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The Learning Effects of Visualizing Sound Waves using Augmented Reality in Middle School Science Education

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Abstract. We developed an augmented reality (AR) teaching material to help beginning students learn about sound waves, especially in terms of their propagation and the generation of oscilloscope waveforms. We implemented this study in the classroom with 125 seventh-grade students who had already learned about sound waves through traditional instructional methods. We examined the learning effects of the AR teaching material by comparing the results of the pre- and post-tests. The outcomes showed that using AR to represent sound waves – an invisible phenomenon – is an effective approach for improving students' understanding of the concept.

1. Introduction

Self-sufficient automation propelled by artificial intelligence (AI), big data (BD), and the Internet of Things (IoT) – collectively referred to as Industry 4.0 – has been progressing due to industrial transformation. This revolution in automated technology will introduce self-sufficient robots to perform about half of the jobs traditionally carried out by humans, making it imperative to develop human resources that can respond to this industrial shift and create new jobs [1]. Information and communications technology (ICT) education was developed with such human resource development in mind [2,3]. In ICT education, introducing devices (such as tablets) is not so critical; rather, it is important to establish a teaching method in which AI, BD, and the IoT are incorporated into the curriculum [4]. Previous studies have illustrated this by reporting on the introduction and effects of AI in web-based learning [5], as well as pervasive knowledge acquisition by integrating BD into the classroom [6].

This study focuses on the use of sensors (i.e., built-in tablets) for middle school science education. Studies on the use of sensors in education have been conducted over the past twenty years and have reported that introducing real-time measurement using sensors significantly improves students' learning of dynamic concepts [7]. Today, incorporating virtual representations into real space not only enables real-time measurement, but also facilitates a more intuitive understanding of phenomena among learners [8-13]. Owing to the importance of ensuring a certain level of understanding among learners, particularly in compulsory education, visualizing scientific phenomena is an effective means by which to improve the learning of students who require extra support in science classes.

This study aims to determine the effects that visualizing sound waves using augmented reality (AR) has on students' learning. Japanese students learn about the concepts of sound waves, sound amplitude, frequency, and velocity in the seventh grade as part of their compulsory middle-school curriculum. However, the notion of sound waves is considered difficult for students to understand. Based on a survey of middle school students, Eshach and Schwartz reported that many did not grasp the idea of sound propagated through air [14]. Even among university students, many of them have misconceptions about sound waves [15-17]. Sound propagation through air is difficult to understand because it is not directly observable.

Japan's Courses of Study standards recommend use of an oscilloscope to measure waveforms as a method of visualizing the propagation of sound waves through air [18]. However, many students still lack a correct understanding of the subject matter. Misconception tests conducted by Helm revealed that very few students understood that the waveform's horizontal axis represents cycles (time) [19]. In fact, 80% or more of teachers also held the misconception that the horizontal axis represents wavelength (i.e., distance). Middle school textbooks use string vibration with constant tension as the sound source, and teach that oscillation amplitude and wavelength correspond to volume and pitch, respectively. In addition, students learn about sound reception using oscilloscope waveforms. However, students cannot interpret the oscilloscope waveforms correctly unless they have a precise understanding of the relationship between wavelength and frequency; this is because a waveform's horizontal axis represents time. Since students are not taught how to formulate the relationship between wavelength and frequency in middle school, it is extremely challenging for them to understand oscilloscope waveforms theoretically, because doing so necessitates thinking about the time evolution of density waves spreading out spatially. We expect that students will develop a better understanding of sound waves by visualizing temporal changes in sound wave propagation and oscilloscope waveform dynamics with the help of AR.

In the present study, we developed a learning material that can visualize sound wave propagation and oscilloscope waveform dynamics using AR. We implemented this material in the classroom with middle school students who had previously learned about the topic using conventional approaches. We examined the learning effects of the AR teaching material by comparing the results of a pre-test administered before the class and those of a post-test conducted afterward.

2. Teaching Aid Development

For the tablets, we used Nexus 7 (2013) with an Android OS and developed the AR software using Unity. In Unity 2017, the AR camera is available by default, and it is possible to develop marker-based AR software in conjunction with Vuforia. We used the tablet's rear camera as the AR camera and created the software using two markers, as illustrated below (Fig. 1).

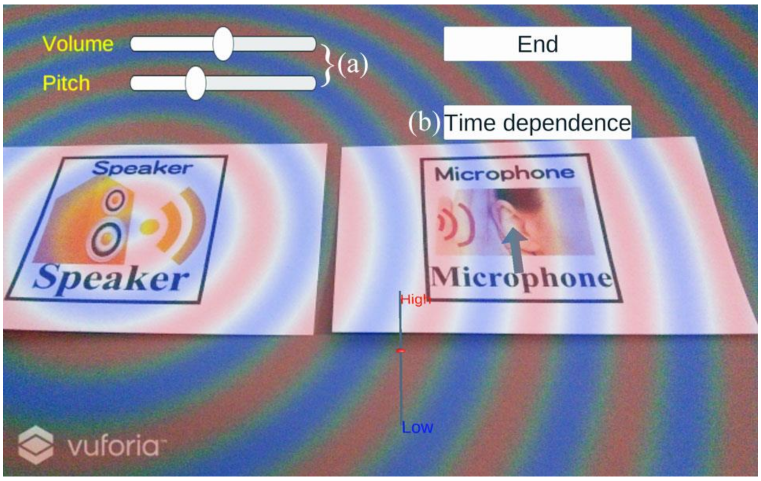


Fig. 1. Screenshot of a tablet showing AR markers for sending (left) and receiving (right) being recognized by the rear camera. Volume and the pitch can control (a). The displays for the receiving marker can be changed into three modes (b).

2.1 Visualizing sound propagation dynamics

We created an AR marker for sound wave excitation to improve students' understanding of sound wave propagation dynamics (Fig. 1, left). When the camera recognizes the marker, the tablet's speaker excites a sine wave. The user can alter the amplitude and frequency of this sine wave (Fig. 1[a]). The sine wave is drawn from the marker's center, and AR depicts its propagation through space using a shader. The red areas indicate places where air density is high, while the blue areas point to zones where it is low. To visualize sound wave propagation, the temporal progress was modified to 1/1,000, and the spatial scale to 1/40.

2.2 Visualizing oscilloscope waveform dynamics

We created a receiving AR marker to help learners understand oscilloscope waveform dynamics when receiving sound waves (Fig. 1, right). When the camera recognizes both the receiving side and the transmitting side AR markers, there is an expression of the temporal change in air density at the arrow in the marker's center. To help learners understand the oscilloscope waveform dynamics by examining the temporal change in air density, each time the button in Fig. 1(b) is pressed, the mode switches between the following three types:

Mode 1: The screen in Fig. 2(a) is displayed when the camera recognizes the receiving marker. The position of the red dot moves up and down depending on air density changes associated with sound wave propagation at the arrow. Through this observation, students learn about the temporal change in air density associated with sound waves (amplitude, cycles).

Mode 2: When the button in Fig. 1(a) is pressed, the receiving AR marker displays the changes, as shown in Fig. 2(b). The red dot at the arrow moves along the horizontal axis to show temporal change, and along the vertical axis to show shifts in air density. The red dot is set to return to 0 ms when it reaches 4 ms. By observing this, students learn how temporal changes in sound waves can be depicted in graph form.

Mode 3: When the button in Fig. 2(b) is pressed again, the receiving AR marker display is switched, as shown in Fig. 2(c). In this mode, only the red dot's trajectory, and not the dot itself, is shown. The phase of the waveform at 0 ms is specified to always be zero. By observing this, students learn about oscilloscope waveforms. When the button is pressed again, the display returns to the image shown in Fig. 2(a).

Since the receiving marker moves during the measurement, it is also possible to learn about waveform changes caused by the Doppler effect.

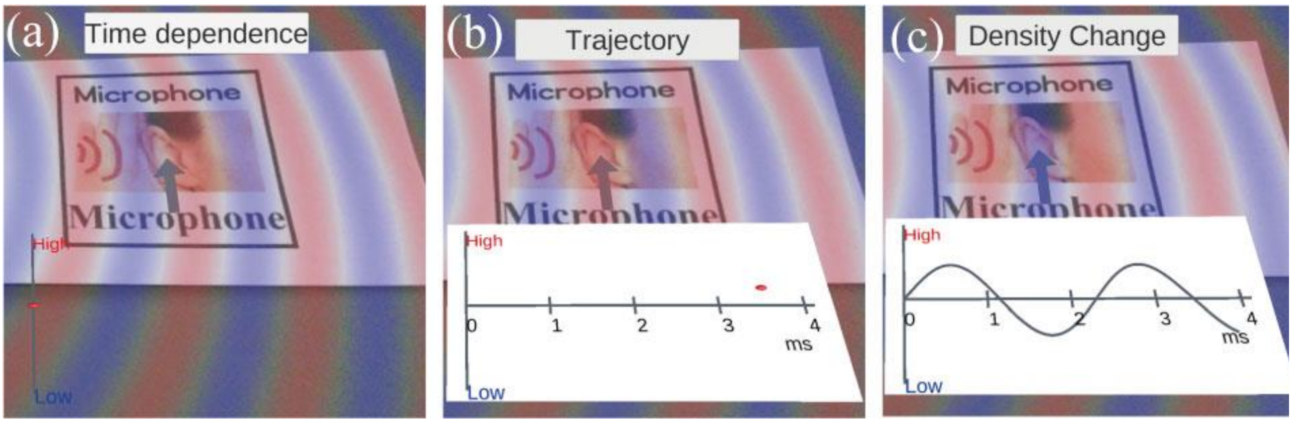


Fig. 2. The three display modes for the receiving marker: (a) the temporal change in air density at the arrow; (b) changes in air density in relation to a graph where the horizontal axis indicates time; and (c) the oscilloscope waveform as observed at the arrow.

3. Methodology

Class practice was conducted with middle school student participants who had used our AR learning material. We examined the material's learning effects by comparing the results of the pre-test conducted before the class and those of the post-test conducted afterwards.

3.1 Classroom practice

We conducted a 50-minute class with 125 seventh-grade middle school students (four classes in total) on January 15, 2018 (Fig. 3). In each class, the students were divided into groups of three or four, and tablets running developed AR software for each group were used. The students had already learned about the properties of sound using conventional approaches prior to December 2017.

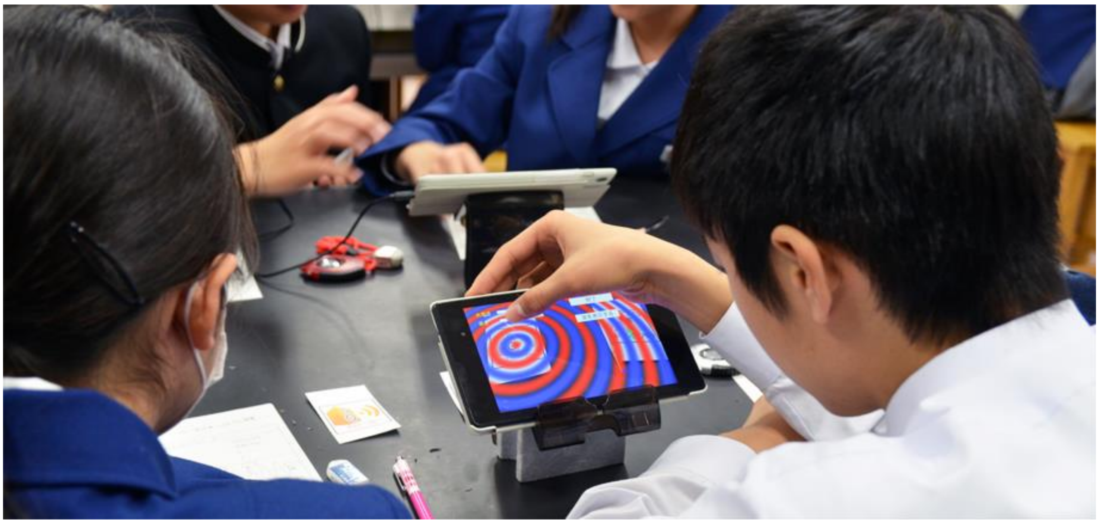


Fig. 3. Class in session

3.2 Survey questions

Fig. 4 displays the survey questions used to measure the material's learning effects. We asked the same questions before the class practice (pre-test) and afterward (post-test). We examined the learning effect based on a comparison of the results.

In Question 1 (Q.1), we investigated the students' level of understanding of oscilloscope waveforms. It included a question about the waveform changes associated with volume increases (Q.1-1), a question about the waveform changes associated with pitch decreases (Q.1-2), and questions about the meaning of the waveform's vertical (Q.1-3) and horizontal axes (Q.1-4).

Question 2 (Q.2) asked about the changes in the spatial distribution of air density associated with pitch decreases (Q.2-1), the spatial changes in air density related to sound wave propagation, and its correspondence with oscilloscope waveforms (Q.2-2).

3.3 Survey results

Fig. 5 shows the results of a comparison between the correct answer rates of the pre-test r_{pre} [%] and post-test r_{post} [%], as a normalized gain g, defined as $g=\frac{r_{post}-r_{pre}}{100-r_{pre}}$ [20].

For Q.1 on the pre-test, although more than 60% of learners answered Q.1-3 accurately, the correct answer rate for Q.1-4 – which asked about the oscilloscope waveform's horizontal axis – was only

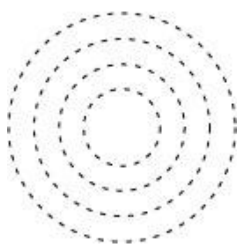
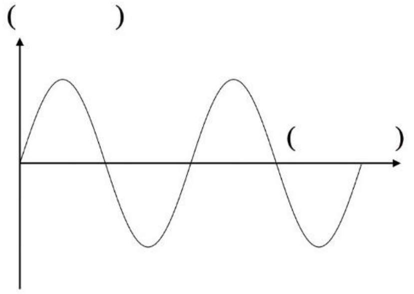
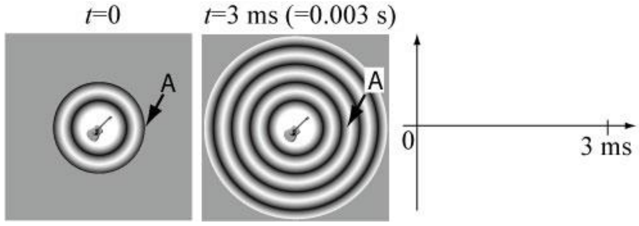
<table>
<tr><td>Q.1: The sound waveform observed by an oscilloscope is shown in the figure below. Answer the following questions.</td><td colspan="2">Q.2: Sound propagates through the density vibration of the air. The figure below shows the density fluctuation of the air caused by the sound propagation of a guitar. Answer the following questions.</td></tr>
<tr><td>How does the waveform change when you increase the volume or lower the pitch? Draw each waveform with the solid and dotted lines in the figure, respectively.</td><td>How does air density change when the pitch is lowered? Draw the high-density lines in the figure (the dotted lines show the high-density trajectories of the original sound).</td><td></td></tr>
<tr><td>What do the vertical and horizontal axes stand for? Fill in the blanks in the figure.

</td><td colspan="2">The sound is observed at position A. At t=0, the sound reaches A (left figure). After 3 ms, the sound spreads, as shown in the middle figure. Draw the oscilloscope waveform at t=3 ms in the graph on the right.

</td></tr>
</table>

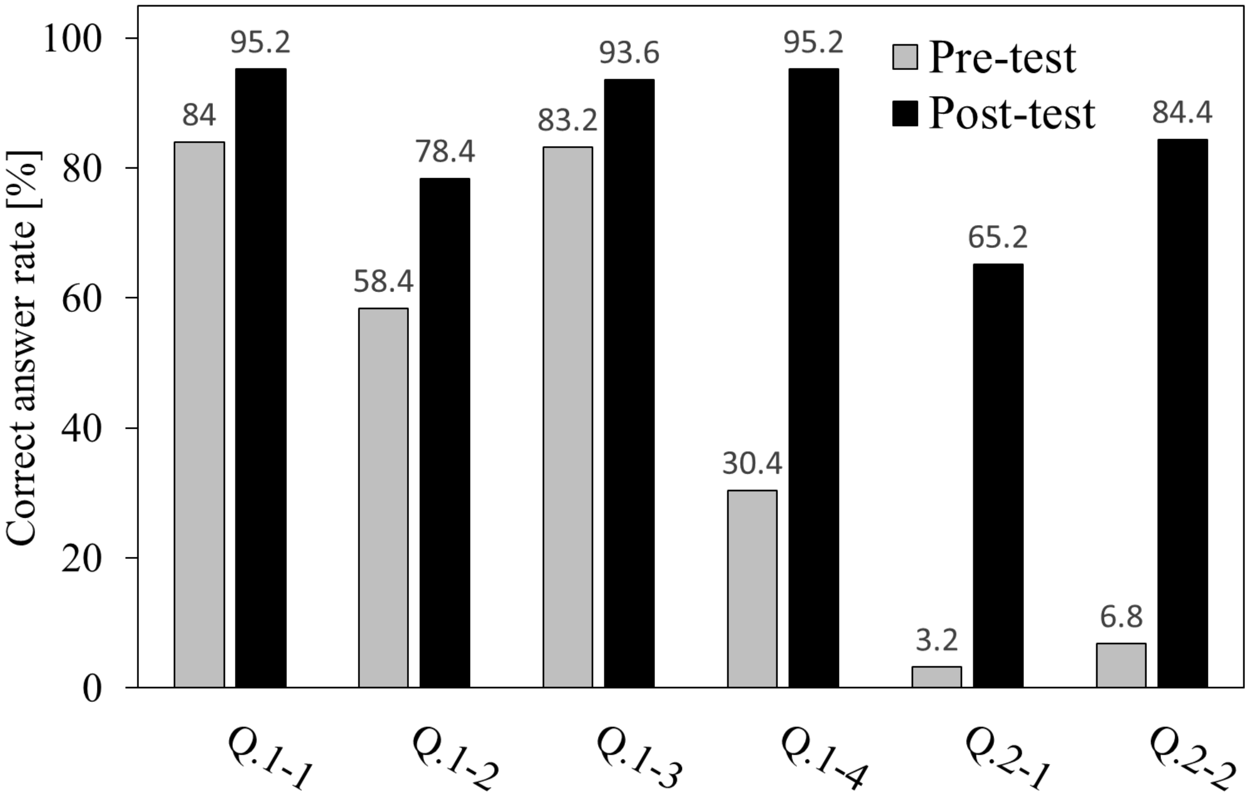
Fig. 4. Contents of the pre- and post-tests

30%. In the post-test results, more than 80% of learners answered Q.1-4 correctly, and a large gain of g=0.93 was obtained.

For Q.2, although the correct answer rate was low on the pre-test (not exceeding 10%), more than 70% of learners answered this question correctly during the post-test.

4. Discussion

In this section, we will discuss the survey results. The correct answer rate on the pre-test was high for the topics of amplitude change associated with volume (Q.1-1) and the meaning of the oscilloscope waveform's vertical axis (Q.1-3); moreover, the students demonstrated an understanding of the concept of amplitude based on previous, conventional education on the subject matter. However, the percentage of students who knew that the oscilloscope waveform's horizontal axis represents time was only 30% on the pre-test (Q.1-4), indicating that conventional learning does not provide students with sufficient understanding of the correspondence between changes in wavelength and frequency. To grasp the correspondence between changes in string length in harmonic motion and changes in frequency, it is necessary first to understand that the wavelength of a density wave propagated through space changes in relation to string length, and then to consider how it corresponds with frequency. Seeing that the correct answer rate for Q.2-1 was only 3.2% on the pre-test, we discovered that conventional learning approaches left many students with a poor understanding of the relationship between string length in harmonic motion and the wavelength of density waves propagated through space.



g-value:	0.70	0.48	0.62	0.93	0.64	0.83

Fig. 5. Comparison of pre- and post-test correct answer rates (top) and the normalized *g*-value (bottom)

By using the AR learning material developed for this study, the correct answer rate for question Q.2-2 – which required an understanding of the abovementioned concepts – increased during the post-test. We obtained a large gain of g=0.83.

We will now discuss the use of the AR learning material developed for this study. In this learning material, we modified the elapsed time to 1/1,000 of the actual time and the space to 1/40 of the real space in order to visualize invisible sound wave propagation. Therefore, if students were to only use this learning material, they might gain an incorrect understanding of sound speed and wavelength. Although learners were alerted to these two points during the class practice, we do not think that this learning material alone is an adequate substitute for actual oscilloscope measurement. We assume that students' understanding of sound waves can be improved by conducting actual oscilloscope speed measurements after first introducing sound wave propagation and oscilloscope waveform dynamics, using the AR learning material developed for this study.

5. Conclusion

We developed an AR learning material that visualizes sound wave propagation in the air – a concept that is difficult for students to understand due to its invisibility – and oscilloscope waveform dynamics in reception; we then conducted the class practice with seventh-grade middle school students, who had already learned about these ideas through traditional instructional practices. Comparing the pre- and post-test results revealed that AR representations are effective in improving learners' understanding of oscilloscope waveforms, as well as the changes in wavelength density that accompany changes in pitch.

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