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The effects of an augmented reality based magnetic experimental tool on students' knowledge improvement and cognitive load

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Abstract

While the use of experiments is important for developing students' scientific knowledge and skills, challenges may arise when teachers and students are conducting experiments in class, such as non-reusable experimental resources, safety issues and difficulties simulating some specific effects. Augmented reality (AR) technology affords an alternative approach to conducting experiments by bringing students a virtual–real mixed learning environment. In this study, taking junior high school physics knowledge on the magnetic field as an example, we designed and developed an AR-based mobile simulated experiment tool. This study investigates the effect of the AR-based experiment on students' knowledge improvement and cognitive load compared with 3D and traditional experiments. A sample of 122 ninth-grade students was randomly chosen and assigned to three groups (AR, 3D and Traditional). The results demonstrate that students in the AR group performed better than those in the 3D and Traditional groups in terms of their knowledge improvement. The AR group students also experienced the lowest cognitive load among the three groups. Moreover, students had positive perceptions about AR and 3D tools. The implications of this study are discussed.

KEYWORDS

augmented reality, cognitive load, magnetic experiment

1 | INTRODUCTION

An experiment is a procedure carried out to support, refute or validate a hypothesis and is highly useful in allowing students to obtain knowledge and skills, particularly in engineering (Cooper, Vik, & Waltemath, 2015; Singh, Mantri, Sharma, Dutta, & Kaur, 2019). In traditional laboratory settings, real-world physical materials or apparatuses severed as manipulatives to support teaching or learning (Zacharia & Michael, 2016). However, issues still exist, such as high-cost instruments, non-reusable experimental resources, unpredictable safety problems and difficulties simulating some specific effects (Shufan, Qingtang, Suxiao, Yuanyuan, & Linjing, 2018). With the rapid development of Information Communication Technologies (ICT), experiment simulation has become possible. Use of a three-dimensional (3D) virtual experiment that aims to create a complete simulated environment to support student's experimental operation via personal computer (PC) or tablet has been taken into consideration among researchers in educational settings; some previous studies have demonstrated its benefits for students learning (Dalgarno, Bishop, Adlong, & Bedgood, 2009; Winkelmann et al., 2020). Given that physical experiments and virtual 3D experiments have their own unique affordances, certain researchers have considered the combination and integration of these two manipulatives into education (e.g., Olympiou & Zacharia, 2012; Zacharia & Michael, 2016). However, the parallel combination (i.e., first virtual manipulatives, then physical manipulatives when conducting experiments) in previous studies (e.g., Wang & Tseng, 2018), to some extent, splits the connection between the virtual and real worlds, and thus may impair students' hands-on experience by increasing their perceived cognitive load. In this regard, presenting related information on the real objects in real time seems to be a good solution, and augmented reality (AR) has become a viable alternative.

In an AR-created learning environment, virtual objects can be overlaid upon real-world scenes (Azuma, 1997), thereby providing students with an intuitive way of obtaining information and knowledge (Pellas, Fotaris, Kazanidis, & Wells, 2019). This makes AR a promising technology that may assist teaching and learning (Ibáñez & Delgado-Kloos, 2018); in fact, it has been widely used in recent years (e.g., Fidan & Tuncel, 2019; Garzón, Pavón, & Baldiris, 2019; Hung, Chen, & Huang, 2017). While AR has shown its potential in education, studies concerning the comparison of AR-based experiments and traditional physical experiments are rare, let alone examine the three conditions (AR, 3D, traditional) together.

In this study, an AR experimental tool concerning the knowledge of magnetism, which was an important topic in junior high school physics discipline, was designed to support the students' laboratory learning. To investigate its educational effectiveness, a 3D simulation experiment and a traditional physical experiment concerning the same knowledge as conveyed by the AR version were both included as control conditions in our study. According to previous studies (Ewais & De Troyer, 2019; Hsu, 2017; van Merriënboer & Sweller, 2005), different types of support within the context of laboratory learning may expose students to materials and device–environment interaction tasks with different level of complexity; thus, they may have different impacts on students' cognitive load and further influence their learning performance and perceptions of learning tools. Thus, this study mainly focused on measuring these three aspects (i.e., knowledge improvement, cognitive load and perception of learning tools).

2 | LITERATURE REVIEW

2.1 | Magnetism learning and augmented reality

Magnetism is an important topic in junior high school physics learning. The term describes a physical phenomenon that is mediated by magnetic fields (Stöhr & Siegmann, 2006). However, a magnetic field is an abstract topic that can only be depicted by imaginary curves (i.e., magnetic induction line), and the non-visibility of magnetic repulsion and attraction may lead to much confusion in students (Cai, Chiang, Sun, Lin, & Lee, 2017). In traditional physics classes, students utilize real permanent magnets to perceive the attraction and repulsion force between magnetic poles, while magnetic pins are used to simulate the distribution of the magnetic field. However, the magnetic pins are easily adsorbed on both ends of the magnet (Liu et al., 2019) and the residue is difficult to clean. To address these issues, researchers have adopted AR technology to visualize the magnetic field (e.g., Matsutomo, Mitsufuji, Hiasa, & Noguchi, 2013; Matsutomo, Miyauchi, Noguchi, & Yamashita, 2012).

AR technology allows virtual objects to be superimposed upon or composited with the real world (Azuma, 1997). Unlike other 3D simulation technologies, which mainly create a whole simulated environment isolated from the real world, AR creates a connection between the virtual and real environments (Milgram, Takemura, Utsumi, & Kishino, 1995). This feature brings learners more convenient and richer experiences than those in traditional virtual learning environments, particularly as portable mobile devices become pervasive (Akçayır & Akçayır, 2017; Mekni & Lemieux, 2014). The interactions in this virtual–real mixed environment constitute a more convenient simulation method of conducting magnetism experiments, that is, a real-time visualized magnetic field is superimposed on the physical magnets (Liu et al., 2019). In this regard, students could have a more intuitive observation of the magnetic field aligned to the real magnet that facilitates their learning about magnetism.

However, the studies concerning AR-simulated magnetic experiment and its educational applications are rare, and most of them focused on the technology level (e.g., Matsutomo et al., 2012, 2013). For example, Matsutomo et al. (2012) proposed an AR-based magnetic field visualization system, in which students could simulate the magnetic field using a real bar magnet in front of a computer camera. However, as the author described, the simulation method in their work is time-consuming; thus, the real-time simulation seems to be impossible without a high-performing PC, a fact that restricts its educational availability. In Cai et al.'s (2017) work, the magnetic field of a bar magnet was simulated using AR technology and motion-sensing technology by interacting with two hands. The results demonstrated that students in the AR group performed well in terms of learning outcomes and most students held positive attitudes towards the AR simulation. This was a pioneering work on simulating and evaluating the magnetic field of a permanent magnet in an educational setting. However, a computer and KINECT were also required for their study, which may limit the scalability of its educational applications. In this vein, it is meaningful to design and develop an AR simulated application concerning the characteristic of permanent magnets and related knowledge on portable devices, as this is an important topic in the junior high school physics curriculum.

However, although a high-quality virtual–real mixed magnetism experiment based on AR is needed, there are challenges regarding AR environments. For example, complicated tasks and large amounts of information may increase students' cognitive loads (Dunleavy, Dede, & Mitchell, 2009), as discussed in the next section.

2.2 | Cognitive load

Cognitive load is a multidimensional construct that represents the load imposed on learners' cognitive systems while performing a specific task (Paas & Van Merriënboer, 1994). Generally, there are three types of cognitive load: intrinsic, extraneous and germane loads (Sweller, Van Merrienboer, & Paas, 1998). *Intrinsic cognitive load (ICL)* relates to the difficulty of learning materials and cannot be directly manipulated by instructional designers. *Extraneous cognitive load (ECL)* relates to poorly designed instructional materials and can be influenced by instructional designers, while *germane cognitive load (GCL)* relates to the working memory resources that learners devote to the information relevant to learning. In an AR learning environment, the ECL of learners could be reduced for its virtual–real fusion and natural interaction characteristic (Azuma, 1997). Specifically, the information associated with physical objects and locations can be real-time presented as the learner progresses through the task. This spatiotemporal aligned information can help learners connect disjointed pieces of information (Bujak et al., 2013; Lai, Chen, & Lee, 2019). These unique affordances indicate that AR has great potential to reduce learners' cognitive load (i.e., reduce ECL, facilitate ICL and GCL), as has been demonstrated by empirical studies (e.g., Lai et al., 2019; Thees et al., 2020). However, conclusions are not always consistent, and certain research results have indicated a contradictory situation. For example, Dunleavy et al. (2009) found that students perceived a high cognitive load in an AR environment. Altmeyer et al. (2020) discovered that AR-supported lab work had a similar cognitive load to non-AR lab work. In view of the mixed results on cognitive load in AR identified by Ibáñez and Delgado-Kloos (2018), further investigation is required.

According to Paas, Tuovinen, Tabbers, and Van Gerven (2003) and Sweller et al. (1998), the assessment factors of cognitive load consist of mental load (ML), mental effort (ME) and performance. *ML* indicates the cognitive capacity required to process the complexity of a task, whereas *ME* reflects a learner's cognitive capacity or resources that are actually allocated to complete the learning task. These two dimensions usually are correlated; specifically, in an encounter with a complicated learning task or material, one could perceive high ML and thus devote more ME to performing or finishing it (Paas & Van Merriënboer, 1994). In this regard, researchers frequently combined both of them to rate the cognitive load of an individual (Mutlu-Bayraktar, Cosgun, & Altan, 2019). The learner's performance is related to differential learning items and errors, and can always be measured with standard acquisition tests. Generally, these three dimensions are always combined to discuss a positive instructional efficiency with respect to high performance and low cognitive load (ML, ME) (Paas & Van Merriënboer, 1994). This study investigated these three dimensions to attempt to fill the current research gap.

2.3 | Research questions

This study proposed an AR simulated experiment to facilitate students' learning about magnetism. To investigate its educational efficiency, an experiment was conducted. The aim of this study is to examine the effect of the AR tool and compare it to the effects of 3D and traditional experiments in terms of students' knowledge improvement and cognitive load. Moreover, it also examines the students' perceptions of the AR and 3D tools and experiences, which can indirectly reflect students' own ability towards digital learning materials (Davis, 1989), in order to provide a more comprehensive understanding.

Based on cognitive load theory and the unique affordances of AR (e.g., natural interaction, virtual–real fusion), we hypothesized the AR experimental tool would have a positive effect on students' learning when compared with other conditions. This study attempts to answer the following questions:

1. Does the AR experiment have any positive impact on junior high school students' knowledge improvement when compared with the 3D and traditional experiments?
2. Does the AR experiment have any positive impact on junior high school students' cognitive load level when compared with the 3D and traditional experiments?
3. What are the students' perceptions about the 3D and AR experimental tools, and the AR experimental learning experience?

3 | METHODOLOGY

3.1 | Design of materials

3.1.1 | Traditional experiment materials

To guarantee applicability of the learning materials in real teaching settings, we designed the learning materials based on the junior high school physics syllabus in China. In the Chinese junior high school ninth-grade physics textbook, the chapter concerning magnetic fields includes three topics: the magnetic phenomenon, the magnetic field of a permanent magnet and the geomagnetic field. As shown in Figure 1a, the traditional experimental tools consist of real magnets, a plastic demonstration board with magnetic pins in it, etc. Coins, wooden sticks and metal plates serve as auxiliary tools for students to experience the magnetic phenomenon. To understand the magnetic field, students put one or more magnets on the board, and the magnetic pins are arranged to follow the direction of the magnetic field. Students learn about the geomagnetic field from the textbook and through the teacher's guidance, starting from the phenomenon whereby the compass points south. To replicate the content of the traditional lesson, based on the characteristics of the respective technologies, we designed AR- and 3D-based applications to combine three main themes: Magnetic World Introduction, Magnetic Field Exploration and Knowledge Extension. The modules of the AR and 3D experimental tools are shown in Figure 1b,c, respectively.

3.1.2 | AR-based magnetic field experimental tools

To guarantee the affordances of AR (i.e., natural interaction, virtual–real fusion) truly benefit students in the current study, real-time spatiotemporal alignment of information is important. Accordingly, the main objective of AR version is to provide an accurate visualization of a magnetic field in real-time by a suitable algorithm. After reviewing the existing works on magnetic field calculation, we found some alternative methods that may be applicable: finite element method (FEM),

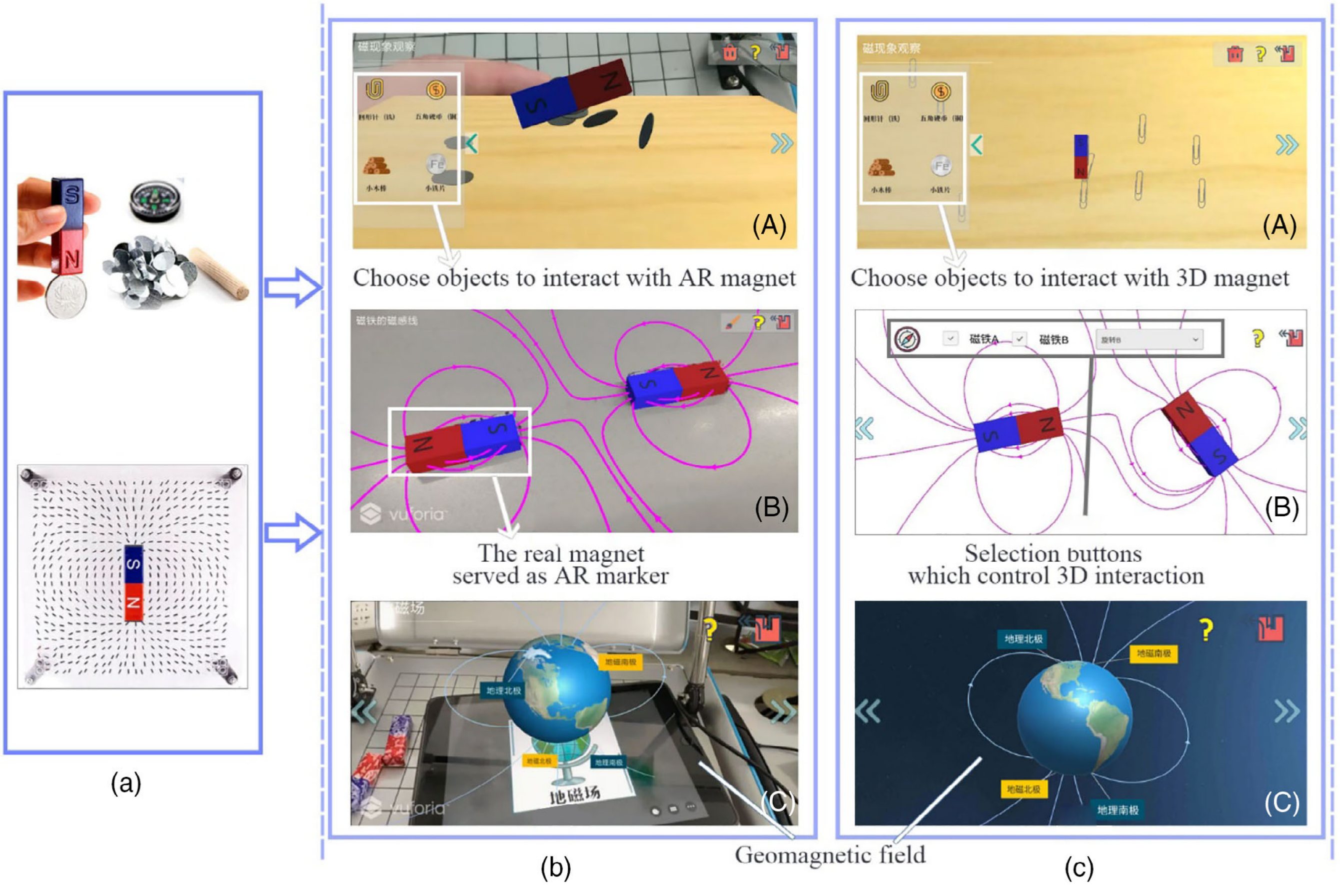

FIGURE 1 Typical modules of the three versions of the experimental tool: (a) Traditional version containing a real magnet on a plastic demonstration board with magnetic pins in it and some auxiliary objects; (b) The AR version, which utilizes real magnets as markers to simulate the magnetic induction line and image marker to visualize the geomagnetic field; (c) The 3D version, which uses touch interaction to control the virtual magnets and earth model [Colour figure can be viewed at wileyonlinelibrary.com]

boundary element method (BEM) and analytical method. Given that some previous studies delineated the FEM and BEM may limit its educational application scalability by requiring many calculations with a high-performing PC (Matsutomo et al., 2012, 2013), we tried two analytical methods [*method A*: realized in the work of Cai et al. (2017); *method B*: proposed by Gou, Yang, and Zheng (2004)], both of which mainly utilize mathematical methods and physical concepts that can be expressed with complete mathematics algorithms and theory, for conducting magnetic field calculation. By applying the demos implemented by these two methods on the same tablet (the tablet later used in the class teaching) with a screen size of 8 in., we found that, unlike the obvious lagging phenomenon caused by *method A*, *method B* can smoothly visualize the magnetic field (i.e., the magnetic induction line aligned to the real magnet in real time), by combining the Biot–Savart Law with the Law of Molecular Circulation. After further consulting some detailed information about this method (e.g., how to deal with the situation when magnet position changes) with physics professionals, we determined and finalized the algorithm formula based on *method B*. The experiments showed that the calculation results are conforming to the fact and magnetic field of bar magnet can be visualized in real time on mobile devices without any delay.

Based on the methods described above, the AR magnetic field application was developed. This tool consists of three modules that correspond to the three themes in traditional setting (i.e., Magnetic World Introduction, Magnetic Field Exploration and Knowledge Extension), as shown in Figure 1b:

1. *Magnetic Phenomena Observation*: This module provides four different objects: paper clips, copper coins, wooden sticks and metal plates. Students can scan the real magnet to interact with these virtual objects and understand which objects can be absorbed on the magnet and the basic properties of magnets.
2. *Simulation of Magnetic Induction Line*: This module utilizes real magnets as markers to visualize the magnetic induction line on them. Students can feel the forces between magnets while observing the real-time change to the magnetic induction line. This helps students to learn the properties of the magnetic field through embodied experiences.
3. *Geomagnetic Field Simulation*: This module aims to help students master knowledge about the geomagnetic field by visualizing it. Students can scan the corresponding image marker to present the virtual earth with its magnetic induction line.

In general, the visualizing effects conformed to the actual situations and each module of the AR experimental tool ran well on mobile devices after three rounds in which the modules were modified based on the ideas of three senior physics teachers.

3.1.3 | 3D-based magnetic field experimental tools

Similar to the AR experimental tool, the 3D experimental tool, which is shown in Figure 1c,A–C, also covers knowledge points in the textbook and consists of the same modules as the AR version. Students interact with the magnet through single-finger translation and two-finger rotation. In this system, the interactions are mainly haptic operations between students and the mobile device.

3.2 | Research design

An experiment was conducted in a junior high school in western China to compare students' learning gains and cognitive loads under three conditions: a traditional experiment, an AR experiment and a 3D experiment. This public school met the national school construction standards; thus, the classroom teaching situation here is close to the real teaching context in most schools in mainland China. A randomized Pretest–Post-test Control (PPC) design was adopted, with participants randomly assigned to one of the three conditions. The experimental condition was the AR experiment setting, while the 3D and traditional experiment settings served as the control conditions. Moreover, to make sure students are only influenced by the three different interventions, we strictly manipulated the learning conditions: treat the students with the same teacher; design the learning tools in the same module; and allocate the same time for each module of experiment.

3.2.1 | Participants

In this study, 126 ninth-grade students were invited to participate. They were randomly divided into three groups: the AR group (n = 42), the 3D group (n = 42) and the traditional group (n = 42). The students in each group were divided into seven subgroups with six students in each, and they were all taught by a physics teacher with 5 years teaching experience. In addition, three undergraduates knowledgeable in the materials served as assistants in case any unexpected conditions related to the tools should arise. After the data collection procedure, four students (three in the traditional group, one in the AR group) were eliminated from the data analysis because they did not complete the post-test. Therefore, our final sample comprised 122 participants (AR group: 41; 3D group: 42; traditional group: 39).

3.2.2 | The experimental procedure

The experimental procedure is presented in Figure 2. Two days before the experimental class, all three groups were given a pretest on Magnetic field knowledge (25 min). On the day of the experiment, to diminish the novelty effect mentioned by previous research (Akçayır & Akçayır, 2017), an enculturation session (20 min) was conducted to familiarize the students in the AR and 3D groups with the AR and 3D environments. The materials used in the enculturation session were not related to knowledge of magnetism. During this period, the traditional group students read the experimental textbook to understand the issues to which they needed to pay attention in the experiment.

The class teaching was then carried out in three different settings assisted by different experimental materials (45 min). During this period, for each group using the AR tools, a tablet holder was provided to place their device to avoid any recognition issues. The specific learning situations are shown in Figure 3. We next administered the post-test to examine students' magnetic field knowledge, cognitive load and perceptions of the tools (35 min). An additional interview was also conducted to further explore AR group students' feelings and attitudes about the experimental class.

3.2.3 | Data collection and instrument design

In this study, multi-fact data were collected, including students' knowledge quiz scores, the cognitive load level and their perceptions of the AR/3D learning tools. Semi-structured interviews were conducted with three students to further examine their learning experiences in the AR environment.

Magnetic field knowledge quiz

The magnetic field knowledge quiz aimed to test students' mastery of knowledge before and after the learning activity. The quiz was designed by three senior physics teachers who had taught the course for more than 10 years. After three rounds of discussion and polishing, all three teachers agreed with the finalized question items to measure the knowledge in the magnetic field chapter. It consisted of two types of questions: multiple choice (8 items, 2 points each) and fill-in-the-blanks (3 items; 9 blanks 2 points each). The knowledge quiz was used to test all three groups in the pre- and post-tests. To prevent students from remembering the answers between rounds, the order of the questions or options was changed slightly in each test. The detailed items and their corresponding knowledge points are shown in Table 1. The KR20 analysis (Kuder & Richardson, 1937) shows the reliability coefficient of the pretest and the post-test, respectively, were 0.64 and 0.61, indicating the test's moderate reliability.

Cognitive load scale

To measure students' cognitive load in different learning settings, we used the cognitive load scale based on the measures of Cheng (2017) and modified by the scale of Paas and Van Merriënboer (1993). The scale included two items that measured students' ME (i.e., invested cognitive capacity) and ML (i.e., perceived task difficulty), respectively.

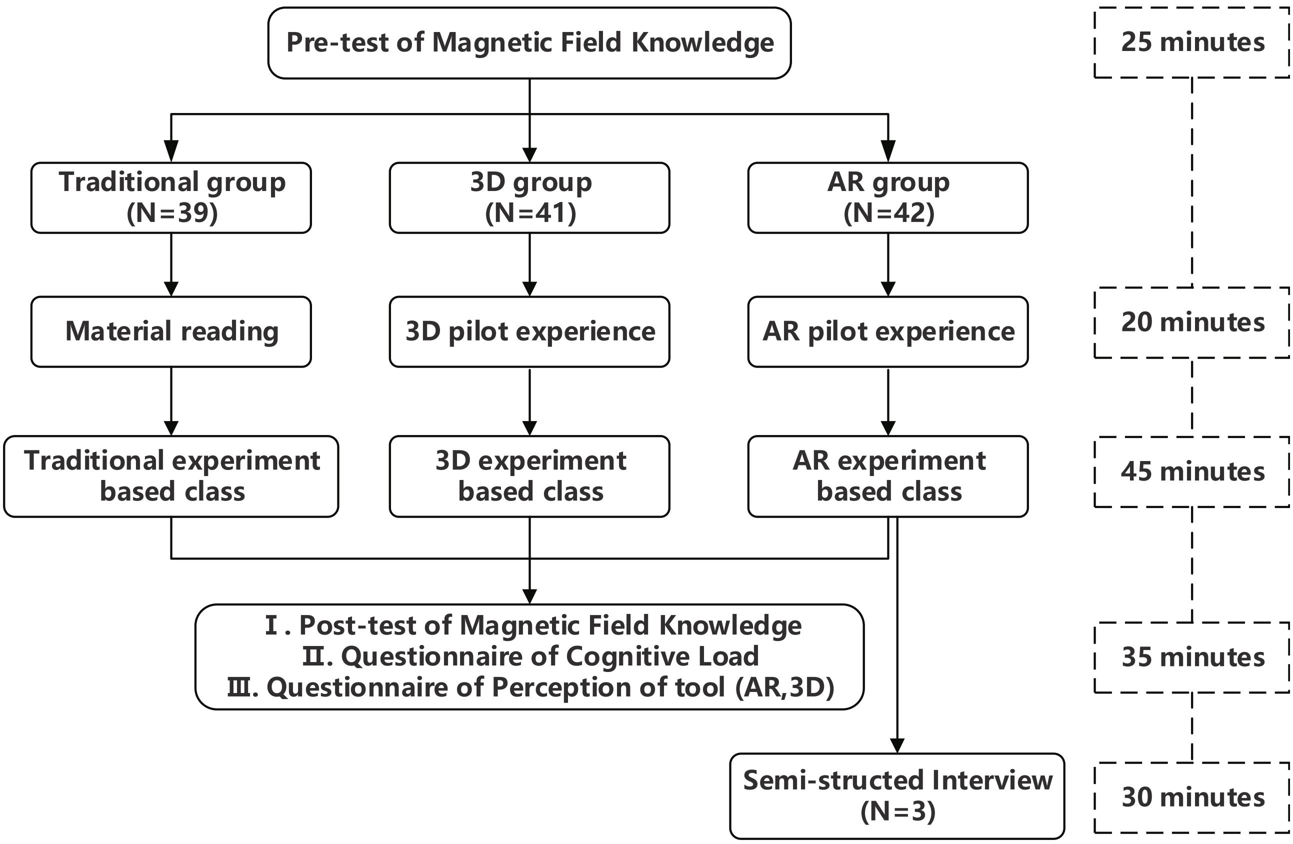

FIGURE 2 Experimental procedure

FIGURE 3 The three experimental learning situations: (a) Students in the Traditional group using real magnets and a plastic demonstration board to conduct the experiment; (b) Students in the 3D group using a pad with 3D magnetic application to conduct the experiment; (c) Students in the AR group using a real magnet and pad with AR magnetic application to conduct the experiment [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 1 Distribution of questions

Question type	*N*	Total score	Corresponding knowledge
Multiple choice	8	16	Magnetic field strength/properties/distribution
Fill-in-the-blanks	3	18	Geomagnetic field; Magnetization

The numerical values and labels assigned to the categories ranged from '*very very low mental effort/pressure (1)*' to '*very very high mental effort/pressure (9)*'. The cognitive load scale was administered to the participants in all three groups after the experiments. The Cronbach's α for the scale is .825, indicating high internal consistency for the scale.

Students' perception of the AR and 3D learning tools

Perception of the AR and 3D learning tools consisted of three dimensions: perceived usefulness (PU) (five items), perceived ease of use (PE) (five items) and continuance intention to use (CI) (three items). The PU and PE dimensions were adapted from the TAM Scale developed by Davis (1989), which measured students' degree of acceptance of the learning media. Specifically, PU aimed to measure students' subjective feelings and degree of satisfaction with the technologies. PE refers to the degree to which a person believes that using a particular system will be free of effort; that is, the extent to which they can easily use the system. The CI scale was developed by Joo, So, and Kim (2018) based on the work of Taylor and Todd (1995), and the content was changed to measure students' continuous intention to use the experimental tools in different groups. All items of these scales were rated on a 5-point Likert scale. The Cronbach's α for PU, PE and CI were .873, .684 and .903 respectively, indicating an acceptable reliability of the scale.

Semi-structured interview

Semi-structured interviews were conducted after the research intervention for a deeper understanding of the students' experiences with the AR experiments. The interview questions consisted of three parts: (a) How do you feel about the AR-based experiment? (b) How does AR help you to learn? and (c) What do you think about using AR for learning in a wider educational context? We randomly selected three volunteers for one-to-one interviews after the AR lesson. Each interview lasted for 8–10 min and was recorded with the permission of the interviewees. The audio interviews were then transcribed for data analysis.

4 | RESULTS

4.1 | Improvement of content knowledge

To investigate the students' level of mastery of magnetic field knowledge, a paired-sample *t* test was conducted. The full mark on the test was 36. The descriptive statics of pre- and post-test are shown in Table 2. Paired-sample *t* test results show significant improvements from pretest to post-test for all three groups (AR group: $t = 9.35$, $p < .001$; 3D group: $t = 6.885$, $p < .001$; traditional group: $t = 5.851$, $p < .001$).

As shown in Table 2, a one-way analysis of variance (ANOVA) for pretest scores was not significant [$F(2,119) = 0.185$, $p \geq .05$], indicating students in each group shared the same knowledge level concerning magnetism before the treatment. As such, we further compared post-test scores with an ANOVA, and significant differences were found [$F(2,119) = 16.75$, $p < .001$, $\eta^2 = 0.22$] among three groups. Accordingly, the Tukey's HSD (honestly significant difference) method was used to make a pairwise comparison of the differences between each pair of groups. The learning gains of the AR group were found to be significantly higher than those of the 3D group (Mean Difference = 3.02, $p < .05$, Cohen's $d = 1.13$) and the traditional group (Mean Difference = 2.89, $p < .05$, Cohen's $d = 1.11$), while the traditional group had a similar score to the 3D group (Mean Difference = 0.128, $p > .05$).

In summary, all three groups' content knowledge on magnetic fields improved after the experimental intervention. The students in the AR environment had significantly higher improvement on content knowledge than those in the 3D and traditional groups. There was no significant difference in content knowledge improvement between the 3D group and traditional group, implying that 3D experiments do not have a remarkable influence on content learning when compared to traditional experiments.

4.2 | Cognitive load

To investigate whether there were significant differences in students' cognitive load among the three groups, a one-way ANOVA was conducted to examine the impact of different experimental conditions on students' cognitive load when conducting the experiments. The cognitive load scale was divided into two dimensions: ML and ME. As shown in Table 3, there was a significant difference among the three groups both in ML [$F(2,119) = 7.225$, $p = .001 < .05$, $\eta^2 = 0.108$] and ME [$F(2,119) = 7.324$, $p = .001 < .05$, $\eta^2 = 0.109$). In addition, the correlation test found a positive correlation between these two dimensions (correlation coefficient = .496, $p < .001$).

Tukey's HSD method was conducted to further compare different groups' ME and ML. Regarding ML, significant differences were found both between the AR and 3D groups, and between the AR and traditional groups (AR-3D: Mean Difference = −1.080, $p = .001 < .05$, Cohen's $d = 0.88$; AR-traditional: Mean Difference = −0.700, $p = .048 < .05$, Cohen's $d = 0.5$). Specifically, the 3D group experienced the highest ML (3.74), followed by the traditional group (3.36) and AR group (2.66). This implies that the 3D tool imposed the highest experimental information interaction on students, while the AR tool

TABLE 2 Descriptive statistics of students' pre- and post-test scores and ANOVA results

		Pretest score			Post-test score		
Group	*N*	Mean	*SD*	*F*	Mean	*SD*	*F*
AR	41	22.68	5.002	0.185	31.02	2.485	16.762***
3D	42	22.07	5.483		28.00	2.803	
Tradition	30	22.05	5.477		28.12	2.716	

***$p < .001$.

TABLE 3 Descriptive statistics of students' cognitive load and ANOVA results

		Mental effort			Mental load		
Group	*N*	Mean	*SD*	*F*	Mean	*SD*	*F*
AR	41	2.85	1.32	7.324**	2.66	1.32	7.225***
3D	42	3.95	1.36		3.74	1.13	
Tradition	30	3.65	1.31		3.36	1.48	

***$p < .001$;
**$p < .01$.

TABLE 4 Independent sample *t* test on students' perceptions of the technologies between the AR and 3D groups

Dimension	Group	*N*	Mean	*SD*	*t*
PU	AR	41	4.21	0.63	0.831
	3D	42	4.10	0.52	
PE	AR	41	3.83	0.58	0.589
	3D	42	3.75	0.61	
CI	AR	41	4.26	0.63	0.569
	3D	42	4.18	0.60	

Abbreviations: CI, continuance intention; PE, perceived ease; PU, perceived usefulness.

imposed the lowest. Furthermore, the traditional group had a similar but slightly lower information interaction compared to the 3D group.

For the results of ME, the AR group also showed a significant difference to the other two groups (AR-3D: Mean Difference = −1.099, $p = .001 < .05$, Cohen's $d = 0.82$; AR-traditional: Mean Difference = −0.736, $p = .039 < .05$, Cohen's $d = 0.61$). Specifically, the 3D group invested the most ME (3.95), followed by the traditional group (3.65), while the AR group invested the least ME (2.85). The results demonstrate that integrating AR in experiments significantly reduced the amount of cognitive capacity students allocated for complementing the learning tasks by providing a virtual–real fused environment to help students construct knowledge.

4.3 | Students' perceptions and experiences of the technologies

The perception survey was administered to the AR and 3D groups after the experimental intervention to investigate their acceptance of and intention to use AR and 3D technologies for their learning. The mean and *SDs* of students' perceptions of technologies are shown in Table 4. An independent samples *t*-test revealed that there was no significant difference between the two groups in PU, PE or CI. In addition, the PU (AR: M = 4.21, 3D: M = 4.10) and CI (AR: M = 4.26, 3D: M = 4.18) of all groups were higher than 4, implying that students had a highly positive view on the use of AR and 3D for the physics experiments and they were keen to use them in their future learning. With regard to the PE dimension, the results show that the majority of students found the experimental tools easy to use and learn (AR: M = 3.83, 3D: M = 3.75).

To further investigate students' perceptions and experiences in AR class, we randomly selected three students (two boys and one girl) in the AR group for in-depth interview after the AR experiment lesson.

When asked about their perceptions of the AR class, all three students indicated that they were fond of this kind of learning. They considered the AR class interesting and it helped them to visualize the abstract knowledge by superimposing virtual objects onto a real scene. As one student shared, 'Using the pad to do the experiment was very interesting. The "cold magnet" became vivid in my eyes. It increased my class commitment and the class atmosphere was more active than usual. I think it was helpful for our physics learning'.

As for the AR technologies, students had different perceptions. Two of the students were satisfied with the AR technology in terms of its usability and they thought it was very easy to operate the system in the AR environment. The other student shared 'It is still difficult for me to use the AR technology because the navigation was not very clear. I haven't used other AR apps before. Although my group members helped me to finish the experiment, I need more time to digest the knowledge. Perhaps more time could be allocated for us to become familiar with the AR technology before the lesson'.

During the interview, the students demonstrated a strong willingness to continue to use AR in further lessons, particularly in science subjects such as chemistry. As one student stated, 'If conditions permit, I would prefer to use AR experiments. Compared with the traditional experimental lesson, AR presents us with more intuitive scientific phenomena. With AR, we could operate some dangerous experiments that are not possible in real lab settings'.

5 | DISCUSSION AND CONCLUSION

This study designed, developed, and evaluated an AR-based mobile experimental environment to assist students in learning magnetic field knowledge in a junior high school in China. To ascertain the educational effectiveness of the AR environment, a 3D application with equivalent information and traditional experiment was introduced in our study. An experimental study was conducted to compare these three learning environments for physic experiments (specifically, the magnetic field) in terms of students' knowledge improvement and cognitive load level.

The study found that students in the AR group performed better in terms of knowledge improvement than those in the 3D group and traditional group. This finding is in line with the review of Garzón et al. (2019), which found that most AR studies showed positive effects on students' learning when compared with other technologies. Regarding cognitive load, the AR group showed the least ML, which implies the characteristics of AR were fully utilized through the tools we designed; specifically, the virtual magnetic field can real-time superimpose on the real magnet, hence the spatial and temporal continuity of information were guaranteed, and students' perceived task difficulty (ML) was reduced (Lai et al., 2019). This finding is in line with the findings of Lee, Chen, and Chang (2016) and the continuity principle of multimedia learning (Mayer & Moreno, 1999). As for the results of ME, students in the AR group invested significantly lower ME than those in the other two groups. This implies that students in the AR condition were more able to process the complexity of the experimental task, which is consistent with some previous studies (e.g., Küçük, Kapakin, & Göktaş, 2016; Lee et al., 2016). Furthermore, the positive correlation between ML and ME corresponded to the cognitive load theory (Paas & Van Merriënboer, 1994). Overall, these findings indicate that the AR experimental tool significantly reduces students' cognitive load more than the other two groups by allowing abstract concepts (magnetic) to be transformed into concrete concepts and providing students with natural interactions (Azuma, 1997) using real magnets.

The perceptions of students in different groups towards the experimental tools were also examined and the results indicated that students in both the AR and 3D groups held positive views on the technologies in terms of their PU, PE and CI. This corresponds to former studies (e.g., Ewais & De Troyer, 2019; Liou, Yang, Chen, & Tarng, 2017), which found that students tended to have high positive perceptions towards AR or 3D learning tools due to its unique affordances (i.e., natural interaction, virtual–real fusion). Furthermore, the results of PE of the AR and 3D technologies were slightly lower than the other two dimensions, implying that not all students were very competent in using the AR and 3D technologies. Moreover, the findings from the in-depth interviews revealed that the AR technology notably enriched the students' learning experiences. As one student mentioned, AR increased his class commitment and learning interest by making the abstract concept concrete for him. This is similar to the study by Cai et al. (2020), who found that students felt AR could help them understand abstract concepts better. The results of the interview also support the survey findings. One student stated that it was still difficult for him to easily use the AR system, which may explain why the PE of the AR group was not higher than the other two dimensions. The strong willingness to use AR for learning in the future was evidence for the results of CI. To sum up, the AR technology is a promising experimental tool that enhances students' learning.

This study has both theoretical and practical significance. From a theoretical perspective, the presented work focused on a magnetic field experiment in junior high school physics, it used AR as a mediator to virtualize the experiment and enriched students' learning experiences. Unlike some existing studies (e.g., Hung et al., 2017; Singh et al., 2019), which took image as their AR marker, this study utilized the real object (bar magnets) as the AR marker and thereby allowed students not only to feel the attraction and repulsion force between different magnets but also to observe the changes in the magnetic induction line at the same time. The empirical findings of this study indicate that the AR experimental tool could reduce students' ML and ME and increase their knowledge improvement, thereby positively influencing their perceptions of this tool. Thus, this study filled a research gap in AR adoption and teaching about magnetism. Few prior researchers have provided a portable mobile experimental tool for conveying magnetic field knowledge in junior high school that is suitable for large-scale teaching and learning. Although Cai et al. (2017) found AR in magnetism teaching was feasible and had a positive influence on students' learning gains and attitudes, their system, which used KINECT as an auxiliary tool, required a high-performance PC. This rendered large-scale class teaching and learning impossible. Our research thus extended the research of Cai et al. (2017) and further investigated its effects on cognitive load. From the practical perspective, the findings of this study have implications for educators in enabling better design and implementation of experiments to enrich students' learning. This proposed AR experimental tool helped students understand and master the basic knowledge of the magnetic field while reducing their cognitive load.

Two distinctive features of our proposed AR experimental tool are delineated as follows: *a) serving the real magnet as the AR marker. b) using the professional algorithm to calculate the magnetic field*. As stated in the literature (Sırakaya & Alsancak Sırakaya, 2020), marker-based AR studies have mostly been conducted in K-12 settings. However, the majority used image markers. Object markers, which incorporate their own characteristics into AR experiences, show a significant positive effect on students' learning by providing multichannel interactions. More research on the design of AR learning environments is required in the future. For example, in the exploration of the laws of Newtonian mechanics, real wood blocks could be used as the marker, and AR could be used to visualize the real-time change of the force on it in different directions.

The magnetic field is an important science topic from middle school to university. Calculation of the magnetic field requires a complex differential and integral procedure. Some researchers have visualized it using Bezier curves (Liu et al., 2019), while others have used the magnetic field of a 'geometrically equivalent' solenoid with many turns to simulate it (Mannus, Rubel, Wagner, Bingel, & Hinkenjann, 2011). However, these methods may not have an authentic effect and cannot completely cover all situations, thus potentially leading to misconceptions among students. With the maturity of technology and the improvement of mobile device performance, it is feasible to make more realistic simulations using these complex but useful algorithms. This study recommends using professional algorithms to present some specific phenomena in the future, such as the simulation of acoustic waves.

One interesting finding of our study is that students in the 3D group showed similar results to the traditional group in terms of both knowledge improvement and cognitive load. This implies that not everything virtualized is good; we must consider the actual teaching and learning situations. In our case, students may have felt bored with the 3D application's interaction, which contains many different finger operations, while the absence of real magnets did not allow students to have an intuitive and deep understanding of the topic.

The semi-structured interviews provided evidence to support students' perceptions of AR for learning. According to Sırakaya and Alsancak Sırakaya (2020), the qualitative method has rarely been used in AR studies. More qualitative studies could be conducted to examine students' experiences in AR learning environments.

This study has a number of limitations. First, the number of students interviewed was few. For a comprehensive understanding and interpretation, it could be more convincing to recruit more volunteer interviewees from different groups and synthesize the results. Second, the student must have the same magnet as the developers, which restricts more people from conveniently using this AR tool. To avoid this, we would (a) switch the recognition target to two-dimensional image or (b) make several common magnet experiment instruments in primary and secondary schools. Third, the comparison of different calculation methods lacking rigour in this paper needs to be further explored in subsequent work. Fourth, this study administered a pre-test and post-test without considering the novelty effect on students' learning. Therefore, a delayed test could be conducted in the future.

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CONFLICT OF INTEREST

The authors declare no conflicts of interest.

PEER REVIEW

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available on request from the corresponding author.

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APPENDIX A: COGNITIVE LOAD SCALE

1. During the learning process, I have to understand the content of the learning material by investing more effort (mental effort).
2. During the learning process, the way in which the learning material is presented and explained gives me a lot of pressure (mental load).

APPENDIX B: PERCEPTIONS OF THE TOOLS SCALE

Perceived usefulness
1. This AR/3D physics learning tool can help me understand the experimental principle
2. Using this AR/3D physics learning tool can improve my learning efficiency
3. Using this AR/3D physics learning tool helps me complete classroom tasks more effectively
4. Experimenting with such AR/3D physics learning tools is more effective than other learning software I have used
5. I think this AR/3D physics learning tool is helpful for physics learning
Perceived ease of use
1. The AR/3D physics learning tool has clear navigation and friendly interface, and will not distract me
2. When using the AR/3D physics learning tool for experiments, I always run into one or more problems (R)
3. The hints in this AR/3D physics learning tool can help me better operate the experiment to solve the problem
4. When the content of the program shows an error, I can easily restore and come back to the previous experimental state
5. I think it is easy to use this AR/3D physics learning tool
Continuance intention to use
1. I am willing to use such a program in my future studies
2. I hope to use AR/3D learning tools in more disciplines
3. I am willing to recommend this AR/3D learning tool to my friends