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Integrating augmented reality into acoustics learning and examining its effectiveness: a case study of Doppler effect

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Abstract
While augmented reality (AR) technology has shown the potential to facilitate students' hands-on activities, few studies have explored its effectiveness in acoustic topics. This paper introduces an AR-based application for learning about the Doppler effect and investigates its educational effectiveness on students' learning achievement, interest, and attitude compared to a two-dimensional (2D) learning tool. Eighty-five junior high school students participated in our study, and they were randomly assigned to two groups (AR: $n=44$, 2D: $n=41$). The results revealed that students in the AR group outperformed those in the 2D group in terms of their learning achievement and interest. Both groups showed positive attitude toward the Doppler class and physics learning. Moreover, students presented a high level of cognitive perception toward the AR learning tool. This study provides a case for the application of AR in acoustics learning.

Keywords Augmented reality · Acoustics education · Learning interest · Learning attitude · Cognitive perception

1 Introduction

Acoustics, a field that studies the properties and behavior of sound waves, has numerous practical applications in our daily lives, such as the echoes that occur between the valleys and the Doppler effect observed between vehicles and people (Fahy, 2001). In education domain, it is essential for students to understand the fundamental concepts and underlying principles of acoustics to comprehend various phenomena, including the generation and propagation of sound and the Doppler effect (Cai et al., 2022; Doll et al., 2009). Traditional teaching tools, such as blackboards, slides, and videos, have been employed to establish a connection between theory and reality when teaching

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Extended author information available on the last page of the article acoustics concepts (Giménez et al., 2008; Mosabala, 2014). However, these tools are limited in their ability to provide an intuitive understanding of the spatial and temporal dependence of sound, which is crucial for learning sound (Giménez et al., 2008). Meanwhile, due to the invisible and intangible nature of sound (Cai et al., 2022), students often struggle to comprehend abstract acoustics concepts, such as sound waves, sound motion, and sound frequency (Giménez et al., 2008; Rossing et al., 2013). Furthermore, traditional teaching methods may not provide students with enough opportunities to engage with these concepts in a hands-on, interactive manner, leading to a lack of practical understanding (Liu et al., 2021).

Augment reality (AR) superimposes virtual objects onto the real world, enabling users to interact with virtual-real mixed information in real-time (Azuma, 1997). In recent years, AR has demonstrated its potential to enhance students' laboratory experience (Sırakaya & Alsancak Sırakaya, 2020), by facilitating their hands-on activities (Cai et al., 2017, 2022; Thees et al., 2022; Yu et al., 2022). Specifically, AR can present invisible phenomena and make them manipulable while students operate real equipment. For example, AR can visualize the magnetic fields and align them to the magnets in real time while students use their bodies or hands to move and rotate the magnet (Cai et al., 2017; Liu et al., 2021; Yu et al., 2022). Moreover, the convenience of AR, which can be deployed on a portable mobile device, makes it easy to integrate into a large-scale classroom setting (Cai et al., 2017; Yu et al., 2022). This integration enables students individually or collaboratively to complete tasks (Cai et al., 2017, 2022; Thees et al., 2022; Yu et al., 2022). The existing literature demonstrates that AR can effectively improve students' learning achievement and decrease their cognitive load (Buchner et al., 2022; Liu et al., 2021). AR has been implemented in various scientific topics, including visualizing the measuring data of electric circuit (Thees et al., 2022), providing natural interactions with magnetic induction lines (Cai et al., 2017), and enabling the manipulation and visualization of Coulomb forces (Tomara & Gouscos, 2019).

Regarding acoustics learning, AR has been considered an effective learning tool to integrate auditory and visual information (Best et al., 2020; Salmi et al., 2017), making it possible to visualize sound that is typically invisible and intangible. According to Mayer's modality principle, combining visual and auditory stimuli can enhance students' learning (Mayer, 2002). Therefore, with the help of AR, it is meaningful to visualize sound waves that change over time and their auditory properties using a mobile device's camera, screen, and speakers. According to previous studies, AR was primarily used in musical instrument learning, such as overlaying the fingers' information on the piano keyboard (Huang et al., 2011) and augmenting the theremin with visual cues (Johnson et al., 2020). Moreover, several researchers have attempted to enhance the learning of acoustics concepts and phenomena by augmenting sound propagation, speed of sound waves, and the Doppler effect, and have found that this positively affects students' learning experiences (Cai et al., 2022; Lazoudis et al., 2011). However, the effects of the aligned auditory and visual information on students' learning achievement and affective factors remain insufficiently explored. Furthermore, the utilization of AR has not been fully exploited to its advantage in improving students' hands-on manipulation during physics sound experiments or exploring scientific phenomena (Cai et al., 2022). Therefore, the first goal of this paper is to examine the effect of acoustics AR on students' learning achievement.

Previous studies have investigated the impact of AR on students' learning outcomes, yet they have often overlooked the measurement of affective outcomes, such as learning interest and attitude (De Jong et al., 2013). In education field, students' learning attitude and interest play an important role in facilitating meaningful learning (Akçayır et al., 2016; Bryant et al., 2013; Çetin & Türkan, 2021; Kapici et al., 2020). The learning interest is an important motivational factor and is considered the precondition of intrinsic motivation and a predictor of learning achievement (Chen & Liu, 2020; Hulleman & Harackiewicz, 2009; Shen et al., 2007). Repeated exposure to learning topics that trigger situational interest can help students develop sustaining interest, which forms the basis for persistent engagement in knowledge building (Bergin, 2016; Chen & Liu, 2020). With an enduring interest in science, students might attend more science-related courses and choose science as a future career (Hulleman & Harackiewicz, 2009). To cultivate enduring interest in an AR acoustics class, the first step is to investigate whether the AR manipulation promotes interest and achievement. Therefore, the second goal of this paper is to examine the effect of an AR-based acoustics application on students' learning interests.

When students face challenges in processing abstract concepts (e.g., the sound wave), their attitudes toward the course would accordingly decrease (Sahin & Yilmaz, 2020). AR has the potential to make abstract concepts concrete by visualizing them and providing students with interactive hands-on experiences (Liu et al., 2021; Sahin and Yilmaz, 2020). As a result, more relevant AR-based learning environments were developed to help students develop a positive learning attitude (e.g., Çetin and Türkan, 2021; Sahin and Yilmaz, 2020). However, although the impact of AR on learning attitude has been extensively studied for various scientific topics, there is a paucity of research examining the use of AR for teaching acoustics concepts. Further investigation is necessary to explore if activation of both the aural and visual channels through AR can foster students' positive learning attitudes.

The purpose of this study was to investigate whether the use of AR can enhance students' acoustics learning, specifically focusing on the Doppler effect. As a result, we developed an AR application called "DopplerAR" to teach junior high school students about this topic. A quasi-experiment was conducted to compare its effectiveness with a two-dimensional (2D) based application, and students' learning achievement, interest, and attitude were examined. Furthermore, we also investigated students' cognitive perceptions toward the AR learning tools, as these perceptions can indirectly reflect their aptitude for digital learning materials (Cai et al., 2014, 2020; Liu et al., 2021), thereby providing a comprehensive understanding of the effectiveness of AR in teaching acoustics concepts. By examining the potential of AR for acoustics education, this study contributes to the existing body of knowledge on technology-enhanced acoustical learning and provides insights into the effective integration of AR in hands-on inquiry activities. This work will also provide an exemplary case to enrich the *Immersive Learning Knowledge Tree* (Beck et al., 2021).

2 Literature review

2.1 Acoustics education and AR-based learning

Acoustics is taught in various disciplines, such as music, science, and physics, with the aim of imparting students' knowledge of the acoustical phenomenon and related scientific principles (Cai et al., 2022; Rossing et al., 2013). However, the invisible and intangible nature of sound can easily mislead students, preventing them from developing their own conceptions of learning (Cai et al., 2022; Fahy, 2001). For example, students may easily believe that the sound traveled in a straight line (Fahy, 2001). Furthermore, understanding acoustics requires a simultaneous understanding of the spatial and temporal dependence of sound (Giménez et al., 2008). In this respect, traditional teaching resources, such as blackboards, slides, and videos, may not be enough. This issue can be solved by simulations that could provide a continuous representation of sound and information over time. Previous studies utilized some non-interactive animations to present the Doppler effect (Giménez et al., 2008). While this approach may provide certain advantages over traditional methods, the lack of hands-on experience may hinder students' ability to integrate the auditory and pictorial information, thereby negatively influencing their learning interest and achievement (Chen & Liu, 2020).

AR allows virtual information to be superimposed on or combined with real-world objects (Azuma, 1997). Learners can acquire both knowledge and experience through interacting with AR-created virtual-real mixed world (Liu et al., 2021). In recent years, AR has demonstrated great potential for educational purposes, particularly in assisting unreachable experiments, such as the magnetism experiment (Cai et al., 2017; Liu et al., 2021), heat thermo experiment (Thees et al., 2020), electric circuit experiment (Thees et al., 2022), and optical experiment (Cai et al., 2021). AR can help students to connect disjointed pieces of information by creating a spatiotemporal-aligned environment (Lai et al., 2019; Liu et al., 2021). According to Mayer and Moreno (1999)'s contiguity principle, students would benefit from these simultaneously and adjacently presented words and pictures. From the cognitive perspective, aligned information can also decrease some redundant element interactions, thereby lowering students' mental effort and promoting their learning performance (Sweller, 2010). The most commonly reported affordances of AR include boosting students' learning achievement, increasing their sense of self-efficacy, and reducing their cognitive load, as highlighted in some previous reviews (Buchner et al., 2022; Garzón & Acevedo, 2019).

In the field of acoustics education, an ideal application of augmented reality (AR) is to align corresponding sound information, such as sound waves and visual cues (Cai et al., 2022; Johnson et al., 2020), with audible objects, such as scientific experimental tools, musical instruments, and speakers (Cai et al., 2022; Johnson et al., 2020; Church & Marasoiu, 2019). By reviewing the literature, we found most AR studies in acoustic education focused on music education, especially for the learning of musical instruments; researchers advocated overlaying visual cues on the real instrument (e.g., piano; Huang et al., 2011; theremin; Johnson et al., 2020; drum; Sakkal and Martin, 2019) to guide students' learning attention (Johnson et al., 2020). Meanwhile, some AR researchers have endeavored to promote the learning of acoustics concepts and phenomena. In Lazoudis et al. (2011)'s *Science Center To Go* project, the *Mini-fire truck* application was used to teach students about the Doppler phenomenon. The sound wave patterns were presented via the manipulated movement between a mini fire truck and a listener. Students expressed that they could gain understanding from the way AR presents the propagation and speed of sound waves. However, the apparatus was found to have difficulty representing the phenomenon when observers moved (Lazoudis et al., 2011), which may negatively impact students' hands-on experience. Cai et al. (2022) developed three applications (Ears and Sounds, Doppler Effect, and 3D Stereo) to facilitate students' conceptions of learning science. The result demonstrated that students generally held positive conceptions of learning science and a high level of scientific epistemic beliefs toward the AR acoustic learning experience. However, while those studies have implemented AR in acoustics learning, none investigated its effect on students' conceptual understanding and affective outcomes. Moreover, the adoption of AR has not fully utilized its advantages in enhancing students' hands-on manipulation in physics sound experiments or science phenomenon exploration. According to Yaghoub Mousavi et al. (1995), activating the auditory channel would offload some essential cognitive processing from the visual channel. This, in turn, can assist students in better understanding abstract and difficult learning information. Therefore, our study aimed to develop an AR application for learning acoustics, with a focus on investigating its impact on students' learning achievement.

2.2 Learning interest

Interest is a powerful motivator that drives individuals to engage, engross, or be entirely absorbed in activities to achieve certain goals (Dewey, 1913). In a learning activity, students' high level of interest would generate enthusiasm and motivation toward tasks (Tai et al., 2022), making it one of the most significant factors that directly or indirectly affect learning outcomes (Hidi, 1990; Palmer, 2009; Shen et al., 2007; Tai et al., 2022). In general, interest can be classified into two types: the personal interest that relates to an individual's long-term inclination toward a certain topic and the situational interest that relates to a student's short-term preference for a specific environment (Hidi, 1990). Multiple experiences of situational interest have the potential to develop into personal interest (Palmer, 2009). As such, researchers have been searching for effective learning technologies to increase students' situational interest, so as to develop long-term learning interests. In recent years, AR has shown its potential to facilitate students' positive emotions and, ultimately, increase learners' interest by providing virtual-real interaction and visualizing abstract knowledge (Bressler & Bodzin, 2013; Chen & Liu, 2020; Lee et al., 2016). Using AR, students can learn effectively and effortlessly, while simultaneously igniting their interest in science (Palmer, 2009). Chen and Liu (2020) explored the effects of AR on learning interest during a chemistry class, demonstrating that AR can effectively promote interest in science. Lee et al. (2016) discovered that AR could help to increase the interest of elderly adults in spatial ability training activities (Lee et al., 2016). AR's benefits in enhancing learning interest have been demonstrated in various subject areas, including chemistry experiment (Chen & Liu, 2020), science learning

(Bressler & Bodzin, 2013), and electromagnetism inquiry (Radu & Schneider, 2019). In our research, the DopplerAR would be designed to stimulate both students' auditory and visual channels. We hypothesized that integrating multimodal information and interaction would activate students' minds and improve their interest in learning about acoustics. In this regard, we were curious about examining students' interest in learning about the Doppler effect through the proposed AR application.

2.3 Learning attitude and cognitive perception

Attitude refers to the general tendency of an individual to respond favorably or unfavorably to an object, person, institution, or event (Ajzen, 1998). It is considered as a state of mind that manifests with learners' cognitive, behavioral, and emotional components (Breckler, 1984; Kapici et al., 2020). Students' attitudes toward science influence their efficacy in laboratory work (Akçayır et al., 2016), which in turn affects their willingness to continue learning science or pursuing a career in a related field (Kapici et al., 2020). When adopting new technologies, the learning process is associated with changes in students' attitudes (Cheng, 2017). Research has shown that the use of virtual technologies in hands-on experiments would help students build positive attitudes toward the science (Kapici et al., 2020; Yu et al., 2022). Unlike other instructional simulation technologies (e.g., 2D, 3D), AR provides an exciting, interactive, and immersive learning environment for students (Fidan & Tuncel, 2019), thus having the potential to facilitate their positive attitude. Several studies have revealed the positive impact of AR-assisted instruction on learning attitudes (e.g., Cai et al., 2020; Çetin and Türkan, 2021; Fidan and Tuncel, 2019; Yu et al., 2022). According to the technology acceptance model (Davis, 1989), the high degree of usefulness and ease of use of learning technologies would generate students' positive attitudes. Therefore, we sought to investigate the impact of AR assistance on students' attitude toward acoustics learning.

In an AR-based learning environment, it is crucial for the application to efficiently assist students in perceiving, interpreting, and understanding information (Cai et al., 2014, 2020; Liu et al., 2021). To determine the accuracy of an AR experiment in delivering physics concepts and its accessibility to different users, researchers have investigated participants' perceptions from several aspects, such as cognitive validity and accessibility (Cai et al., 2014, 2020), perceived usefulness, ease of use, and continuance intention (Liu et al., 2021). According to the literature, previous studies have primarily focused on students' technological perception towards AR based on the technology acceptance model (e.g., Álvarez-Marín et al., 2021; Liu et al., 2021), while overlooking some cognitive aspects of the AR tool and class. Regarding cognitive perception, few studies attempted to use cognitive validity and accessibility (CV and CA) to represent it. Specifically, CV indicates the extent to which the mental processes that learners use to perform tasks mirror the processes students use to perform the same tasks in real-life situations (Field, 2013), while CA reflects the extent to which a product can be used effectively, efficiently, and satisfactorily by intended users in a specific context (Miesenberger et al., 2019). For instance, Cai et al. (2014) incorporated AR into the learning of substance composition and found that the visualization of atoms could enhance students' CV and CA. In particular, students reported that the AR tool was beneficial for their learning, and they could efficiently operate the software. In our study, we were interested in determining whether the DopplerAR can accurately represent the acoustics concept that is being taught and can meaningfully engage students with the experiment. Accordingly, we utilized CV and CA as two essential dimensions to reflect students' cognitive perception, as suggested in previous studies (Cai et al., 2014, 2020). We hypothesize that the combination of auditory and visual information in the DopplerAR would have a high CV and CA, thus enhancing students' learning experience.

2.4 Research questions

This study aimed to explore the effectiveness of AR on students' acoustics learning when compared to a 2D simulation. Specifically, students' learning achievement, interest, attitude, and cognitive perception were examined to address the following research questions:

1. What are the differences in acoustics learning achievement between students in AR group and 2D group?
2. What are the differences in acoustics learning interest and attitude between students in AR group and 2D group?
3. What are the students' cognitive perceptions of DopplerAR?

3 Method

3.1 Learning materials

Doppler effect is a phenomenon that describes the changes in the frequency of a wave caused by relative motion between the wave source (e.g., sound, light) and the observer (Andrade, 1959). This phenomenon can be experienced in daily life; for instance, the sound of an approaching car engine or siren is higher in pitch than when it is receding. According to the Chinese junior high school physics syllabus (Ministry of Education of the People's Public of China, 2022), students are required to understand the Doppler phenomenon and its underlying principle. However, in a traditional class, the changing frequency of sound waves was hard for students to "visualize" in their minds, which would hamper their understanding of the Doppler effect. The difficulty of this topic may arise from the invisibility of waves and the limitations of static figures to depict a phenomenon that inherently involves movement (Mosabala, 2014). According to previous studies, it is possible to use AR to visualize and auralize some acoustics phenomena on markers, thereby facilitating students' understanding and perception of the sound or music (Cai et al., 2022; Mei & Yang, 2021). Therefore, this study developed the "DopplerAR" learning application according to the junior high school physics syllabus to enhance students' understanding of the Doppler effect.

As shown in Fig. 1. The DopplerAR consists of four modules, including *1. Generation and propagation of sound*, which provides some examples in our life of how

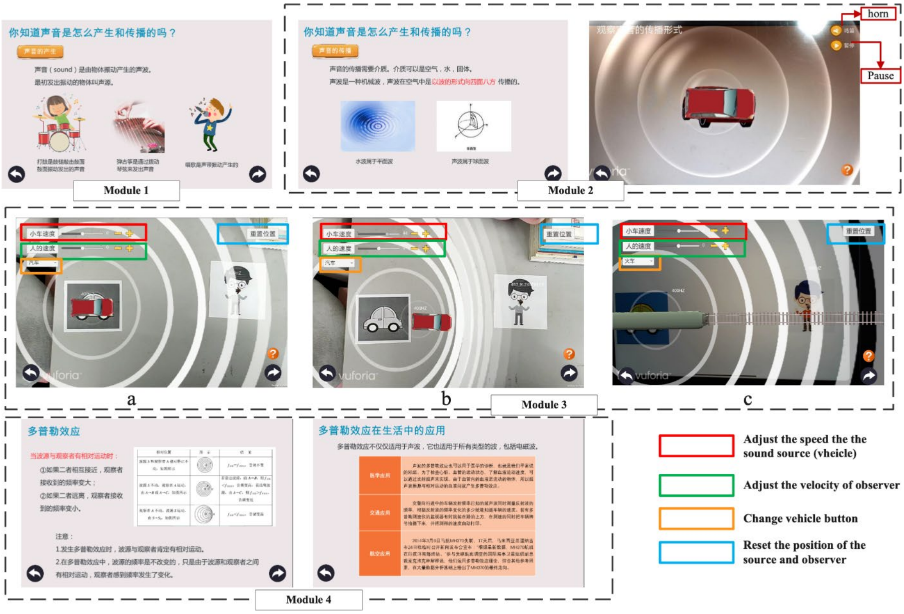

Fig. 1 The DopplerAR application (exploration modules): *Module 1*. Generation and propagation of sound. *Module 2*. Forms of sound propagation. *Module 3*. Doppler effect exploration. *Module 4*. The applicational examples of the Doppler effect

sound might be generated. *(2) Forms of sound propagation*, which impart the basic theory that sound propagates in the form of waves. (3) *Doppler effect exploration*, which provides students the AR markers to explore the principle of the Doppler effect, and *(4) The applicational examples of the Doppler effect*, which makes a conclusion on the knowledge of the Doppler effect and gives some applicational examples of the Doppler effect in our life. Modules 1 and 4 were mainly designed with words, pictures, and audio to introduce the basic acoustic knowledge related Doppler effect, while modules 2 and 3 provide some hands-on explorations with AR markers. Specifically, in the exploration session of module 2 (see the right part of Fig. 1- module 2), students can scan some AR markers (e.g., car, train) and interact with the two top right buttons to play and pause the sound of the horn. The corresponding sound wave will be real-time visualized.

In module 3 (see Fig. 1, module 3), we set up two types of AR markers: vehicles and kid. Regarding the vehicle, a 3D cartoon-style model of a car and a train were provided so that students could experience the Doppler effects in diverse settings. Figure 1- *a* represents the situation when the sound source (car) and observer (kid) stay relatively static, Fig. 1-b represents the situation when relative movement occurs between the observer (kid) and the source (car), and Fig. 1-c simulates the situation that when vehicle change to a train. Students can freely manipulate the top left buttons to adjust the speed of the sound source (vehicles) and observer (kid), as well as change the vehicles. Moreover, the top right button allows students to reset the position of both source and observer to their original status. With the DopplerAR, students can autonomously conduct the experiment by setting up the position, direction, and initial speed of the sound source (vehicles) and the observer (kid). Additionally, they can emulate the relative movement between the sound source and observer by moving the AR markers with their hands.

During the experiment, we also provided students with inquiry guidance to facilitate their knowledge acquisition during collaboration (Kollar et al., 2007). As shown in Tables 1, we set up four different scenarios in which the car is moving or stationary relative to the kid, to guide students' step-by-step inquiry. Students could use AR markers to physically manipulate the movement state of a vehicle and its position relative to the kid, as the car/train was keeping horning (See Fig. 1- module 3). The corresponding sound wave was real-time visualized, and changes in sound pitch were reflected by the tablet speaker. During this activity, students were tasked with demonstrating their understanding of the Doppler effect by filling in the provided box with either " > ", " < ", or " = ". Afterward, the instructor will explain the correct solutions and the underlying principles, allowing students to check their answers and develop their understanding.

We also provided a 2D-based application, featuring videos and a simulation covering the key concepts from modules 1, 2, 3, and 4 of DopplerAR. Unlike the AR version, students can only interact with the "play" and "pause" buttons to watch the pre-designed aminations or videos of the Doppler effect corresponding to the four situations outlined in Table 1. Additionally, they were also required to complete the inquiry materials during the learning process.

The two applications were administered in control (2D) and experimental (AR) groups. The detailed process will be delineated in the following section.

3.2 Participants and procedure

In this study, a control group posttest designed quasi-experiment was conducted to examine the effects of the DopplerAR on students' learning achievement, learning interest, learning attitude, and cognitive perception when compared to a 2D Doppler effect simulation. From two classes of a public junior high school in Wuhan, China, a total of 85 students aged 14–15 years were selected, reorganized, and randomly assigned to two groups: the AR group ($n=44$), which underwent intervention via DopplerAR, and the 2D group ($n=41$), which received treatment through 2D simulation (see Fig. 2). Next, students in each condition were further divided into 10 subgroups, each consisting of 3–5 students, based on their regular class achievement as

Table 1 The inquiry guidance: S represents the sound ***source*** (vehicles), O represents the sound ***observer*** (kid), f represents the frequency of the wave emitted by the sound source, and F represents the frequency received by the observer

Scenarios	*Result*
(1) The S and the O are relatively stationary	$F \square f$
(2) The O is moving; the S is stationary	If O is moving close to A, then $F \square f$ If O is moving away from A, then $F \square f$
(3) The S is moving; the O is stationary	If A is moving close to O, then $F \square f$ If A is moving away from O, then $F \square f$
(4) Both O and S are moving	If they are moving "face-to-face", then $F \square f$ If they are moving "back-to-back", then $F \square f$

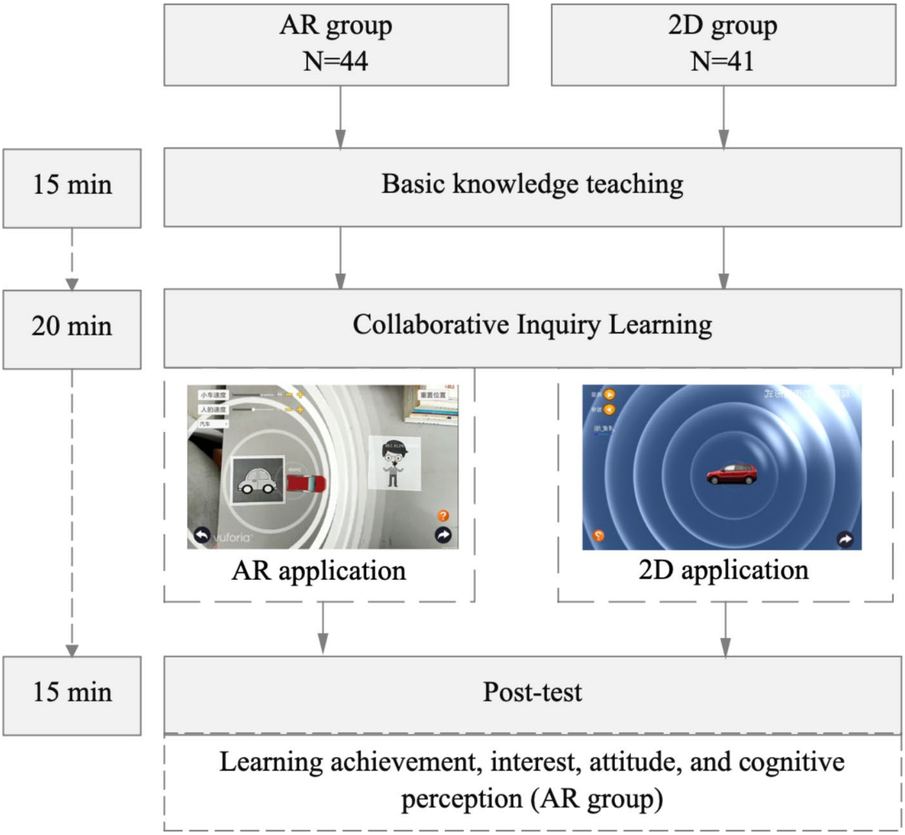

Fig. 2 The experiment procedure

evaluated by their physics teacher, to ensure each group had a similar composition. Students were required to collaboratively complete the AR inquiry activities in a regular physics course. None of the students had taken the Doppler class previously, and the experiment was initiated at the beginning of the new semester.

It is noteworthy that in the last semester, these students have learned some basic concepts of energy, pressure, and motion, including force and acceleration and how they are related to Newton's law of motion, which were considered as the prior knowledge of learning sound (Rossing et al., 2013). Additionally, according to the exam scores of the last semester (the total score was 100), there was no significant difference ($t\ (83) = 1.220$, $p = .226$) between the AR group ($M = 85.72$, $SD = 5.55$) and 2D group ($M = 84.15$, $SD = 6.39$). Furthermore, this school has implemented tablet instruction for several years, and every student can proficiently use a tablet. To this end, we assumed all the students shared a similar baseline regarding their prior knowledge and tablet-using experience. The entire experiment procedure was then designed, as shown in Fig. 2.

The experiment procedure consists of three phases. In the first phase (15 min), a physics teacher conducted a basic knowledge teaching on the Doppler effect, which included some real-world examples (e.g., When the train passes by, how does the sound of horn change), and an introduction to the Doppler effect. Two guiding questions were then provided to help students consolidate their understanding of the Doppler effect: Q1. In the Doppler effect, the observer perceives a change in the frequency of the sound, so is the frequency of the sound heard by the observer the same or different from the frequency of the sound source? Why? Q2. What is the relationship between the frequency of the sound source, the frequency perceived by the observer, and the relative velocity between them when the Doppler effect occurs?

With these questions, students moved to the second phase (20 min), either supported by DopplerAR (experiment group) or 2D application (control group). Specifically, we provided each subgroup (3–5 students) in two conditions with a tablet. Students should task with interacting, observing, and discussing to synthesize their answers to the questions given, with the assistance of their corresponding learning materials on a tablet (see Fig. 3) and the inquiry guidance (see Table 1). It is noteworthy that, while all students had access to the tablet in this session, one student typically acted as the operator, and others were observers. In this context, all group members were encouraged to offer their advice on performing the experiment and addressing the questions.

After completing the experiment, students in both groups were required to finish a post-test, including a Doppler knowledge quiz, a learning interest scale, and a learning attitude scale. Moreover, students in the AR group were also required to finish a scale concerning their cognitive perception of the AR learning material.

3.3 Instruments

3.3.1 Doppler knowledge quiz

The students' learning achievement was reflected by a Doppler knowledge quiz, it was designed by researchers based on the questions pool of Chinese junior high school physics discipline and checked by a middle school teacher who has 5-year

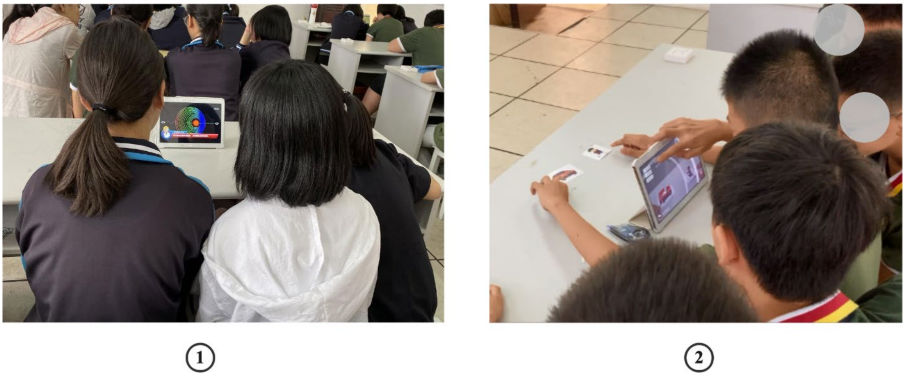

Fig. 3 Experimental situations: **(1)** 2D group: a 2D Simulation-based application was utilized to impart the basic principle of the Doppler effect **(2)** AR group: an AR-based app was provided to visualize the Doppler experiment, thereby providing the hands-on interaction with AR markers

teaching experience. Ten multiple-choice and three fill-in-the-blank questions with total scores of 20 and 6, respectively, comprise the finalized quiz (2 points for each). An example of a fill-in-the-blank item was: "When the observer is stationary relative to the medium and the wave source moves away from the observer, the frequency received by the observer will become___"; an example of a multiple-choice item was: "What is true about the Doppler Effect? A. When the Doppler Effect occurs, the frequency of the wave source changes. B. When the Doppler Effect occurs, the frequency received by the observer changes. C. The Doppler effect occurs when the observer and source have the same velocities. D. Only sound waves can generate the Doppler Effect." The Spearman-Brown coefficient for the quiz was 0.678, suggesting acceptable reliability in the internal consistency (LeBreton & Senter, 2008).

3.3.2 Scales

The study utilized various scales to measure students' learning interest, learning attitude, and cognitive perception toward the AR learning tool. Specifically, the learning interest scale (see section A in Appendix), comprising 9 items, was adapted from the measure of Hwang and Chang (2011) and modified to assess the level of interest in the course. Additionally, the learning attitude scale was leveraged to measure students' attitudes toward the Doppler learning and physics discipline after the intervention; it was adapted from Hwang and Chang (2011)'s scale and covered 7 items (see section B in Appendix). Furthermore, a learning attitude scale was provided to explore the students' perceived cognitive validity and accessibility (CV and CA) of the AR learning tool. The CV and CA constructs, consisting of 5 and 4 items, respectively, were adapted from the measurement of Cai et al. (2014), which originated from the scale developed by Chu et al., (2010). Lastly, an optional open-ended question was included to gather some qualitative feedback from students on the AR Doppler class (see section C in Appendix).

The items of each scale were in a five-point Likert rating in which the numerical value ranged from "*strongly disagree* (1)" to "*strongly agree* (5)." The learning interest and learning attitude scale were administered in both groups, while CV and CA were only used in the AR group. The Cronbach's α of these constructs (learning interest, learning attitude, CV, and CA) were 0.81, 0.76, 0.83, and 0.76, respectively, indicating the high reliability of the scales.

4 Results

The Shapiro-Wilks test, normal Q-Q plots, and box plots were first conducted to check the normality of the data. Results showed that, except for the learning achievement, learning interest and attitude were all approximately normally distributed in both groups. Therefore, a Mann–Whitney U test was conducted to compare students' learning achievement between groups, while an independent sample t-test was performed in both learning interest and attitude dimensions to compare the difference between the two groups. Besides, to obtain a more comprehensive understanding of the impact of each factor, we used the η^2 (small effect size $=0.01$, medium effect

Table 2 Descriptive statistics of learning achievement and results of Mann-Whitney U test

DV	Group	*N*	*M*	*SD*	*U*	*p*	η^2
learning achievement	AR	44	24.000	1.614	658.500	0.022	0.062
	2D	41	23.073	2.102			

Table 3 Descriptive statistics of learning interest and learning attitude and results of independent sample T-test

DV	Group	*N*	*M*	*SD*	*t*	*df*	*p*	Cohen's *d*
learning interest	AR	44	4.303	0.495	2.134	83	0.036	0.463
	2D	41	4.070	0.510				
learning attitude	AR	44	4.419	0.432	-0.144	83	0.886	/
	2D	41	4.432	0.413				

size = 0.06, and large effect size = 0.14) to calculate the effect size of learning achievement, while the Cohen's *d* (small effect size = 0.2, medium effect size = 0.5, and large effect size = 0.8) was employed as the measurement of effect size on learning interest and learning attitude (Cohen, 1988, 1992). The results are shown in Tables 2 and 3.

4.1 Learning achievement

According to the results of Mann–Whitney *U* test (see Table 2), the students in the AR group (M=24.000, SD=1.614) exhibited a significantly higher level of knowledge acquisition on the Doppler effect compared to those in the 2D group (M=23.073, SD=2.102) (U=658.500, p=.022), with a medium effect ($\eta^2 = 0.062$). The outcome implies that the DopplerAR can significantly facilitate students understanding of the Doppler effect when compared to the 2D application, by rendering the Doppler effect audible and visualizing its corresponding sound wave in real-time. This manipulation of dual-modality data is advantageous to the students.

4.2 Learning interest and attitude

The independent sample t-test was used to compare students' learning interest and attitude, and the results are shown in Table 3. As for the learning interest, after the treatment, students in the AR group (M=4.303, SD=0.495) presented more interest in Doppler effect. They were willing to learn more about the acoustic knowledge (t=2.134, p=.036<.05, Cohen's d=0.463) than those in 2D group (M=4.070, SD=0.510), which indicated DopplerAR did arouse students' curiosity on physics learning.

In terms of the learning attitude, the results showed that both two groups presented high but similar attitude toward the Doppler class and physics learning (p=.886; AR: M=4.419, SD=0.432; 2D: M=4.432, SD=0.413).

4.3 Cognitive perception of the AR learning

The CV and CA were utilized to assess students' cognitive perception of DopplerAR, the descriptive statistics are shown in Table 4. In general, the CV and CA were all

Table 4 Descriptive statistics of students' perception of the DopplerAR

No.	Items	*N*	*M*	*SD*
	Cognitive Validity	**44**	**4.086**	**0.711**
1	I think that AR presentation makes the learning materials more detailed and easier to understand.	44	4.318	0.708
2	I think that using this kind of inquiry AR learning tool is very helpful for learning physics.	44	4.205	0.823
3	This AR learning tool is more effective than any other software I have ever used.	44	3.659	1.160
4	Using this AR software enables me to master important knowledge points in an in-depth manner and comprehend the principles I did not understand in the past.	44	4.068	1.043
5	The AR learning tool provides abundant space for me to think and try, which aids me in solving problems.	44	4.182	0.815
	Cognitive Accessibility	**44**	**4.568**	**0.429**
6	Operating AR software is not difficult.	44	4.477	0.628
7	Learning to use AR tools does not cost me a great deal of time and energy.	44	4.455	0.548
8	The content of and procedures for this learning activity are clear and understandable to me.	44	4.568	0.545
9	I can grasp how to operate AR software within a very short timeframe.	44	4.773	0.522

higher than 4, indicating that students in AR group hold a positive perception on the DopplerAR.

As for the result on CV, out of the five items, questions 1, 2, and 5 have the highest score with a point average higher than 4.15. These results suggest that students think the AR learning materials are rich in information, easy to use, and beneficial for improving learning, thinking, and problem solving. The remaining two items, 3 and 4, had relatively low ratings (3.659, 4.068), indicating that while the majority of the students agreed that DopplerAR was useful for learning, some of its characteristics might be insufficient to promote students' in-depth understanding.

Regarding the CA result, all four items had high scores close to the full mark of 5, suggesting that junior high school students find it easy to use the DopplerAR.

To better understand students' learning experience, apart from their quantitative ratings on CV and CA, we also collected their subjective feedback on the AR experience and received 12 students' responses (7 boys, 5 girls). According to the results, the qualitative content can be categorized into *perceptions of the AR learning experience* and *perceptions of AR learning tool.*

As for the *perceptions of the AR learning experience*, five out of twelve students provided their feedback. Among them, four indicated that the AR class was interesting, and three declared that the aural-visual aligned learning content made it easy for them to understand the Doppler effect. Additionally, all students who provided feedback on the AR learning experience expressed that this type of class facilitated their experimental operation and helped them understand abstract phenomena. For example, Student #11 stated, "While it is not my first time using AR, the learning content in this AR class piqued my interest, and I think the step-by-step exploration did help me to solve the questions on the inquiry guidance sheet. If possible, I would like to experience more classes that are supported by AR."

Regarding the *perceptions of AR learning tool*, nine students gave their feedback. According to their responses, we found that seven students highlighted the usability of DopplerAR and indicated that it was easy to use in terms of the ***UI design*** (#35: “The color and user interface were designed well, which did not split my attention”), ***the interaction*** (#37: “The interaction with markers is really interesting”), and ***the function of DopplerAR*** (#41: “The abstract learning content was reasonably visualized with the AR tool, which made me feel excited, especially when seeing the sound wave superimposed on the small car”).

In addition to the positive feedback, some students pointed out the defects of DopplerAR. On the one hand, the *arrangement of learning content* was questioned, as Student #39 wrote, “While this application has four modules, we only had the hands-on experience with module 3, and other modules mostly consisted of pictures, words, and videos, which could also be included in the teachers’ slides. If possible, I would like to experience more inquiry-based learning experience using AR interaction”. On the other hand, the *interaction method* was also criticized, as depicted by Student #34, “The interaction with the AR marker is incredibly intriguing, but I find it a little challenging because I have to position the child on the car’s driving path. The phenomenon was not clear if I placed it in a different direction.”

5 Discussion and conclusion

While AR has been increasingly adopted in physics education, its integration with acoustics has rarely been discussed. The Doppler effect, which involves the understanding of the changes in sound waves caused by relative movement between a sound source and receiver, is difficult to grasp by using traditional learning resources (Mosabala, 2014). To address this, we developed an AR-based application to support students’ learning of the Doppler effect. To ascertain its educational efficacy, a 2D Doppler effect application was also introduced in this study. We conducted a quasi-experiment to compare the learning achievement, learning interest, and learning attitude of students in the two groups. Moreover, a CV and CA scale, as well as an open-ended question were utilized to assess students’ cognitive perception of the AR-based experimental tool. The findings are discussed below.

As for the learning achievement, the students in AR group achieved a significantly higher score than those in 2D group, implying that DopplerAR can effectively promote students’ learning on the topic of Doppler effects by superimposing the abstract sound wave on the sound generator (i.e., car and train). This result reaffirmed the educational benefits of AR on learning gains and was consistent with previous studies (e.g., Buchner et al., 2022; Cai et al., 2022; Liu et al., 2021; Yu et al., 2022). According to Mayer and Moreno (1999)’s contiguity and multimodal principle, the combination of disjoint information and using of aural-visual multimedia representation could facilitate students’ learning. In the current context, the virtual-physical encoded environment created by DopplerAR can assist students in autonomously manipulating the sound source and observer and enabling them to “see” the changes of the sound (Bujak et al., 2013), thereby improving their learning outcome and helping them concrete the Doppler effect representation in their minds. In terms of learning interest, students demonstrated significantly higher levels of interest in the use of AR as compared to their 2D counterparts. This indicated that the AR successfully piqued students' interest in learning about acoustics, which reinforced the AR's advantages on learning interest (e.g., Bressler and Bodzin, 2013; Chen and Liu, 2020; Lee et al., 2016; Radu and Schneider, 2019) and extended its application to acoustic education. When it comes to learning attitude, students in the two groups presented similar high results, showing that both 2D and AR simulation could develop students' positive attitudes toward the learning of physics. This result was in line with former studies which revealed the positive effect of virtual simulation on the learning attitudes (e.g., Cai et al., 2020; Çetin and Türkan, 2021; Fidan and Tuncel, 2019; Yu et al., 2022). Although AR group did not show significantly higher results than 2D group, the high rating (greater than 4.4) to some extent signified the usability of DopplerAR in developing learners' positive attitudes.

We also collected students' CV and CA to examine their cognitive perception of DopplerAR. Generally, the results demonstrated that the DopplerAR shared the same cognitive process involved in real-world Doppler experiments, and the students can effectively, efficiently, and satisfactorily complement their learning tasks (Miesenberger et al., 2019; Winke et al., 2018). This tallies with the findings of previous studies (Cai et al., 2017, 2020; Liu et al., 2021). One low value was found on the item that related to the AR's effectiveness when compared to other learning media. This may explain why students in both groups exhibited similar learning attitudes after treatment. However, it may also indicate some potential shortcomings of the DopplerAR class. For instance, according to our observation, certain students showed a strong preference for interacting with the two types of AR markers (i.e., kid and vehicles). When the sound was generated as they moved the AR markers, they expressed excitement and even shouted during class. However, when performing the experiment, they were hesitant to look at the questions on the inquiry guidance, which may also lower their learning outcomes and exemplify why some students may believe the DopplerAR is insufficiently effective.

The open-ended question results further corroborated our quantitative findings. Students considered the DopplerAR is easy to use in terms of well-designed UI elements, smooth interactions, and helpful functions. Moreover, they reported that the aural-visual aligned learning content could assist them in understanding the abstract concept of the Doppler effect, while also aiding in the completion of experimental operations, thereby generating interest in the topic. It is obvious that AR enhanced students' learning experience, which echoes the findings of Cai et al. (2014, 2020) and partially reinforces the positive results on learning achievement, interest, attitude, and CA. However, students expressed some concerns regarding the insufficient time for hands-on inquiry and the inconvenience of positioning, highlighting the need for clear guidance and appropriate time during AR-based classes. These issues may also account for the relatively low scores on items 3 and 4 of the CV scale.

In summary, our study proposed an AR application to aid in the acoustics learning of junior high school students on the concept of the Doppler effect and conducted a comprehensive evaluation by comparing it to a 2D application. We found AR positively impacted learning achievement, learning interest, and cognitive perception, leading us to recommend the integration of more acoustics AR applications in both formal and informal education settings. AR can harness the unique characteristics of sound, utilizing mobile device functions to create interactive experiments that activate multiple sensory channels of learners (e.g., optical, acoustical, and haptic sensory). Additionally, our study indicated that AR and 3D materials have the same benefits for promoting learning attitude toward learning. However, we suggest drawing this conclusion cautiously by considering some boundary conditions, such as the learning topics, the manipulative types, and the intervening time. Meanwhile, further exploration through longitudinal studies is necessary to examine the learning attitude changes over time when using different types of manipulatives. Lastly, this study also reiterated the benefits of collaborative inquiry by using AR during a regular class, emphasizing the importance of investigating AR collaboration learning mechanisms, such as interaction patterns among students in varying class settings.

This study has some limitations that should be acknowledged, as well as some future directions for consideration. First, it is important to note that DopplerAR does have some flaws as mentioned by students, such as the virtual child and car cannot automatically parallel and face in the same or opposite direction. Although students can rotate the AR markers to align them, this high level of "autonomy" may cause inconvenience for them during hands-on activities. In this regard, we should consider the appropriate guidance in future AR works. Moreover, with regard to the insufficient inquiry activities and issues with user interaction, we suggest designing more easily manipulable operations that would decrease the extraneous element interaction and the amount of extraneous learning content that is not related to inquiry activities (Sweller, 2010). Second, the inquiry guidance used to facilitate collaboration was not recorded or scored, which limited the findings of our results. In the future, we will consider this procedural data to get a thorough understand of how students learn and collaborate when they are treated with AR. Third, it is worth noting that we did not strictly control the number of students in each subgroup during the intervention, which may influence their collaborative patterns and learning efficiency (Lin et al., 2012; Wang & Yu, 2023). As such, further investigation into the effects of group numbers on learning achievement would be beneficial in future studies. Fourth, although our study collected qualitative responses from 12 students, obtaining additional subjective responses or conducting interviews during an AR class may yield more robust qualitative evidence. Meanwhile, the intervening time is relatively short. We would like to conduct a long-term investigation to explore the learning and affective outcomes in greater depth. Furthermore, we recognize the need to address the lack of a pretest in subsequent studies. Finally, more research should be done to verify our findings' generalization in more acoustic topics.

6 Appendix. Scale items

A.	*Learning interest*
1	I think the Doppler effect is very interesting
2	I think it is interesting to learn more knowledge about sound

A.	*Learning interest*
3	I think it is very interesting to get knowledge through group experiments during class
4	It is very interesting to explore and learn the Doppler effect course with classmates
5	It is very interesting to answer questions while exploring in groups in the course
6	The teacher's explanation in class caught my attention
7	Anything about sound is very interesting to me
8	Compared with other courses, I am more interested in physics courses
9	I am looking forward to learning other courses in physics
B.	***Leaning attitude***
1	I think it is useful to study the Doppler effect
2	I think it is useful to study physics
3	I think it is meaningful to learn something related to physics
4	Learning and observing physics is very important, not only the knowledge in the textbook, but also meaningful in addition to the textbook
5	I will actively search for physics-related information in books or on the Internet
6	When I encounter problems in the process of studying physics, I will actively seek solutions from teachers, classmates, books or the Internet
7	I think learning physics is important to everyone
C.	***open-ended question***
1	How do you feel about using AR tools to aid learning? Furthermore, do you have any suggestions for a course like this? If yes, kindly list a few.

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Data Availability The collected and analyzed data during the current study are available from the corresponding author on reasonable request.

Declarations

Competing interests There is no competing interest.

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