emerging Technologies in Learning, 14*(20), 106–119. https://doi.org/10.3991/ijet.v14i20.11463

Özmen, H. (2004). Some student misconceptions in Chemistry: A literature review of chemical bonding. *Journal of Science Education and Technology, 13*(2), 147–159. https://doi.org/10.1023/B:JOST.0000031255.92943.6d

Pellas, N., Fotaris, P., Kazanidis, I., & Wells, D. (2019). Augmenting the learning experience in primary and secondary school education: A systematic review of recent trends in augmented reality game-based learning. *Virtual Reality, 23*(4), 329–346. https://doi.org/10.1007/s10055-018-0347-2

Prinz, A., Bolz, M., & Findl, O. (2005). Advantage of three dimensional animated teaching over traditional surgical videos for teaching ophthalmic surgery: A randomised study. *British Journal of Ophthalmology, 89*(11), 1495–1499. https://doi.org/10.1136/bjo.2005.075077

Rahman, N. A., & Eliya, N. H. (2010). *Tahap kemahiran visualisasi dan gaya pembelajaran pelajar-pelajar bidang kejuruteraan UTM Skudai*. Masters thesis, Universiti Teknologi Malaysia, Malaysia. Retrieved from http://eprints.utm.my/28534/

Rehman, I., Ullah, S., & Raees, M. (2019). Two hand gesture based 3D navigation in virtual environments. *International Journal of Interactive Multimedia and Artificial Intelligence, 5*(4), 128–140.

Roca-González, C., Gutiérrez, J. M., García-Dominguez, M., & Mato Carrodeguas, M. D. C. (2017). Virtual technologies to develop visual-spatial ability in engineering students. *Eurasia Journal of Mathematics, Science and Technology Education, 13*(2), 441–468. https://doi.org/10.12973/eurasia.2017.00625a

Rosen, Y., & Tager, M. (2013). *Computer-based assessment of collaborative problem-solving skills: Human-to-agent versus human-to-human approach*. Pearson Education. Retrieved from https://www.researchgate.net/publication/258629038_Computer-based_assessment_of_collaborative_problem-solving_skills_Human-to-agent_versus_human-to-human_approach_Boston_MA_Pearson_Education

Roslan, R., Ayub, A. F. M., Ghazali, N., & Zulkifli, N. N. (2021). The influence of perceived ease of use, perceived usefulness, social influence, and perceived enjoyment towards continuance intention in using a gamified e-quiz mobile application. *Journal of Institutional Research South East Asia, 19*(2), 258–285.

Saidin, N. F., Halim, N. D. A., & Noraffandy Y. (2019). Framework for developing a mobile augmented reality for learning chemical bonds. *International Journal of Interactive Mobile Technologies, 13*(07), 54–68. https://doi.org/10.3991/ijim.v13i07.10750

Santrock, J. W. (2008). *Educational psychology*. McGraw-Hill.

Shatri, K., & Buza, K. (2017). The use of visualization in teaching and learning process for developing critical thinking of students. *European Journal of Social Sciences Education and Research, 4*(1), 22–25. https://doi.org/10.26417/ejser.v9i1.p71-74

Shelton, B. E., & Hedley, N. R. (2002, September). Using augmented reality for teaching earth-sun relationships to undergraduate geography students. In *Proceedings of the First IEEE International Workshop Augmented Reality Toolkit*. IEEE. http://doi.org/10.1109/ART.2002.1106948

Shen, K. S. (2019). Measuring the appeal of mobility-augmented reality games, based on the innovative models of interaction: A case study. *SN Applied Sciences, 1*: 1708. https://doi.org/10.1007/s42452-019-1763-y

Singhal, S., Bagga, S., Goyal, P., & Saxena, V. (2012). Augmented chemistry: Interactive education system. *International Journal of Computer Applications, 49*(15), 1–5. http://doi.org/10.5120/7700-1041

Sorby, S. A. (2007). Developing 3D spatial skills for engineering students. *Australasian Journal of Engineering Education, 13*(1), 1–11. https://doi.org/10.1080/22054952.2007.11463998

Stanger-Hall, K. F., Shockley, F. W., & Wilson, R. E. (2011). Teaching students how to study: A workshop on information processing and self-testing helps students learn. *CBE – Life Sciences Education, 10*(2), 187–198. http://doi.org/10.1187/cbe.10-11-0142

Strijbos, J. W., Martens, R. L., & Jochems, W. M. G. (2004). Designing for interaction: Six steps to designing computer-supported group-based learning. *Computers & Education, 42*(4), 403–424. https://doi.org/10.1016/j.compedu.2003.10.004

Suhadi, S. M., Mohamed, H., Abdullah, Z., Zaid, N. M., Aris, B., & Sanmugam, M. (2016). Enhancing student's higher order thinking skills (hots) through the socratic method approach with technology. *International Journal of Knowledge-Based Organizations, 6*(4), 14–27. https://doi.org/10.4018/ijkbo.2016100102

Swart, A. J., Lombard, K., & de Jager, H. (2010). Exploring the relationship between time management skills and the academic achievement of African engineering students – A case study. *European Journal of Engineering Education, 35*(1), 79–89. https://doi.org/10.1080/03043790903480316

Taber, K. S. (2001). Building the structural concepts of chemistry: Some considerations from educational research. *Chemistry Education Research and Practice, 2*, 123–158. http://doi.org/10.1039/B1RP90014E

Talanquer, V. (2018). Importance of understanding fundamental chemical mechanisms. *Journal of Chemical Education, 95*(11), 1905–1911. https://doi.org/10.1021/acs.jchemed.8b00508

Tan, K. C. D., Goh, N. K., Chia, L. S., & Boo, H. K. (2001). Alternative conceptions of chemical bonding. *Journal of Science and Mathematics Education in Southeast Asia,* *XXIV*(2), 40–50. Retrieved from https://repository.nie.edu.sg/bitstreams/16ae6491-3628-4b29-90ca-cfa4594afe61/download

Tsai, C. C. (2020). The effects of augmented reality to motivation and performance in EFL vocabulary learning. *International Journal of Instruction, 13*(4), 987–1000. https://doi.org/10.29333/iji.2020.13460a

Tsai, C. H., & Yen, J. C. (2014). Teaching spatial visualization skills using OpenNI and the Microsoft Kinect sensor. In J. Park, Y. Pan, C. S. Kim and Y. Yang (Eds.), *Future Information Technology: Lecture Notes in Electrical Engineering* (Vol. 309) (pp. 617–624). Springer. https://doi.org/10.1007/978-3-642-55038-6_97

Uzuntiryaki, E., & Geban, Ö. (2016). Effect of conceptual change approach accompanied with concept mapping on understanding of solution concepts. *Instructional Science, 33*(4), 311–339.

Vavra, K. L., Janjic-Watrich, V., Loerke, K., Phillips, L. M., Norris, S. P., & Macnab, J. (2011). Visualization in science education. *Alberta Science Education Journal, 41*(1), 22–30. Retrieved from https://sc.teachers.ab.ca/SiteCollectionDocuments/Vol.%2041,%20No.%201%20January%202011.pdf#page=24

Willingham, D. T. (2007). Critical thinking: Why it is so hard to teach?. *American Educator, Summer,* 8–19. Retrieved from https://eduq.info/xmlui/bitstream/handle/11515/19710/Crit_Thinking.pdf

Wojciechowski, R., & Cellary, W. (2013). Evaluation of learners' attitude toward learning in ARIES augmented reality environments. *Computers & Education, 68*, 570–585. https://doi.org/10.1016/j.compedu.2013.02.014

Wu, H. K., & Shah, P. (2004). Exploring visuospatial thinking in chemistry learning. *Science Education, 88*(3), 465–492. https://doi.org/10.1002/sce.10126

Yang, K. J., Chu, H. C., & Yang, K. H. (2015, July). Using the augmented reality technique to develop visualization mindtools for chemical inquiry-based activities. In *Proceedings of the 2015 IIAI 4th International Congress on Advanced Applied Informatics* (pp. 354–357). IEEE. https://doi.org/10.1109/IIAI-AAI.2015.222

Yuen, S. C. Y., Yaoyueneyong, G., & Johnson, E. (2011). Augmented reality: An overview and five directions for AR in education. *Journal of Educational Technology Development and Exchange, 4*(1), 119–140. http://doi.org/10.18785/jetde.0401.10

Zakaria, S., Othman, B. A., Mohammed, H., Zaid, N. M., & Abdullah, Z. (2014, August). Penerapan kemahiran berfikir aras tinggi melalui model stesen rotasi pelbagai mod. In *Proceedings of the Konvensyen Antarabangsa Jiwa Pendidik* (pp. 11–13). Retrieved from https://www.researchgate.net/publication/274701680_Penerapan_Kemahiran_Berfikir_Aras_Tinggi_Melalui_Model_Stesen_Rotasi_Pelbagai_Mod

Zulkifli, N. N., Halim, N. D. A., Yahaya, N., & Van der Meijden, H. (2020). Patterns of critical thinking processing in online reciprocal peer tutoring through Facebook discussion. *IEEE Access, 8*, 24269–24283. http://doi.org/10.1109/ACCESS.2020.2968960