Journal of Science Education and Technology
https://doi.org/10.1007/s10956-022-10014-z

Effects of an Augmented Reality-Based Chemistry Experiential Application on Student Knowledge Gains, Learning Motivation, and Technology Perception

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Accepted: 25 November 2022

Abstract

The microscopic composition of substances is a piece of essential but abstract knowledge in chemistry. Junior high school students may experience difficulty in mental representation when learning micro concepts, which leads to problems such as unsatisfactory academic performance and low learning motivation. Augmented reality (AR) is an optimal choice for presenting abstract concepts and invisible phenomena. Consequently, this study developed an AR application including three-layer experiential learning activities and integrating multiple external representations (text, pictures, 3D models, operations, etc.). To assess the effect of the AR application on students' knowledge gains, learning motivation, and technology perception, an experiment was conducted with 95 ninth-grade students aged 13–15 years who were randomly assigned to two groups (AR and non-AR). The results show that the AR application helped increase students' knowledge gains. Although there was no significant difference in the retention test between the two groups, scores on the transfer test were significantly higher for the AR group than for the non-AR group. Moreover, the AR application significantly improved students' motivation to learn. Finally, students had a positive perception of AR technology.

Keywords Augmented reality · Microscopic composition of substances · Learning motivation · Technology perception · Chemistry education

Introduction

Chemistry is a vital science discipline involving the study of the composition, structure, properties, and chemical reactions of substances (Srisawasdi & Panjaburee, 2019). Chemical concepts are often utilized to explain phenomena involved in daily life, and such concepts are also closely related to other science concepts (Özmen, 2011). However, learning chemical concepts is not straightforward (Chen & Liu, 2020; Özmen, 2004), as students need to establish the relationships and distinctions between three levels of chemical representations: macroscopic, submicroscopic, and symbolic (Johnstone, 1993). Understanding submicroscopic and symbolic representations might be a challenge for new chemistry learners since they are invisible and abstract (Gilbert, 2009; Stieff & Wilensky, 2003; Wu et al., 2021). In particular, when students observe a chemical equation, they may have difficulty visualizing and understanding the particulate nature of the substances the symbols represent and the dynamic chemical reaction phenomena involved (Treagust et al., 2003). These challenges may lead to students' unsatisfactory academic performance and low learning motivation (Ewais & Troyer, 2019; Fidan & Tuncel, 2019). Consequently, it is necessary to improve the learning methods and tools used in chemistry teaching (Cai et al., 2014; Srisawasdi & Panjaburee, 2019).

In chemistry education, external representations have been used to promote meaningful learning and enhance conceptual change (Özmen, 2011). Studies have indicated

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Published online: 23 December 2022

that pictures and ball-and-stick models can help students develop accurate mental models of various chemical phenomena (Levy, 2013; Plass et al., 2012). However, the dynamic motion of an atom's 3D structure is difficult to capture using static representations (Bernholt et al., 2019; McElhaney et al., 2015). Additionally, animations or videos can show how chemical reactions change over time (Berg et al., 2019), which may support students in connecting the macroscopic and submicroscopic levels (Barak & Hussein-Farraj, 2013). However, animations have the drawback in that they cannot provide students with the opportunity to manipulate concrete models. Recently, the development of augmented reality (AR) technology has made interactive simulation experiments a more promising method for chemistry learning (Habig, 2020; Nechypurenko et al., 2018).

Although numerous studies have examined the effectiveness of AR on students' learning performance (Cai et al., 2014; Chen & Liu, 2020; Ewais & Troyer, 2019; Habig, 2020; Lee & Kellogg, 2020), studies in which AR is combined with learning theory are limited. In particular, research on using AR to help students establish connections between different levels of chemical representations still needs to integrate technology and learning theory more effectively (Ainsworth, 2008; Chiu & Linn, 2014). In this study, an AR-based experiential application—ArAtom—was developed to teach students the microscopic composition of substances. In addition, Kolb's (1984) experiential learning model was incorporated into the application and the learning activities to enable a smooth integration of AR within the learning process. This study aimed to investigate the effectiveness of ArAtom on student knowledge gains, learning motivation, and perception of technology.

Literature Review

Representation in Chemistry Learning

Representation, the way knowledge is stored and presented, can be divided into internal and external representation. Internal representations consist of building blocks involving mental models, which constitute students' content knowledge of a particular topic or domain (Rau, 2017). Johnstone (1993) proposed three levels of representation in chemistry: macroscopic, submicroscopic, and symbolic. Specifically, the macroscopic level involves observable chemical phenomena such as color changes and precipitate generation (Berg et al., 2019). The submicroscopic level refers to the arrangement and motion of molecules and atoms. Chemistry at the symbolic level is represented by symbols, numbers, formulas, and equations (Wu et al., 2001). The complexity of chemistry learning is attributed to the need to understand the relationships among these three levels of representing chemical phenomena. However, learners have difficulties transferring knowledge from one level to another (Bain et al., 2018). For example, some students view H_2O as a representation of one particle without the conception of atoms or a collective entity since they do not recognize that water is formed by the aggregation of many water molecules (Wu & Shan, 2004). Chemistry education researchers have noted that the causes of these chemical misconceptions include the abstract nature of chemical concepts, the separation between life experience and chemical knowledge, and the lack of relevant pedagogical practice skills (Sirhan, 2007; Srisawasdi & Panjaburee, 2019; Yakmaci-Guzel, 2013). Therefore, an ability to scientifically represent and explain the submicroscopic-level dynamics of a chemical system is necessary for students to comprehend the macroscopic-level behavior of such systems and to connect the critical components of multi-level chemistry knowledge effectively (Levy, 2013).

In past decades, researchers and science educators have explored effective methods and pedagogies to address students' learning difficulties in understanding chemical concepts. The multiple external representation (MERs) method, in which pictures, models, animation, and various representations are combined to illustrate chemical concepts (Gilbert, 2009; Kozma et al., 2000; Wu & Puntambekar, 2012), is widely used in chemical teaching and learning (Adadan, 2013; Pikoli, 2020). Gilbert et al. (1998) proposed four modes of representations that can be used to support the visualization of concepts: concrete (sometimes referred to as material or physical), verbal, symbolic, visual, and gestural representations. According to Ainsworth's (1999) functional taxonomy of multiple representations, MERs may facilitate learning by complementing information, constraining interpretations, and constructing deeper understanding. For example, Rau (2015), in a study involving 158 undergraduate students in a general chemistry introductory course, found that using virtual simulations (with multiple graphical representations) significantly improved the students' conceptual understanding of the atomic structure and chemical bonding concepts. In Sunyono et al. (2015)'s work, learning with multiple representations, rather than conventional learning, was found to be more effective in constructing students' mental models about understanding the concept of atomic structure. As shown by these and other studies (Baptista et al., 2019; Berg et al., 2019), MERs promote learners' comprehension of the acquired information and their ability to transfer such knowledge effectively. From the perspective of Mayer's cognitive theory of multimedia learning (Mayer, 2005), MERs provide students with both visual and auditory stimuli, which then trigger students to use both cognitive channels (images and language) to form a coherent mental model of chemical concepts.

Although MERs have the potential to support the learning process, it is likely that, without a practical design and in unsuitable combinations, MERs may negatively affect the learning process (De Jong et al., 1998). In this context, scholars have suggested that technology support can facilitate the learning-promoting effect of MERs (Horz & Schnotz, 2010) by helping reduce irrelevant components of the cognitive load when learning with MERs. In this study, we utilized the taxonomy of MERs proposed by Lemke (1998) and Tsui (2003), in which verbal-textual, symbolic-mathematical, visual-graphical, and actional-operational components are distinguished. This taxonomy contains different symbol systems and captures the multidimensionality of external representations used in science that are also suitable for chemistry learning. Moreover, to address the issue whereby traditional multimedia technology cannot readily provide learners with an actional-operational representation at the microscopic level, we considered AR with these four components of MERs.

Augmented Reality Application in Chemistry Education

AR is a technology in which virtual elements generated by computers, such as videos, graphics, animations, texts, or audios, are superimposed onto real-world backdrops in real-time (Azuma, 1997; Dunleavy et al., 2009; Wu et al., 2013). With the increasing research on AR in education, several meta-analysis studies on AR have been published, reporting effect values ranging from 0.36 to 0.72 (Garzón & Acevedo, 2019; Ozdemir et al., 2018; Santos et al., 2014; Tekedere & Göker, 2016), which indicate that AR has a positive impact on education.

There have been several studies on the application of AR in chemistry, especially those showing substances' microstructure. For example, Zheng and Waller (2017) developed an AR application called ChemPreview, which can manipulate bio-molecular structures at an atomic level. It can also be used to interact with a protein in an intuitive way using natural hand gestures. Likewise, Lee and Kellogg (2020) introduced an open-source AR application called Palantir, which visualizes the protein molecular structure and allows the 3D model to be controlled by zooming and rotating gestures on mobile device screens. Additionally, two application prototypes were developed for university courses. Ewais and Troyer (2019) developed an AR application that enables students to explore different reactions with several atoms and molecules. They mainly investigated female students' attitudes toward AR applications, but the learning effectiveness was not examined. In addition, some studies have introduced AR applications and applied them to practical teaching. For instance, Chen and Liu (2020) investigated the effects of AR combined with different approaches. The results showed that the hands-on AR group performed significantly better on a chemical reaction concept test and interest questionnaire than the demonstration AR group. It was also found that AR had a long-term retention effect on knowledge mastery. Cai et al. (2014) developed an inquiry-based AR learning tool for "the composition of substances", which could promote students' cognitive performance and learning attitudes, as indicated by their study findings. However, this AR tool run on a desktop computer and did not take full advantage of the convenience of mobile AR technology.

Overall, the findings of previous studies provide concrete evidence for the usability of AR in chemistry subjects. AR used in chemistry learning has two main benefits. First, AR can help visualize atoms and molecules in the microscopic world by displaying virtual elements alongside natural objects (Wu et al., 2013). Second, AR can provide an interactive operation experience at the micro-level since AR allows users to interact with virtual objects naturally and obtain real-time feedback (Akçayir & Akçayir, 2017). These benefits realize the integration of multiple representations to present learning content from the technical level and help students understand micro concepts.

However, some researchers have drawn attention to limitations associated with AR in education. Squire and Jan (2007) contended that without a well-designed interface and guidance for students, AR could be too complicated for them to use. In addition, due to some problems, such as unresponsive touch features and inaccurate recognition in location-based AR applications (Akçayır & Akçayır, 2017; Cheng & Tsai, 2013; Dunleavy et al., 2009), students may require excessive additional lecture time. Assessing its user acceptance to apply new technology into a specific domain is crucial to improve its quality for future use. Therefore, one of the research objectives of this study was to evaluate students' perception of AR application using the technology acceptance model developed by Davis (1985), which is widely used to measure students' technology perception of the learning media (Liu et al., 2020).

Motivation in Chemistry Education

Motivation is an internal condition that initiates, guides, and sustains a goal-oriented action in pupils (Koballa & Glynn, 2013). In chemistry education, learning motivation has been viewed as an essential factor determining the success of chemistry learning (Barak et al., 2011; Vaino et al., 2012). However, previous research has found that some students experience difficulty in forming mental representations when learning microscopic concepts, which leads to low learning motivation (Ahmad et al., 2021; Ewais & Troyer, 2019). This problem can be explained by the expectancy-value theory, which considers that a student's learning motivation is predominately determined by the expectancy of success and subjective task values (Wigfield, 1994). Chemistry is often regarded as a challenging and complex subject for the former. The invisible and abstract nature of chemical concepts sometimes leads to a lack of confidence among students in their ability to complete relevant learning tasks. For the latter, atoms and molecules are chemical concepts that require understanding at a microscopic level, which has a less direct connection with students' life experiences. Therefore, students may underestimate the value of chemistry learning.

Given that learning motivation is significant for chemistry learning, it is essential to design learning materials that can arouse students' interests and motivate them (Srisawasdi & Panjaburee, 2019). As a novel technology, AR has been employed in classroom teaching and effectively enhances students' learning motivation (Chang et al., 2019; Yu et al., 2022). Moreover, literature has shown that the instructional material motivation survey (IMMS) based on Keller's ARCS model (2010) was an effective instrument that can assess students' motivation in the simulation-based learning environment by looking at four dimensions: attention, relevance, confidence, and satisfaction. For example, Yu et al. (2022) designed an AR learning tool named "MagAR" to assist students' magnetism learning by visualizing the magnetic induction line. IMMS was applied to investigate how AR may affect students' learning motivation with different levels of learning anxiety. The results indicated that AR could significantly motivate students with high anxiety. Likewise, in Chang et al. (2019)'s work, AR was utilized to promote motor skills learning. Students reported significantly greater attention, relevance, and confidence when compared to those assigned video materials. In this regard, we also aimed to evaluate the effect of AR on students' motivation through the lens of the ARCS model.

The Aim of the Study

In this study, an AR-based experiential learning application for the microscopic composition of substances was developed, and an experiment was conducted to verify its educational efficacy. First, we considered whether this application could improve students' knowledge gains (RQ1). Second, given that students have low motivation in chemistry learning, especially in microstructure learning, we considered whether this application could improve students' learning motivation (RQ2). Finally, as many studies imply (Akçayır & Akçayır, 2017; Cheng & Tsai, 2013; Dunleavy et al., 2009), technical usability is one of the limitations of AR applications. We considered students' perceptions of the AR application (RQ3). This study aimed to answer the following questions.

RQ1. How does the AR experience influence students' understanding of chemical knowledge?

RQ2. How does the AR experience influence students' learning motivation in chemistry?

RQ3. What are the students' perceptions of the AR-based experiential learning tool?

Methods

This study aims to take unique advantages of AR to address the learning challenges of microscopic representations in secondary school chemistry, and to examine the effects of AR learning application on students' knowledge gains, learning motivation, and technology perception through experimental research. First, considering that previous studies have highlighted the significance of integrating AR with learning theory, this study took the experiential learning model as the theoretical basis, which is proven to be an effective framework for understanding student contextual learning processes. Second, we combed the knowledge points about "the microscopic composition of substances" from the Chinese ninth-grade chemistry textbook to form the instructional content framework in this study. Third, based on the experiential learning model and learning content framework, we developed an AR learning application that includes three layers of experiential learning activities. Finally, we conducted an experimental study in a junior high school in southwestern China. The specific research process is described below.

Experiential Learning Theory

Experiential learning regards learning as the process of experience transformation and knowledge creation (Jarmon et al., 2009). In Kolb's (1984) experiential learning model, individuals acquire learning experience in two ways: concrete experience (the specific perception of learning content and learning environment) and abstract conceptualization (learners' internal explanation of concepts or description of symbols). Furthermore, two processing methods are used in experience transformation: reflective observation and active application. Reflection includes the learner's recall, attention, and evaluation of the experience and transforms this experience into the learning process. The application tests the concept in a new context. Experiential learning is a continuous cycle and spiral process, which is consistent with the cognitive spiral model (Ebert, 1994).

Instructional Content Design

Figure 1 shows the structure of instructional content. The design of instructional content should establish a close connection among the three levels of representations in chemistry: macro, micro, and symbolic. In the Chinese junior

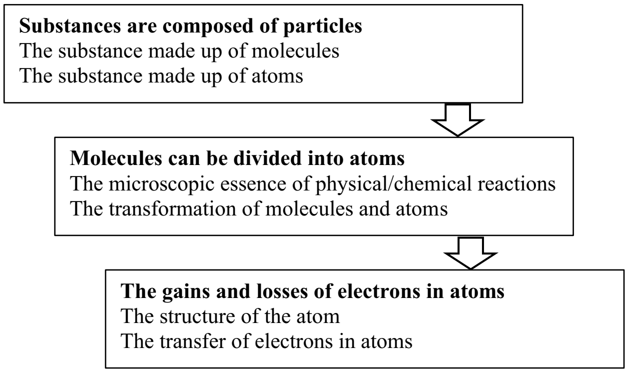

Fig. 1 The structure of instructional content

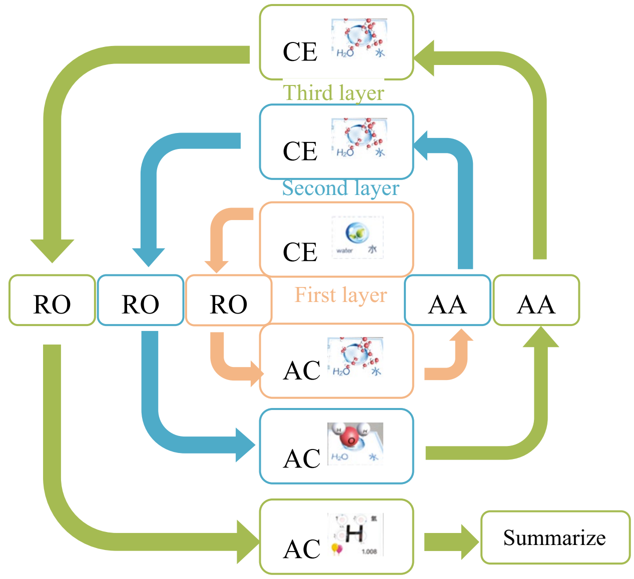

Fig. 2 The three-layer experiential learning activities (CE concrete experience, RO reflective observation, AC abstract conceptualization, AA active application)

high school ninth-grade chemistry textbook, the chapter on molecules and atoms includes two distinctive concepts: "Substances are composed of microscopic particles" and "Molecules can be divided into atoms." The former uses macro phenomena to initiate thinking and establish a connection from the macro to the micro level. The latter focuses on understanding substance changes from the perspective of microscopic particles, taking specific reactions as examples to help students initially understand the nature of chemical reactions. Furthermore, the gain and loss of electrons inside the atoms help students understand the changing laws of atoms. The three parts of instructional content were closely interlinked—accordingly, the following AR application designs three-layer experiential learning activities based on this instructional content structure.

AR-Based Experiential Learning Application Design

Unity 3D was used as the development platform, and Vuforia SDK was imported to realize AR functions. Versions for Android and iOS were released, which can be installed and run on mobile devices such as mobile phones or tablets. From the content design, AR is combined with the four stages of the experiential learning model: concrete experience, reflective observation, abstract conceptualization, and active application. As shown in Fig. 2, these four stages are a continuous cycle forward process, including three layers of experiential learning activities.

The First Layer: Visualizing the Three Levels of Substance Composition (Macro-Sub-Micro-Micro) by Operating the Slider

Concrete Experience Seven common substances were selected as instructional cases, including water (H_2O), oxygen (O_2), hydrogen (H_2), dry ice (CO_2), alcohol (C_2H_5OH, take 75% alcohol for disinfection as an example), diamond (C), and iron (Fe). Each substance is visualized in three states (i.e., macroscopic, sub-microscopic, and microscopic). Taking water as an example (see Fig. 3), students select the AR marker representing liquid water and scan it with the camera, and the macro state of liquid water will be superimposed on the AR marker through feature matching and three-dimensional registration. In addition, students can manipulate the AR marker (e.g., rotate, move) to trigger changes of the virtual model in real time. Next, students manipulate the slider to switch to the microscopic composition of liquid water. Many disordered water molecules will appear on the screen. Subsequently, students again operate the slider to switch to a water molecule. They will find that a water molecule is composed of two hydrogen atoms and one oxygen atom. Meanwhile, critical information about experimental content is presented on the screen, which helps students gain a better understanding of the learning content.

Reflective Observation and Abstract Conceptualisation The entire process follows the learning order from macro to micro—known to unknown—to build the relationship between macro substances and micro particles. Students develop an intuitive perception of the microscopic composition of substances through concrete interactive experiences such as manipulating the AR marker and dragging the slider. In addition, by operating and observing seven common substances, students can conclude that substances are composed of atoms and molecules and establish the chemical concepts of microstructure.

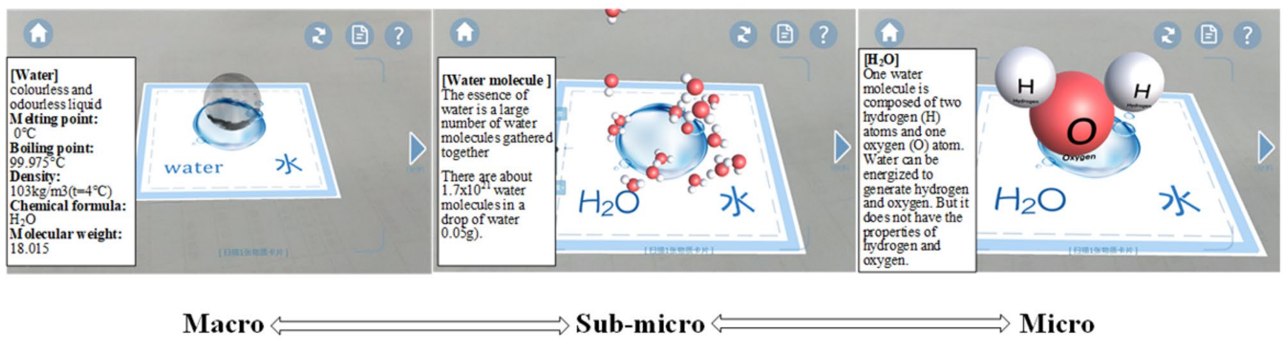

Fig. 3 The first layer of experiential learning

Active Application In the first layer of experiential learning, students understand that molecules and atoms are the fundamental particles of substances. Understanding the relationship between molecules and atoms requires students to apply the concepts acquired in the first stage to new problems through active experiments.

The Second Layer: Visualizing the Relationship Between Molecules and Atoms and the Microscopic Nature of Chemical/Physical Reactions

Concrete Experience Four kinds of reactions (i.e., water evaporation, water electrolysis, hydrogen and oxygen ignition, and carbon and oxygen ignition) were selected as instructional cases. The purpose of this module is to enable students to understand the essential differences between chemical and physical reactions at a microscopic level. Taking the evaporation and electrolysis of water as an example (see Fig. 4), when students select the "heat" button, the movement of water molecules on the screen will accelerate, and the intervals will become larger. When students select the "electrify" button, each water molecule decomposes into one oxygen atom and two hydrogen atoms. Meanwhile, oxygen and hydrogen atoms recombine to form oxygen and hydrogen molecules.

Reflective Observation and Abstract Conceptualisation Through the concrete experience and reflective observation of the four experiments in the second layer, students can summarize the essential differences between physical and chemical reactions. More importantly, students form a further understanding of the interconversion between atoms and molecules.

Active Application In the second layer of experiential learning, students understand that molecules are composed of atoms. However, answering questions such as "What is the structure of the atom?" or "How do atoms form molecules?" requires students to apply the knowledge acquired in the second stage to new problems through active experiments.

The Third Layer: Visualizing the Atomic Structure and the Electronic Gain and Loss of Atoms in Chemical Reactions

Concrete Experience Bohr's atomic structure model of the layered arrangement of electrons is displayed on the screen (see Fig. 5). Students can scale and rotate the model to observe and calculate the number of electrons and orbits outside the atomic nucleus. When students bring two atomic models close to each other, they will observe the electron transfer of the chemical reaction.

Relflective Observation and Abstract Conceptualization Observing the atomic structure and electron transfer in the process of chemical reaction, the rules for the gain

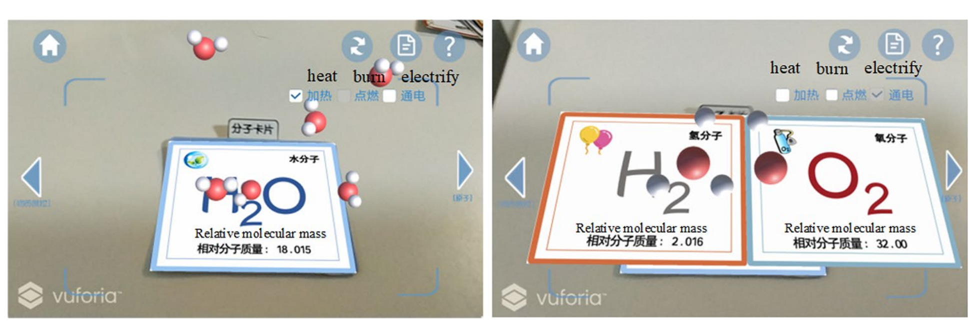

Fig. 4 The second layer of experiential learning

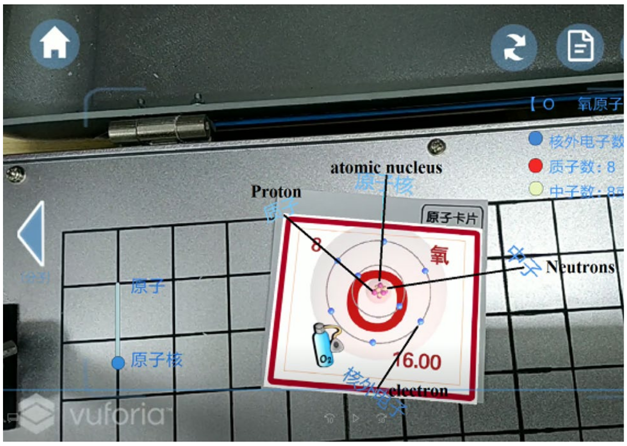

Fig. 5 Bohr's atomic structure model of oxygen atom

and loss of electrons in the process of forming molecules are summarized.

Moreover, the AR tool integrates the four types of external representations proposed by Tsui (2003). The details are listed in Table 1.

Participants

The study was conducted in a junior high school in southwest China. A total of 103 student volunteers aged 13–15 years were randomly divided into two groups: the AR group ($n=47$, including 22 male and 25 female students) in the AR-based experiential learning environment and the non-AR group ($n=56$, including 30 males and 26 females) in the conventional situated learning environment. After the experiment, each student received one stationery (e.g., a notebook or a pen) reward. The two groups were taught by the same teacher, who had been teaching chemistry for more than 5 years. In addition, the students in each group were divided into subgroups of three or four members. In the data processing, it was found that two students did not complete the pre-test, and six did not complete the post-test. Therefore, the final sample of this study consisted of 95 participants (AR group, 46; non-AR group, 49).

Procedure

The entire experimental procedure, which lasted 3 weeks, is shown in Fig. 6. In the first week, before the class started, all students were asked to complete a pre-test measuring their knowledge of "The microscopic composition of substance" (15 min). It is worth noting that to avoid cognitive load caused by the unfamiliar use of AR tools (Dunleavy et al., 2009), we conducted a pre-experience session to familiarize students in the experimental group with the operation process of AR tools (15 min). Then, experimental and control groups studied the first part of the content (i.e., substances are composed of particles) in different environments. In the second and third weeks, the two groups learned the second (molecules can be divided into atoms) and third topics (the gain and loss of electrons in atoms), respectively. The learning process lasted 45 min for each of the three parts. Figure 7 shows the learning situations of the two groups. In order to ensure the validity of this experiment, we tried to eliminate the influence of irrelevant variables as much as possible; that was, the instructor, learning progress, and learning content of the two groups were the same. The only difference was that the learning materials of the two groups were presented in different ways, which ensures that the difference in the post-test between the two groups is caused by whether ArAtom is used or not. Specifically, ArAtom includes a combination of various external representations, such as texts, animations, pictures, and 3D models. More importantly, students can manipulate AR markers and click on experimental conditions to trigger chemical or physical reactions, thus enabling students to participate in inquiry activities. In contrast, in the non-AR group, students learned chemical concepts mainly through text and pictures in the textbook and on slides. Finally, a post-test was conducted to examine students' mastery of knowledge, learning motivation, and perception of the AR tool after completing the learning task in the third week (30 min).

Measuring Tools

Testing Student Knowledge of "The Microscopic Composition of Substance"

The questions in the knowledge tests were designed by two middle school chemistry teachers with more than 10 years of

Table 1 The multiple external representations designed in this study

External representations	Realization form in this research
Verbal-textual	AR markers present the name of particles, relative atomic/molecular mass, and other textual information
Symbolic-mathematical	3D models display the structure of particles
Visual-graphical	Virtual animations display the process of water electrolysis and heating
Actional-operational	Slider controls the state of the particle AR marker can be manipulated to transform molecules and atoms

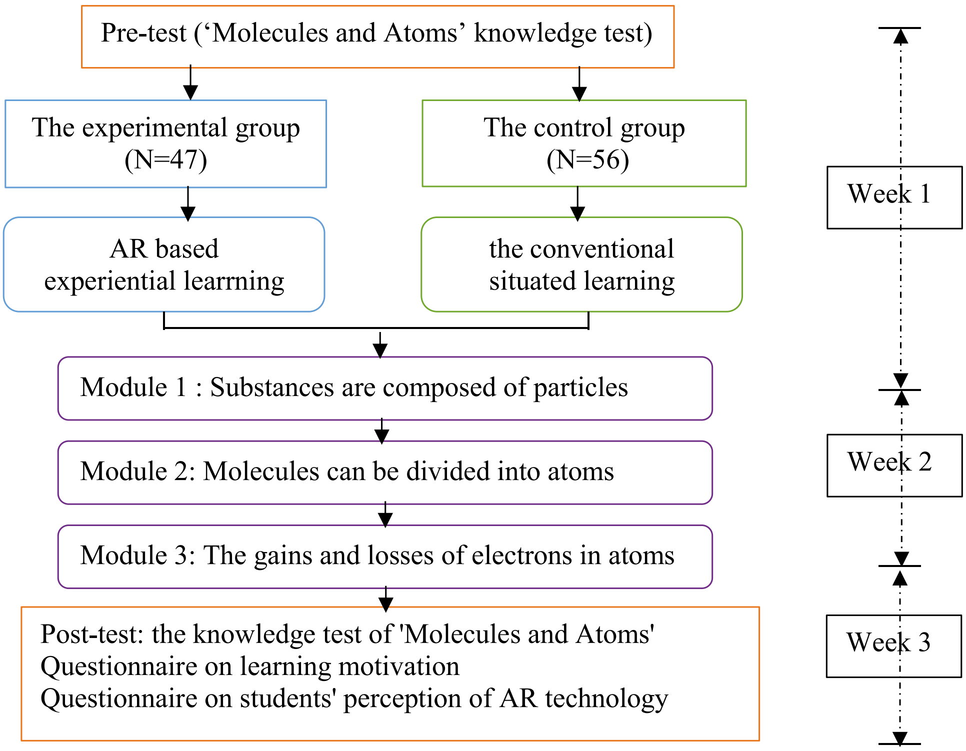

Fig. 6 Experimental procedure

teaching experience. There were ten questions in the pre-test for a maximum possible score of 10 points to examine the difference in prior knowledge between the two groups. The purpose of the post-test was to assess students' mastery of knowledge after studying in different conditions. It included three types of questions, which involved multiple-choice (11 items, 1 point each), fill-in-the-blank (11 blanks, 1 point each), and short answers (2 items, 2 points each), with a maximum possible score of 26 points. The post-test was divided into retention (16 points) and transfer (10 points) performance. Following Mayer (2005), this study defined retention as demonstrating a recollection of taught information. The transfer was defined as the ability to understand taught information and apply it in new settings. For instance, one retention test item is: "Water is composed of _____and diamond is composed of _____?" while an example of a transfer question is "Why are wet clothes easier to dry in summer than winter?" The specific questions are shown in the Appendix. The KR20 (Kuder & Richardson, 1937) values of the pre-and post-tests were 0.79 and 0.83,

Fig. 7 The learning situations of the two groups (**a** students in the non-AR group learned through the traditional teaching method; **b** students in the AR group learned with the ArAtom; **c** the learning materials used in the non-AR group; **d** the learning materials used in the AR group)

respectively, indicating high reliability of the knowledge tests.

Learning Motivation

The learning motivation questionnaire was adapted from Keller's (1983) IMMS (Instructional Material Motivation Scale) scale based on the ARCS (attention, relevance, confidence, satisfaction) model to evaluate students' learning motivation after the learning activities. There are 20 items across four dimensions: attention, relevance, confidence, and satisfaction. Each dimension contains five questions. The questionnaire uses a five-point Likert scale (1 = strongly disagree; 5 = strongly agree).

Technology Perception Questionnaire

The technology perception questionnaire was adapted from Davis (1985). In this study, the questionnaire was used to examine students' perception of AR technology in the experimental group along three dimensions: perceived usefulness (PU), perceived ease of use (PEOU), and use intention (UI), with a total of 10 questions. The questionnaire uses a five-point Likert scale (1 = strongly disagree; 5 = strongly agree).

Data Analysis

Since the sample size of this study is small, the Shapiro–Wilk test was performed and showed that all of the data sets had a normal distribution (pre-test $p > 0.05$; post-test $p > 0.05$; learning motivation $p > 0.05$). Consequently, the independent samples *t*-tests were conducted to investigate the effect of AR on knowledge gains and learning motivation.

Results

Analysis of Learning Outcomes

The descriptive statistics of the pre-test are shown in Table 2. The results revealed that there was no significant difference in chemistry knowledge between the two groups before the experiment ($t = 1.271$, $p > 0.05$).

As presented in Table 3, the post-test results were divided into three parts: total grades (TG), retention performance (RP), and transfer performance (TP). The means of the AR group (TG 20.67; MP 13.54; RP 7.13) for each dimension were higher than those of the non-AR group (TG 17.9; MP 12.88; RP 5). Furthermore, independent sample *t*-tests were conducted to examine the differences between the two groups. Specifically, the TG ($t = -3.65$, $p < 0.05$, $d = 0.75$) and TP ($t = -4.56$, $p < 0.05$, $d = 0.30$) scores of the experimental group were significantly higher than those of the control group, whereas the difference in terms of retention performance was not statistically significant at the 5% level ($t = -1.44$, $p = 0.152$, $d = 0.94$).

Table 2 Students' pre-test scores and independent samples *t*-test results

Group	*N*	Mean	SD	*t*	*p*
Control group	49	7.11	1.45	1.27	0.140
Experimental group	46	7.09	1.24		

In summary, the chemistry knowledge levels of the two groups improved after the experimental intervention. Students in the AR group had significantly higher total grades and transfer performance than those in the non-AR group. However, retention performance was not significantly different between the two groups, indicating that the AR experimental intervention did not have a distinct effect on retention performance compared with the traditional experimental intervention.

Analysis of Learning Motivation

As presented in Table 4, Cronbach's α value for the entire questionnaire was 0.965, and that for each dimension was above 0.800, indicating that the questionnaire was reliable. To further examine the impact of the AR-based experiential learning environment on students' learning motivation, an independent sample *t*-test was conducted (Table 5). The learning motivation questionnaire had four dimensions: attention, relevance, confidence, and satisfaction.

In terms of attention, the AR group showed a significant difference with the non-AR group (mean AR = 4.39, non-AR = 3.11, $t = -12.28$, $p < 0.05$, $d = 2.56$). The results demonstrate that AR technology used in class can arouse students' interest and attract students' attention better than the traditional learning method. Comparing the relevance results, the AR group again had significantly higher scores than the non-AR group (mean AR = 4.20, non-AR = 3.59, $t = -5.65$, $p < 0.05$, $d = 1.16$). This result indicates that using AR to present learning materials could help students establish connections between knowledge points. Regarding confidence, there was a significant difference between the two groups (mean AR = 4.24, non-AR = 3.37, $t = -7.31$, $p < 0.05$, $d = 1.51$), which indicates that AR can help students build up their confidence in learning, especially for abstract micro concepts. For satisfaction, a significant difference was found between the two groups (mean AR = 4.26, non-AR = 3.41, $t = -7.5$, $p < 0.05$, $d = 1.54$), which reveals that the students in the AR environment were more satisfied than those in the traditional learning environment.

Table 3 Students' post-test scores and independent sample *t*-test results

Dimension	Group	*N*	Mean	SD	*t*	*p*	Cohen's *d*
Total grades	Control group	49	17.90	4.29	−3.65	0.000	0.75
	Experimental group	46	20.67	3.02			
Retention performance	Control group	49	12.88	2.43	−1.44	0.152	0.30
	Experimental group	46	13.54	2.01			
Transfer performance	Control group	49	5.00	2.47	−4.56	0.000	0.94
	Experimental group	46	7.13	2.04			

In summary, AR technology was conducive to improving students' learning motivation. All four dimensions showed statistically significant differences between the AR and the non-AR group.

Analysis of Technology Perception

As shown in Table 6, Cronbach's α value for the entire questionnaire was 0.967, and the three dimensions were 0.927, 0.959, and 0.890, respectively; this suggests that the questionnaire was reliable. The technology perception questionnaire was used to measure the perceptions of the AR group students toward the AR application. The results are listed in Table 7. The scores of PEOU (mean = 4.58, SD = 0.50), PU (mean = 4.53, SD = 0.53), and UI (mean = 4.54, SD = 0.56) were higher than 4 (the maximum possible score was 5), implying that students had a high level of acceptance of the AR application.

Discussion

In this study, an AR-based experiential learning application covering the topic "The microscopic composition of substance" was developed to facilitate students' experiential learning in a chemistry course. To assess the effects of the implemented approach on learning, we experimented in a junior high school.

RQ1. How does the AR experience influence students' understanding of chemical knowledge?

First, the students in the AR group demonstrated significantly better knowledge gains than those in the non-AR group. This finding is consistent with previous studies (Akçayır & Akçayır, 2017; Cheng & Tsai, 2013), which consistently conclude that AR applications increase knowledge gains when compared to traditional approaches. In this study, the AR application integrates multiple representations (e.g., chemical symbols and relative atomic mass are presented in AR markers; 3D models display their composition and structure, and animations reflect the state in the reaction), which provide complementary information for students to develop an in-depth understanding by integrating them into a coherent mental model of the content (Ainsworth, 2014). Interestingly, we also found that students could gradually build the spatial imagination of the micro-world through three layers of experiential learning activities. For example, when the teacher asked students how to explain that a shrunken ping-pong ball would expand again when it was in hot water, students in the AR group replied that they could imagine the movement of air molecules, and the interval between them increased. This finding shows that the AR application can help students build spatial imagination and break through the representation dilemma of the micro-world (Rau & Matthews, 2017).

Table 4 The learning motivation questionnaire

Dimension	Items	Cronbach's α
Attention	Q1, Q6, Q11, Q15, Q20	0.888
Relevance	Q3, Q7, Q13, Q16, Q18	0.841
Confidence	Q2, Q4, Q9, Q12, Q19	0.886
Satisfaction	Q5, Q8, Q10, Q14, Q17	0.869
ARCS	20	0.965

Additionally, there was no significant difference in the retention performance between the two groups, contrary to some previous studies (Estapa & Nadolny, 2015; Lai et al., 2019). This result indicates that both AR and traditional paper-based learning materials are effective in facilitating students' memory of conceptual knowledge. According to the multimedia learning theory, the best way to help students remember concepts is to have learning materials presented integrating words and pictures (Mayer, 2005). In our study, the ArAtom and the traditional paper-based learning materials are similar in their function to present text and image information simultaneously, which is the possible reason for the no significant differences in the retention performance. A similar conclusion was also found in Weng et al. (2019)'s study; that is, AR technology did not have a significant effect on students' remembering and understanding levels, which are basic cognitive levels in Bloom's taxonomy. In addition, students in the AR group did not achieve better retention performance than students in the traditional paper-based group as expected, possibly because students in the AR group were overly focused on the AR technology itself and ignored the key conceptual knowledge in the AR system.

Table 5 Students' learning motivation scores and independent samples *t*-test results

Dimension	Group	*N*	Mean	SD	*t*	*p*	Cohen's *d*
Attention	Control group	49	3.11	0.47	− 12.28	0.000	2.56
	Experimental group	46	4.39	0.53			
Relevance	Control group	49	3.59	0.50	− 5.65	0.000	1.16
	Experimental group	46	4.20	0.55			
Confidence	Control group	49	3.37	0.59	− 7.31	0.000	1.51
	Experimental group	46	4.24	0.56			
Satisfaction	Control group	49	3.41	0.52	− 7.50	0.000	1.54
	Experimental group	46	4.26	0.58			

This issue has also been mentioned in the Erbas and Demirer (2019)'s study.

Moreover, there was a significant difference in the transfer performance between the two groups, which revealed that the AR application could help students understand and transfer knowledge. In terms of the technical advantages of AR, the AR application developed in this study simulates real-world substances through virtual objects, which enhances students' ability to relate the acquired knowledge to the real-world environment. Another important reason for the realization of knowledge transfer is the use of this study's three-layer experiential learning circle. In each layer of experiential learning, learners have experienced the process of learning and applying new knowledge so that students can realize the application and transfer of knowledge step by step. Previous studies such as those of Manolis et al. (2013) and Lai et al. (2007) also show that experiential learning offers students the opportunity to utilize knowledge in new situations.

RQ2. How does the AR experience influence students' learning motivation in chemistry?

The results demonstrated that the AR group had higher learning motivation than the non-AR group. This finding is in line with the reviews of Radu (2012) and Akçayir and Akçayir (2017), which indicate that AR can enhance learning motivation and positive attitudes. Specifically, the AR application improved students' learning motivation along the four dimensions of attention, relevance, confidence, and satisfaction. First, students changed from passive recipients to active knowledge explorers in the AR experiential learning environment, where they increased their engagement and attention to knowledge. This result implies that AR can promote interaction between students and the learning material, thus facilitating "learning by doing" (Hsiao et al., 2012). Second, familiar substances from daily life were selected (e.g., water and alcohol), and their molecules and atoms were presented. Therefore, the relationship between the micro and macro worlds was established to enhance the relevance of the learning content for the students. This finding confirms Lin et al. (2013) argument that AR is a supportive instrument for constructing students' knowledge in a way that clarifies the relations among theoretical concepts or principles. The non-AR group presents the learning content in static text and pictures. For novices new to microscopic phenomena, it is challenging to construct mental representations of molecular and atomic motions, which reduces their confidence in learning this point. While AR technology makes abstract content more intuitive and accessible for students to understand, thus enhancing their confidence and satisfaction. This finding is consistent with the findings of previous studies that AR is ideal for explaining micro phenomena that cannot be observed (Ibáñez et al., 2016; Lin et al., 2013).

Table 6 The technology perception questionnaire

Dimensions	Items	Cronbach's α
PEOU	Q1–4	0.927
PU	Q5–8	0.959
UI	Q9–10	0.890
Total	Q1–10	0.967

PEOU Perceived Ease of Use, *PU* Perceived Usefulness, *UI* Use Intention

RQ3. What is the students' perception of the AR-based experiential learning tool?

This study measured three aspects of students' perception of AR technology experience: perceived usefulness, perceived ease of use, and future use intentions. Results revealed that the scores of the three dimensions were all greater than 4 (the maximum possible score was 5), and the scores of the three items indicated that the AR application provided students with positive experiences. This finding corresponds with Liou et al. (2017) and Martin-Gonzalez

Table 7 Descriptive statistics of students' technology perception scores

Dimension	*N*	Mean	SD
PEOU	46	4.58	0.50
PU	46	4.53	0.53
UI	46	4.54	0.56

et al. (2016). In general, no students experienced learning difficulties due to technical usability issues, indicating that students had a positive perception of using this AR application. This finding implies that the AR application can be promoted to a more extensive range of use.

Although, from the data, students have a positive perception of the AR application, according to the teacher, some students in the AR group often asked the teacher to help solve the problems in operation, which is due to the student's lack of proficiency in the use of the AR application. This finding corresponds with the research of Liu et al. (2020), which interviewed students using AR technology. The result shows that more time could be allocated for students to become familiar with AR technology before the lesson.

Conclusion and Limitations

The microscopic composition of a substance is an abstract component of chemical knowledge. Students face difficulties constructing mental representations, leading to unsatisfactory academic performance and low learning motivation. Therefore, this study used AR technology to integrate multiple external representations, such as texts, images, 3D models, and operations, to provide hands-on experience at the micro-level. In addition, the existing studies rarely mention the combination of AR with knowledge structure and students' cognitive development processes. Hence, this study constructed a three-layer experiential learning model that combines AR technology and the learning process to help students build knowledge step by step through three-layer learning activities.

This study has both theoretical and practical implications. The main theoretical innovation of our AR application is the three-layer experiential learning circle constructed based on Kolb's experiential learning model, which provides a new perspective for researchers. Experiential learning is a spiral process consistent with Piaget's view of the process of students' cognitive development. As the practical contribution, this study enriches the research on the application of AR in chemistry, especially in microstructure teaching. The AR application developed in this study was shown to be effective in improving students' knowledge gains and learning motivation. In addition, this study also found that AR has a positive impact on the development of students' spatial imagination, which is crucial for chemistry learning. Moreover, AR tools can be used in various applications, especially in underdeveloped areas. Since AR has low requirements for equipment, only one mobile device is needed to provide AR resources to students in underdeveloped areas, thereby achieving a balanced distribution of educational resources.

This study has some limitations and suggests new directions for future research. First, the three-layer experience learning model constructed in this study is based on the knowledge of the microscopic composition of a substance. Future studies can test whether three-layer or multi-layer experiential learning applies to other disciplines or other types of knowledge. Second, this study found that AR had no significant effect on retention performance; a delay test can be conducted to re-examine the impact of AR on student retention and transfer performance. Finally, this study only uses quantitative data to analyze the pre- and post-test data to test the effectiveness and usability of AR tools. However, it is not clear how students develop chemical concepts during this process, which is the limitation of this study. We plan to explore how AR can facilitate students' conceptual development process based on the knowledge integration (KI) framework (Linn, 2006) in the future.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s10956-022-10014-z.

Funding This work was supported by Wuhan Science and Technology Bureau (grant number: 2020010601012190), Annual General Project of Henan Provincial Philosophy and Social Science Planning (2022BYJ016), Ministry of Culture and Tourism of China (grant number: 20201194075), and Fundamental Research Funds for the Central China Normal University (grant number: 2020YBZZ037).

Data Availability Data can be accessed by sending a request e-mail to the corresponding author.

Declarations

Ethics Approval All procedures performed in studies involving human participants were in accordance with the ethical standards of the Research Ethics Review Committee of Faculty of Education, Central China Normal University.

Consent to Participate The participants were protected by hiding their personal information during the research process.

All participants took part in the experiment voluntarily and they could withdraw from the study at any time.

Consent for Publication Not applicable.

Conflict of Interest The authors declare no competing interests.

References

Adadan, E. (2013). Using multiple representations to promote grade 11 students' scientific understanding of the particle theory of matter. *Research in Science Education, 43*(3), 1079–1105. https://doi.org/10.1007/s11165-012-9299-9

Ahmad, N. J., Yakob, N., Bunyamin, M. A. H., Winarno, N., & Akmal, W. H. (2021). The effect of interactive computer animation and simulation on students' achievement and motivation in learning electrochemistry. *Jurnal Pendidikan IPA Indonesia*, *10*(3), 311–324. https://doi.org/10.15294/jpii.v10i3.26013

Ainsworth, S. (1999). The functions of multiple representations. *Computers & Education, 33*(2–3), 131–152. https://doi.org/10.1016/S0360-1315(99)00029-9

Ainsworth, S. (2008). The educational value of multiple representations when learning complex scientific concepts. In J. K. Gilbert, M.Reiner, & M. Nakhleh (Eds.), *Visualization: theory and practice in science education* (pp. 191–208). Dordrecht: Springer Netherlands. https://doi.org/10.1007/978-1-4020-5267-5_9

Ainsworth, S. (2014). The multiple representation principle in multimedia learning. In R. E. Mayer (Ed.), *The Cambridge handbook of multimedia learning* (pp. 464–486). Cambridge, UK: Cambridge University Press. https://doi.org/10.1017/CBO9781139547369.024

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

Azuma, R. T. (1997). A survey of augmented reality. *Presence of Teleoperators & Virtual Environments, 6*(4), 355–385. https://doi.org/10.1162/pres.1997.6.4.355

Bain, K., Rodriguez, J. M. G., Moon, A., & Towns, M. H. (2018). The characterization of cognitive processes involved in chemical kinetics using a blended processing framework. *Chemistry Education Research and Practice, 19*(2), 617–628. https://doi.org/10.1039/C7RP00230K

Baptista, M., Martins, I., Conceição, T., & Reis, P. (2019). Multiple representations in the development of students' cognitive structures about the saponification reaction. *Chemistry Education Research and Practice, 20*(4), 760–771. https://doi.org/10.1039/C9RP00018F

Barak, M., & Hussein-Farraj, R. (2013). Integrating model-based learning and animations for enhancing students' understanding of proteins structure and function. *Research in Science Education, 43*(2), 619–636. https://doi.org/10.1007/s11165-012-9280-7

Barak, M., Ashkar, T., & Dori, Y. J. (2011). Learning science via animated movies: Its effect on students' thinking and motivation. *Computers & Education, 56*(3), 839–846. https://doi.org/10.1016/j.compedu.2010.10.025

Berg, A., Orraryd, D., Pettersson, A. J., & Hultén, M. (2019). Representational challenges in animated chemistry: Self-generated animations as a means to encourage students' reflections on sub-micro processes in laboratory exercises. *Chemistry Education Research and Practice, 20*(4), 710–737. https://doi.org/10.1039/C8RP00288F

Bernholt, S., Broman, K., Siebert, S., & Parchmann, I. (2019). Digitising teaching and learning–Additional perspectives for chemistry education. *Israel Journal of Chemistry, 59*(6–7), 554–564. https://doi.org/10.1002/ijch.201800090

Cai, S., Wang, X., & Chiang, F. (2014). A case study of Augmented Reality simulation system application in a chemistry course. *Computers in Human Behavior, 37*, 31–40. https://doi.org/10.1016/j.chb.2014.04.018

Chang, K. E., Zhang, J., Huang, Y. S., Liu, T. C., Sung, Y. T. (2019). Applying Augmented reality in physical education on motor skills learning. *Interactive Learning Environments* 1–13. https://doi.org/10.1080/10494820.2019.1636073

Chen, S., & Liu, S. (2020). Using augmented reality to experiment with elements in a chemistry course. *Computers in Human Behavior, 111*, 106418. https://doi.org/10.1016/j.chb.2020.106418

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

Chiu, J. L., & Linn, M. C. (2014). Supporting knowledge integration in chemistry with a visualization-enhanced inquiry unit. *Journal of Science Education and Technology, 23*(1), 37–58. https://doi.org/10.1007/s10956-013-9449-5

Davis, F. D. (1985). *A technology acceptance model for empirically testing new end-user information systems: Theory and results* [Doctoral thesis]. Massachusetts Institute of Technology.

De Jong, T., Ainsworth, S., Dobson, M., van der Hulst, A., Levonen, J., Reimann, P., ... & Swaak, J. (1998). Acquiring knowledge in science and mathematics: The use of multiple representations in technology based learning environments. In *Learning with multiple representations* (pp. 9–40). Pergamon/Elsevier.

Dunleavy, M., Dede, C., & Mitchell, R. (2009). Affordances and limitations of immersive participatory augmented reality simulations for teaching and learning. *Journal of Science Education and Technology, 18*(1), 7–22. https://doi.org/10.1007/s10956-008-9119-1

Ebert, E. S. (1994). The cognitive spiral: Creative thinking and cognitive processing. *The Journal of Creative Behavior, 28*(4), 275–290. https://doi.org/10.1002/j.2162-6057.1994.tb00734.x

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

Estapa, A., & Nadolny, L. (2015). The effect of an augmented reality enhanced mathematics lesson on student achievement and motivation. *Journal of STEM Education, 16*(3), 40.

Ewais, A., & Troyer, O. D. (2019). A usability and acceptance evaluation of the use of augmented reality for learning atoms and molecules reaction by primary school female students in Palestine. *Journal of Educational Computing Research, 57*(7), 1643–1670. https://doi.org/10.1177/0735633119855609

Fidan, M., Tuncel M. (2019). Integrating augmented reality into problem based learning: The effects on learning achievement and attitude in physics education. *Computers & Education,* 142. https://doi.org/10.1016/j.compedu.2019.103635

Garzón, J., & Acevedo, J. (2019). Meta-analysis of the impact of augmented reality on students' learning gains. *Educational Research Review, 27*, 244–260. https://doi.org/10.1016/j.edurev.2019.04.001

Gilbert, J. K. (2009). *Multiple representations in chemical education* (Vol. 4, pp. 1–8). D. F. Treagust (Ed.). Dordrecht: Springer.

Gilbert, J. K., Boulter, C., & Rutherford, M. (1998). Models in explanations, Part 1: Horses for courses? *International Journal of Science Education, 20*(1), 83–97. https://doi.org/10.1080/0950069980200106

Habig, S. (2020). Who can benefit from augmented reality in chemistry? Sex differences in solving stereochemistry problems using augmented reality. *British Journal of Educational Technology, 51*(3), 629–644. https://doi.org/10.1111/bjet.12891

Horz, H., Schnotz, W. (2010). Cognitive load in learning with multiple representations. *Cognitive Load Theory* 229–252. https://doi.org/10.1017/CBO9780511844744.013

Hsiao, K., Chen, N., & Huang, S. (2012). Learning while exercising for science education in augmented reality among adolescents. *Interactive Learning Environments, 20*(4), 331–349. https://doi.org/10.1080/10494820.2010.486682

Ibáñez, M., Di-Serio, A., Villaran-Molina, D., & Delgado-Kloos, C. (2016). Support for augmented reality simulation systems: The effects of scaffolding on learning outcomes and behavior patterns. *IEEE Transactions on Learning Technologies, 9*(1), 46–56. https://doi.org/10.1109/TLT.2015.2445761

Jarmon, L., Traphagan, T., Mayrath, M., & Trivedi, A. (2009). Virtual world teaching, experiential learning, and assessment: An interdisciplinary communication course in Second Life. *Computers & Education, 53*(1), 169–182. https://doi.org/10.1016/j.compedu.2009.01.010

Johnstone, A. H. (1993). The development of chemistry teaching. *Journal of Chemical Education, 70*, 701–705. https://doi.org/10.1021/ed070p701

Keller, J. M. (1983). Motivational design of instruction. In C. M. Riegeluth (Ed.), *Instructional design theories and models: An overview of their current status* (pp. 383–434). Lawrence Erlbaum.

Keller, J. M. (2010). *Motivational design for learning and performance* (pp. 227–286). Springer.
Koballa Jr, T. R., & Glynn, S. M. (2013). Attitudinal and motivational constructs in science learning. In *Handbook of research on science education* (pp. 89–116). Routledge.
Kolb, D. A. (1984). *Experiential learning: Experience as the source of learning and development*. Prentice Hall.
Kozma, R., Chin, E., Russell, J., & Marx, N. (2000). The roles of representations and tools in the chemistry laboratory and their implications for chemistry learning. *The Journal of the Learning Sciences, 9*(2), 105–143. https://doi.org/10.1207/s15327809jls0902_1
Kuder, G. F., & Richardson, M. W. (1937). The theory of the estimation of test reliability. *Psychometrika, 2*(3), 151–160. https://doi.org/10.1007/BF02288391
Lai, A., Chen, C., & Lee, G. (2019). An augmented reality-based learning approach to enhancing students' science reading performances from the perspective of the cognitive load theory. *British Journal of Educational Technology, 50*(1), 232–247. https://doi.org/10.1111/bjet.12716
Lai, C. H., Yang, J. C., Chen, F. C., Ho, C. W., & Chan, T. W. (2007). Affordances of mobile technologies for experiential learning: The interplay of technology and pedagogical practices. *Journal of Computer Assisted Learning, 23*(4), 326–337. https://doi.org/10.1111/j.1365-2729.2007.00237.x
Lee, N. Y., & Tucker Kellogg, G. (2020). An accessible, open-source mobile application for macromolecular visualization using augmented reality. *Biochemistry and Molecular Biology Education, 48*(3), 297–303. https://doi.org/10.1002/bmb.21335
Lemke, J. (1998). Multiplying meaning. *Reading science: Critical and functional perspectives on discourses of science*, 87–113.
Levy, D. (2013). How dynamic visualization technology can support molecular reasoning. *Journal of Science Education and Technology, 22*(5), 702–717. https://doi.org/10.1007/s10956-012-9424-6
Linn, M. C. (2006) T*he knowledge integration perspective on learning and instruction.* R. Sawyer (Ed.). In The Cambridge Handbook of the Learning Sciences. Cambridge, MA. Cambridge University Press.
Lin, T., Duh, H. B., Li, N., Wang, H., & Tsai, 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
Liou, H., Yang, S. J., Chen, S. Y., & Tarng, W. (2017). The influences of the 2D image-based augmented reality and virtual reality on student learning. *Journal of Educational Technology & Society, 20*(3), 110–121.
Liu, Q., Yu, S., Chen, W., Wang, Q., & Xu, S. (2020). The effects of an augmented reality based magnetic experimental tool on students' knowledge improvement and cognitive load. *Journal of Computer Assisted Learning, 37*(3), 645–656. https://doi.org/10.1111/jcal.12513
Manolis, C., Burns, D. J., Assudani, R., & Chinta, R. (2013). Assessing experiential learning styles: A methodological reconstruction and validation of the Kolb Learning Style Inventory. *Learning and Individual Differences, 23*, 44–52. https://doi.org/10.1016/j.lindif.2012.10.009
Martin-Gonzalez, A., Chi-Poot, A., & Uc-Cetina, V. (2016). Usability evaluation of an augmented reality system for teaching Euclidean vectors. *Innovations in Education and Teaching International, 53*(6), 627–636. https://doi.org/10.1080/14703297.2015.1108856
Mayer, R. E. (2005). *The Cambridge handbook of multimedia learning*. Cambridge University Press.
McElhaney, K. W., Chang, H. Y., Chiu, J. L., & Linn, M. C. (2015). Evidence for effective uses of dynamic visualisations in science curriculum materials. *Studies in Science Education, 51*(1), 49–85. https://doi.org/10.1080/03057267.2014.984506
Nechypurenko, P., Starova, T., Selivanova, T., Tomilina, A., & Uchitel, A. (2018). Use of augmented reality in chemistry education. In *Memoires of 1st International Workshop on Augmented Reality in Education. Kryvyi Rih, Ucrania. Kryvyi Rih State Pedagogical University*.
Ozdemir, M., Sahin, C., Arcagok, S., & Demir, M. K. (2018). The effect of augmented reality applications in the learning process: A meta-analysis study. *Eurasian Journal of Educational Research*, *18*, 1–22. https://doi.org/10.14689/ejer.2018.74.9
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
Özmen, H. (2011). Effect of animation enhanced conceptual change texts on 6th grade students' understanding of the particulate nature of matter and transformation during phase changes. *Computers & Education, 57*(1), 1114–1126. https://doi.org/10.1016/j.compedu.2010.12.004
Pikoli, M. (2020). Using guided inquiry learning with multiple representations to reduce misconceptions of chemistry teacher candidates on acid-base concept. *International Journal of Active Learning, 5*(1), 1–10.
Plass, J. L., Milne, C., Homer, B. D., Schwartz, R. N., Hayward, E. O., Jordan, T., Verkuilen, J., Ng, F., Wang, Y., & Barrientos, J. (2012). Investigating the effectiveness of computer simulations for chemistry learning. *Journal of Research in Science Teaching, 49*(3), 394–419. https://doi.org/10.1002/tea.21008
Radu, I. (2012). Why should my students use AR? A comparative review of the educational impacts of augmented-reality. *IEEE International Symposium on Mixed and Augmented Reality (ISMAR), 2012*, 313–314. https://doi.org/10.1109/ISMAR.2012.6402590
Rau, M. A. (2015). Enhancing undergraduate chemistry learning by helping students make connections among multiple graphical representations. *Chemistry Education Research and Practice, 16*(3), 654–669. https://doi.org/10.1039/C5RP00065C
Rau, M. A. (2017). Conditions for the effectiveness of multiple visual representations in enhancing STEM learning. *Educational Psychology Review, 29*(4), 717–761. https://doi.org/10.1007/s10648-016-9365-3
Rau, M. A., & Matthews, P. G. (2017). How to make 'more' better? Principles for effective use of multiple representations to enhance students' learning about fractions. *ZDM: The International Journal on Mathematics Education*, *49*(4), 531–544. https://doi.org/10.1007/s11858-017-0846-8
Santos, M. E. C., Chen, A., Taketomi, T., Yamamoto, G., Miyazaki, J., & Kato, H. (2014). Augmented reality learning experiences: Survey of prototype design and evaluation. *IEEE Transactions on Learning Technologies, 7*(1), 38–56. https://doi.org/10.1109/TLT.2013.37
Sirhan, G. (2007). Learning difficulties in chemistry: An overview. *Journal of Turkish Science Education, 4*(2), 2–20.
Squire, K. D., & Jan, M. (2007). Mad city mystery: Developing scientific argumentation skills with a place-based augmented reality game on handheld computers. *Journal of Science Education and Technology, 16*(1), 5–29. https://doi.org/10.1007/s10956-006-9037-z
Srisawasdi, N., & Panjaburee, P. (2019). Implementation of game-transformed inquiry-based learning to promote the understanding of and motivation to learn chemistry. *Journal of Science Education and Technology, 28*(2), 152–164. https://doi.org/10.1007/s10956-018-9754-0
Stieff, M., & Wilensky, U. (2003). Connected chemistry—Incorporating interactive simulations into the chemistry classroom. *Journal of Science Education and Technology, 12*(3), 285–302. https://doi.org/10.1023/A:1025085023936

Sunyono, S., Leny, Y., & Muslimin, I. (2015). Supporting students in learning with multiple representation to improve student mental models on atomic structure concepts. *Science Education International, 26*(2), 104–125.

Tekedere, H., & Göke, H. (2016). Examining the effectiveness of augmented reality applications in education: A meta-analysis. *International Journal of Environmental and Science Education, 11*(16), 9469–9481.

Treagust, D., Chittleborough, G., & Mamiala, T. (2003). The role of submicroscopic and symbolic representations in chemical explanations. *International Journal of Science Education, 25*(11), 1353–1368. https://doi.org/10.1080/0950069032000070306

Tsui, C. -Y. (2003). Teaching and learning genetics with multiple representations. Unpublished Doctoral Dissertation. Curtin University of Technology, Perth, Australia

Vaino, K., Holbrook, J., & Rannikmäe, M. (2012). Stimulating students' intrinsic motivation for learning chemistry through the use of context-based learning modules. *Chemistry Education Research and Practice, 13*(4), 410–419. https://doi.org/10.1039/C2RP20045G

Weng, C., Otanga, S., Christianto, S. M., Chu, R. J.-C. (2019). Enhancing students' biology learning by using augmented reality as a learning supplement. *Journal of Educational Computing Researc h* 073563311988421. https://doi.org/10.1177/0735633119884213

Wigfield, A. (1994). Expectancy-value theory of achievement motivation: A developmental perspective. *Educational Psychology Review, 6*(1), 49–78. https://doi.org/10.1007/BF02209024

Wu, H. K., Krajcik, J. S., & Soloway, E. (2001). Promoting understanding of chemical representations: Students' use of a visualization tool in the classroom. *Journal of Research in Science Teaching: THe Official Journal of the National Association for Research in Science Teaching, 38*(7), 821–842. https://doi.org/10.1002/tea.1033

Wu, H., & Puntambekar, S. (2012). Pedagogical affordances of multiple external representations in scientific processes. *Journal of Science Education and Technology, 21*(6), 754–767. https://doi.org/10.1007/s10956-011-9363-7

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

Wu, H., Lee, S. W., Chang, H., & Liang, J. (2013). Current status, opportunities and challenges of augmented reality in education. *Computers & Education, 62*, 41–49. https://doi.org/10.1016/j.compedu.2012.10.024

Wu, S., Lai, C., Hwang, G., & Tsai, C. (2021). Research trends in technology-enhanced chemistry learning: A review of comparative research from 2010 to 2019. *Journal of Science Education and Technology*. https://doi.org/10.1007/s10956-020-09894-w

Yakmaci-Guzel, B. (2013). Preservice chemistry teachers in action: An evaluation of attempts for changing high school students' chemistry misconceptions into more scientific conceptions. *Chemical Education Research Practice, 14*(1), 95–104. https://doi.org/10.1039/C2RP20109G

Yu, S., Liu, Q., Ma, J., Le, H., Ba, S. (2022). Applying Augmented reality to enhance physics laboratory experience: Does learning anxiety matter? *Interactive Learning Environments* 1–16. https://doi.org/10.1080/10494820.2022.2057547

Zheng, M., & Waller, M. P. (2017). ChemPreview: An augmented reality-based molecular interface. *Journal of Molecular Graphics and Modelling, 73*, 18–23. https://doi.org/10.1016/j.jmgm.2017.01.019