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The Effect of Training on Localizing Hololens-generated 3D Sound Sources

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Abstract. This study aims to evaluate the effectiveness of three training methods: Visual Guide 1, Visual Guide 2, and Sound Guide, in improving sound localization skills in Augmented Reality (AR) environments using the HoloLens2 device. Sound localization is a critical aspect of human auditory perception, and AR technology offers an immersive platform for training individuals in this skill. The HoloLens2, which employs Head-Related Transfer Function (HRTF) technology, provides a more realistic sound experience in AR by simulating sounds from various directions and distances. In this study, we explore how sound source localization training can help individuals adapt to the general HRTF implemented in AR devices despite that the individual HRTFs are quite different from the general HRTF. To that end, 12 participants were divided into groups of four for each training method, and trained six times every other day for two weeks. The training methods combined visual, auditory, and kinesthetic feedback to enhance the participants' sound localization accuracy in terms of elevation, azimuth, and distance. The experiments were conducted in a controlled testbed environment with minimal external noise interference. The results revealed that Visual Guide 2 provided the most significant training effect across all measured aspects, followed by Sound Guide, which also demonstrated considerable improvement. These findings suggest that training methods incorporating kinesthetic feedback into the visual feedback, as well as relative error guidance into the audio feedback, such as Visual Guide 2 and Sound Guide, are more effective than traditional visual training for sound localization in AR environments. Additionally, Sound Guide showed potential for training visually impaired individuals, as it relies on auditory feedback, rather than visual cues. This study underscores the importance of integrating auditory and kinesthetic feedback in AR-based sound localization training for enhanced outcomes, and highlights the potential applications of such training for various user groups, including those with visual impairments.

Keywords: VR/AR, Sound localization training, HRTF

1 Introduction

Virtual reality (VR) refers to a specific environment or situation created by artificial technology, similar to reality but not actually real, that uses computers and other similar tools.
VR was first developed in 1960 [1], and it has since expanded into various fields, with significant advancements in hardware and content in 2020. Augmented reality (AR) is a technology that superimposes virtual images onto the real world, allowing for a realistic experience in a virtual world. GearVR was developed to run with smartphones, followed by the Oculus Rift in 2016, which could be connected to a PC, and HTC Vive, which was the first to recognize finger movements. Since then, VR peripheral devices have been developed, such as the PlayStation VR, and most recently, HoloLens2.

There are several challenges to localizing 3D sound in VR/AR environments using only auditory cues. One major challenge is that the human auditory system relies on multiple cues to localize sound in three-dimensional space, including interaural time differences, interaural level differences, and spectral cues [2]. In VR/AR environments, these cues can be disrupted or distorted by factors such as the acoustics of the virtual space, the quality of the headphones or speakers used, and the position of the sound source relative to the listener’s head. Another problem is that the accuracy of human sound localization depends on both the direction and frequency of the sound, and on individual differences in auditory perception. This can make it difficult to create a universally effective 3D sound localization system in VR. So, we set out to train people to accurately localize 3D sound, and we saw the results.

The process of spatial navigation relies heavily on visual sensory abilities, and the exact mechanisms by which the brain processes spatial information in the absence of visual input are not yet clearly understood [3]. HoloLens2 offers a different mixed reality feature than other typical VR devices, providing both visual and auditory effects, as well as precise positional and sound information. VR/AR technologies have mostly focused on visual effects, and spatial sound has been considered as a tool to enhance virtual scenes and enrich the user experience [4].

The HoloLens2 used in this study uses the Head Related Transfer Function (HRTF) in the audio engine to deliver sounds generated from various directions and distances in the virtual world to the ears in a manner that in terms of direction, height, distance, and frequency, is similar to the real world. The human ear is a complex organ that is able to detect and localize sound in three dimensions, based on subtle differences in sound arrival time and intensity at the two ears [5]. HRTF processing is based on each person’s ears having a unique shape and size, which affect the way that sound is processed as it enters the ear canal. While HRTF technology is playing a major role in delivering spatially realistic and innovative sound experiences, there are still some challenges.

First, as it is affected by the structure and shape of the human ear, different HRTF filters must be applied to different individuals. Hololens2 is implemented based on a 5.1 multichannel HRTF by default, which is generally not optimized for all users, because HRTF varies from person to person. Research on calculating a personalized HRTF is ongoing [6–8].

The second challenge is based on listening to the sound at the measurement location, so if the user is moving around and listening to the sound, the sense of space may not be consistent. Hololens2 HRTF technology has difficulty maintaining a constant sense of space when the user is moving. It is difficult to get accurate information about the user’s position and movement, and
this needs to be compensated for. HRTF performs well in low-mobility situations, but in high-
 mobility situations, the sense of space is inconsistent.

Besides the ongoing effort to improve VR/AR devices based on implementing better
personalized and motion compensated HRTF, it is necessary to complement such
effort by training the person using the generalized HRTF-based device to adapt to
person- and motion-induced HRTF errors.

Numerous studies have investigated sound spatialization and learning through the
use of Head-Related Transfer Function (HRTF). In a recent study [9], participants
demonstrated significant enhancements in sound localization accuracy, which
included reductions in spherical angle errors, lateral angle errors, and polar angle
errors. Over a period of three days and a total of 108 minutes of training, participants
exhibited error reduction rates in the range (5–20) % across all evaluated domains.
Nevertheless, the study faced certain limitations, such as a relatively small sample
size of (7–11) participants per group, and a focus on short-term effects, with
evaluations conducted over 10 days, leaving the long-term effectiveness of VR-based
sound localization training unexamined. Furthermore, potential individual differences,
including familiarity with VR technology and auditory processing abilities, may
impact the outcomes and constrain the broader applicability of the training. Another
study [10] involved a four-week training period where participants were exposed to
sound intensity variations in both the horizontal and vertical directions. The auditory
target was positioned on a 6m radius circle centered on the participant, with
locations at 22.5° above and below the horizontal. The initial two weeks of training
resulted in significant improvements; however, during the subsequent two weeks, no
additional progress was observed. A limitation of this study is the fixed order in which
the modules were conducted, potentially leading to a precedence effect due to the
specific sequencing of the modules. Moreover, since the test modules were identical
to those in the training, participants continually received feedback on their
performance during the tests, which may have influenced the results. An alternative
approach to improving sound localization ability has been examined through the use
of a virtual auditory game [11]. In this particular study, rather than relying on
traditional location learning techniques, the researchers employed a 3D sound game
called Hoy-Pippi as a novel training method. The experiment involved two groups,
each consisting of five participants: a trained group, and a non-trained group. The
results indicated that in the trained group, the ability to identify sound source
positions improved exclusively. However, the study faced certain limitations, as the
azimuth of stimuli consisted of seven sound source positions with angles ranging
(0–90)° in 15° increments. Consequently in this research, the ability to learn from
various angles was not fully investigated. Another study compared personalized
HRTF sets to generic HRTF sets for dynamic listeners in virtual reality (VR) [12].
This research found that personalized HRTFs can improve the accuracy of sound
localization, especially for sounds behind the listener, for dynamic VR listeners. In
static localization experiments, there were no significant differences in accuracy
between personalized and generic HRTFs, except for minor improvements in quadrant
error percentage with personalized HRTFs. This study suggests that except for
specific situations, there may be no need to use personalized HRTFs for dynamic
listeners in VR, and systematic adaptation to listening with generic HRTFs may be more effective.

In this study, unlike previous sound localization training, a combination of all three types of feedback was used, which was highly effective in improving sound localization skills. In addition, the experimental environment was an AR environment, which increased the realism and generalizability of the experiment.

2 Experimental Design

2.1 Experimental Procedure

The experiment was conducted by the experimenter and the participant together. The experiment was conducted in a testbed environment, and the external noise was controlled at 10 dB. Before entering the testbed, the experimenter introduced the participant to the entire experiment, and confirmed their gender, age, and hearing status. After the experimenter and participant entered the testbed, the participant sat in a test chair, wore the HoloLens2, held a pointer in their hand, and looked straight ahead. For Visual Guide 1 and Visual Guide 2, the sound visualization feature of HoloLens 2 was turned off, so that they could not see the location of the sound. The location of the sound could only be seen in the guided situation (Fig. 4). In the sound guide, the subject wore an eye patch, and listened to the sound generated by HoloLens2.

Participants went through three experimental sessions in sequence: pre-training test, training, and post-training test sessions. There were six test spots and six training spots, with different elevations, distances, and azimuths. For both testing and training, the experimenter plays a 256 Hz tone on the HoloLens2 five times for 5 seconds, and the participant listens to it, and guesses the source of the sound. The participant then points the pointer at the place they think the sound is coming from, allowing for the length of the stick. The experimenter analyzes the coordinates that the participant points to. The experimenter repeats this three times for each spot. There are a total of 6 spots, and each of these 6 spots is repeated 3 times. In the experimental training session, the participant is guided to the actual location of the sound source via HoloLens2 in three different ways: Visual Guide 1, Visual Guide 2, and Sound Guide. The test is not trained separately. At the end of the experiment, the participant and the experimenter leave the test bed. The experiment took about (20–30) min per person.
The location of the training point is stored in the Vicon camera system, and the predicted location of the subject is in the X, Y, Z coordinate system. For precise analysis, the training point was transformed from a spatial coordinate system (X, Y, Z) to a spherical coordinate system (r, θ, φ). The transformed values of the training point in the spherical coordinate system and the predicted location of the subject are calculated using the following formula for absolute error:

$$E_v = |V_a - V_o|$$  \hspace{1cm} (1)

where, $V_o$ is the point locations predicted by subjects, and $E_v$ is the absolute error value.

A total of 12 subjects of different genders and ages participated in the experiment. The average age was 23.4 years old. No subject had any experience of using HoloLens2.

<table>
<thead>
<tr>
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<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Participant</td>
<td>1 2 3 4</td>
<td>5 6 7 8</td>
<td>9 10 11 12</td>
</tr>
<tr>
<td>Sex</td>
<td>M F M M</td>
<td>M F F M</td>
<td>F M F M</td>
</tr>
<tr>
<td>Age</td>
<td>2325</td>
<td>24212326</td>
<td>26222028</td>
</tr>
</tbody>
</table>

### 2.2 Generating Sound Information

To obtain 3D spatial coordinates, we used a Vicon camera system to measure the position of the sound source and the subject’s predicted position. Beacon sensors were used to predict the position of the sound source. The Vicon camera system consists of four infrared (IR) cameras that measure values in a 3D space measuring 3 m width × 2 m length × 2 m height. The Hololens2 connected to the Vicon camera system uses HTRF to simulate sound from different directions and distances in the virtual world.
In this experiment, each participant was instructed to learn locations by playing a buzzer sound at 5s intervals. The experimenter sequentially generated sounds from six locations. The participant listened to the sound coming from Hololens2, and directed the pointer at the location they thought the sound was coming from. The end of the pointer used by the participant had a beacon sensor attached to it. Once the participant determined the location of the sound source, the coordinates recognized by the beacon sensor on the end of the pointer were sent to the experimenter. The experimenter then checked the error in distance ($r$), azimuth ($\theta$), and elevation ($\phi$) against the actual location of the sound source. The experimental space consisted of a semicircle with a maximum radius of 1.5 meters and a maximum height of 1.3 meters relative to the participant’s location.

![Fig. 2.](image)

Fig. 2. (a) Photograph of the setup. (b) Predefined experimental space based on subject frontal arc of (−90 to +90)$^\circ$, maximum distance of 1.5 m, and height up to 1.3 m.

### 2.3 Learning Sound Localization

As described in Section 2.1, the experiment was performed by first conducting a pre-training test session, followed by a training session, and concluding with a post-training test session. In the pre-training and post-training test sessions, we obtained subjects’ performance without feedback on their training, whereas in the training sessions, we provided feedback on their training immediately after each trial. For comparison, we considered three types of feedback: Visual Guide 1, Visual Guide 2, and Sound Guide, as shown in Fig. 3.

Visual Guide 1 provided visual feedback on the location of the sound source when the subject lowered their arm after they finished pointing, while Visual Guide 2 provided visual feedback on the location of the sound source immediately after the subject finished pointing, and the experimenter would end the training session by pointing to the red box shown in the visual feedback. In this case, we used visual and kinesthetic feedback. Figure 4 shows the feedback of the location to the actual sound in Visual Guide 1 and Visual Guide 2. The red boxes are 3cm × 3 cm × 3 cm cubes.

The sound guide provides a guide sound so that the subject can move the pointing stick along the guide sound to reach the actual location of the sound. In this case, the
pitch of the guide sound increased as the distance value increased, and decreased as the distance value decreased. When the pointing stick reached the location of the sound, the sound ended, and the sound guide feedback ended.

(a) 
(b) 
(c)
Fig. 3. Flowcharts of (a) Visual Guide 1, (b) Visual Guide 2, and (c) Sound Guide.

Fig. 4. Example of visual feedback used in Visual Guide 1 and Visual Guide 2 (3cm × 3cm × 3cm red cube) and a comparison of distance, height, and azimuth based on the position of the red cube. (a) Elevation: 14°, Azimuth: −14°, Distance: 412mm, (b) Elevation: −45°, Azimuth: −51°, Distance: 1,510mm, (c) Elevation: 16°, Azimuth: 32°, Distance: 1,711 mm.

3 Results

3.1 Learning Sound Information
According to the average elevation values before training from trials 1–6, Visual Guide 1 remained unchanged, while Visual Guide 2 decreased by 4%, and Sound Guide decreased by 3.2%. For the azimuth angle, Visual Guide 1 decreased by 3.5%, Visual Guide 2 decreased by 8.8%, and Sound Guide decreased by 5.8%. For the distance, Visual Guide 1 decreased by 1.1%, Visual Guide 2 decreased by 8.1%, and Sound Guide decreased by 8.9%. Because all errors, except for the elevation in Visual Guide 1, decreased, the learning increased the spatial precision on that day. In all cases, Visual Guide 2 and Sound Guide, which provide feedback including the Kinetic Guide, showed better reduction rates than Visual Guide 1, which provides only visual feedback.

After the training sessions, the average altitude error reduction was 6.5% for visual guide 1, 5.1% for visual guide 2, and 0.6% for sound guide. There was no significant reduction for Sound Guide because of a large error increase during the third trials, although there was a slight reduction in error when excluding the third trial. Visual Guide 1 and Visual Guide 2 showed error reduction rates for each training session. For the azimuth, Visual Guide 1 had a 4% reduction, Visual Guide 2 had a 2.9% reduction, and Sound Guide had a 0.5% reduction, which was not significant. For the distance, Visual
Guide 1 had a 3.2% increase, while Visual Guide 2 showed a 12.5% reduction in error, and Sound Guide had a 5.8% reduction. Visual Guide 1 and Sound Guide had days with both error reduction and increase, while Visual Guide 2 always showed error reduction.

Fig. 7. (a) Elevation, (b) azimuth, and (c) distance error before and after the day’s training in Visual Guide 1.
Averaging the pre- and post-training results from Day (1−6), we found that for elevation, Sound Guide reduced error by 5.3% and Visual Guide 2 reduced error by 7.9%, while Visual Guide 1 increased error by 7.1%. For distance, Sound Guide and Visual
Guide2 showed short-term training effects, with Sound Guide and Visual Guide decreasing by (14.7 and 14.9) %, respectively, while Visual Guide1 showed no change in error. For azimuth, both Sound Guide and Visual Guide2 showed significant training effects, with all three methods, reducing error by 9.7% for Sound Guide, 5.8% for Visual Guide 1, and 15.1% for Visual Guide2. All training methods showed a training effect, with Visual Guide 2 showing the largest effect. Overall, Visual Guide 2 had the largest training effect, but Sound Guide also had a significant training effect.

The training method in the original study was very similar to Visual Guide 1. However, training methods that integrate kinesthetic feedback with visual feedback or auditory feedback with kinesthetic feedback, such as Visual Guide 2 and Sound Guide, are more effective at sound localization than traditional visual training. We have shown that because it relies on auditory feedback, rather than visual cues, Sound Guide has the potential to train blind people.

4 Discussion

We conducted a study to train sound localization skills using Hololens2 using three learning methods (Visual Guide1, Visual Guide 2, and Sound Guide). We experimented with 12 participants, four for each method, for two weeks. We performed a total of six experiments, two days apart. We conducted a pre-experiment and a post-experiment, and compared the average of the results of the six pre-experiments, the average of the results of the six post-experiments, and the average of the results of the pre- and post-experiments on the same day. Elevation, distance, and azimuth were analyzed.

4.1 The average over experimental results before training

For elevation, except for Visual Guide 1, Visual Guide 2, and Sound Guide showed a decrease in error, and for azimuth and distance, all training methods showed a decrease in error rate. For elevation, all training methods showed a decrease in error, except Visual Guide 1. However, Visual Guide 2 had the largest error reduction, and sound guide also showed a large error reduction, but not as much as Visual Guide 2. Visual Guide 2 and Sound Guide, which are feedbacks that include kinetic guides, showed a greater error reduction rate than Visual Guide 1, which does not include kinetic guides. In the case of Visual Guide 1, the training effect remains after the training session and before the next training session, but in the case of Visual Guide 2 and Sound Guide, the training effect remains larger. We can see that the training method with the kinetic guide has a long-lasting learning effect over time.

4.2 The average over experimental results after training

The average value of the results of 6 trials after training shows that Visual Guide 1 and Visual Guide 2 have reduced errors except for Sound Guide at high altitude. However, in the case of Sound Guide, there was a slight decrease in error, but the increase in error in the third session was large, which affected the average value. For azimuth,
all training methods showed a decrease in error, but Sound Guide showed a slight decrease. For distance, all training methods showed a decrease in error, but Visual Guide 2 showed the largest decrease. Visual Guide 2 always showed a decrease in error, and had the largest error reduction of the three training methods in all aspects.

4.3 Results before and after training on the same day

The pre-training and post-training results for the same day showed that for altitude, Visual Guide 2 and Sound Guide significantly reduced errors, while Visual Guide 1 increased errors.

In the case of distance, Visual Guide 2 and Sound Guide significantly reduced the error, but Visual Guide 1 did not change the error. In the case of azimuth, all training methods significantly reduced the error, but Visual Guide 2 showed the largest error reduction, and Sound Guide also showed a large error reduction. We can say that Visual Guide 2 has the largest training effect in all aspects, but Sound Guide also has a large training effect.

Based on these observations, we compared the performances of three training methods by computing the percentile improvement from the pre-training to the post-training test in terms of the performance averaged over 6 trials.

Table 2 shows the trial-averaged performances of the pre-training and the post-training tests, as well as the percentile improvements with respect to Visual Guide 1, Visual Guide 2, and Sound Guide training methods, arranged in terms of azimuth, elevation, and distance.

<table>
<thead>
<tr>
<th>Training method</th>
<th>Average Error</th>
<th>% Improvement</th>
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</thead>
<tbody>
<tr>
<td>Visual Guide 1</td>
<td>Pre-training</td>
<td>Azimuth(°)</td>
</tr>
<tr>
<td></td>
<td>Post-training</td>
<td>18.6</td>
</tr>
<tr>
<td>Visual Guide 2</td>
<td>Pre-training</td>
<td>17.0</td>
</tr>
<tr>
<td></td>
<td>Post-training</td>
<td>14.5</td>
</tr>
<tr>
<td>Sound Guide</td>
<td>Pre-training</td>
<td>16.4</td>
</tr>
<tr>
<td></td>
<td>Post-training</td>
<td>14.7</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Training method</th>
<th>% Improvement</th>
<th>Azimuth(°)</th>
<th>Elevation(°)</th>
<th>Distance(mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Visual Guide 1</td>
<td>5.7</td>
<td>5.7</td>
<td>25.7</td>
<td>167.1</td>
</tr>
<tr>
<td>Visual Guide 2</td>
<td>15.0</td>
<td>15.0</td>
<td>7.9</td>
<td>14.8</td>
</tr>
<tr>
<td>Sound Guide</td>
<td>10.4</td>
<td>10.4</td>
<td>6.2</td>
<td>17.8</td>
</tr>
</tbody>
</table>
Table 2 shows the mean of the pre-training tests and the mean of the post-training tests for the six experiments, two days apart. Table 3 shows how much better the post-training test averages were, compared to the pre-training test averages. Visual Guide 1 showed a 5.9% improvement on the post-training test over the pre-training test for Azimuth. However, Elevation shows no change from pre-training to post-training. Distance actually decreased by 0.2% after training. For Visual Guide 2, Azimuth improved by 14.7%, Elevation improved by 8%, and Distance improved by 14.8%. For Sound Guide, Azimuth improved by 10.4%, Elevation by 6.2%, and Distance by 17.8%. Compared to Visual Guide 1, Visual Guide 2 and Sound Guide showed larger improvements, or improvements in all areas. Visual Guide 1 used solely visual feedback, while Visual Guide 2 used a combination of visual and kinesthetic feedback, and Sound Guide used both auditory and kinesthetic feedback. What Visual Guide 2 and Sound Guide have in common is that they combine kinesthetic feedback.

5 Conclusion

The HRTFs of individual subjects may differ from each other and from the general HRTF of Hololens2 based on which a 3D sound is generated, causing errors in 3D sound source localization among individuals. Here, training is meant for subjects to learn how to compensate for the differences of their HRTFs from the general HRTF of Hololens2, so that they can accurately localize the Hololens2-generated 3D sound.
source. Note that the differences in HRTF among individuals, as well as among sound source locations, mean that the training effect may differ by individual, and by different sound source location. Therefore, to accurately evaluate the effectiveness of the three training methods in an unbiased way, it is required to take into consideration these differences in training effect. Since the three training methods, Visual Guide 1, Visual Guide 2, and Sound Guide, are applied to different subject groups, we consider that the comparison of their absolute error performance has little meaning compared with their percentile improvements between pre-training and post-training test performances. In addition, since individual trials in sound localizations are conducted with respect to different 3D sound source locations, we consider it more reasonable to average the performances of 6 trials for comparative evaluation to avoid biases due to the performance differences among different sound locations. Figures 5 and 6 show the variation of location averaged performance of the three training methods for the pre-training and the post-training tests, respectively, along 6 repetitions conducted at two day intervals, where the location averaged performance implies the performance averaged over 6 trials of different sound source locations. The performance variation along 6 repetitions is considered due to the subject being familiar with the experiment. We consider it more reasonable to average the performances of 6 trials to avoid the adverse effect of performance differences among different sound locations on comparative evaluation.

This study confirmed that the training methods of Visual Guide 2, which combines visual and kinetic feedback, and Sound Guide, which combines auditory and kinetic feedback, can produce more pronounced training effects than traditional visual training for sound localization in VR/AR environments, and showed that Sound Guide has the potential to train visually impaired people, because it relies on auditory feedback rather than visual cues. It also showed that if the volume of the sound is kept constant, distance learning is possible at the same volume.

This study emphasizes the importance of integrating auditory and kinesthetic feedback in VR-based sound localization training to achieve better results, and highlights the applicability of such training to different user groups, including the visually impaired.

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Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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