A Vibrotactile Device for Enabling Sound Localization and Identification for Deaf and Hard of Hearing Individuals ⋆

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Abstract
Deaf and hard-of-hearing individuals face challenges in identifying the direction and type of sound sources. Enabling sound localization enhances safety, and understanding the type of sound sources improves awareness of the surrounding environment. However, few studies have explored methods to present both sound direction and type information to hearing-impaired individuals. In this study, we designed a sound localization aid device using vibrators suitable for daily use and investigated tactile perception through changes in vibration frequency to represent different sound types. We prototyped two sound localization aid devices: a headphone type and a hat type. For the presentation of sound types, we examined a method of converting sound frequencies to vibrations. We integrated these two systems into a new aid device and evaluated its effectiveness through experiments. The results showed no significant difference in sound localization, but a trend toward significance was observed in sound type identification. Different sound types could be perceived through variations in vibration.

Keywords
Deaf and Hard of Hearing, Sound Localization, Vibrotactile Stimulation, Frequency Characteristics of Perception, Frequency Conversion, Social Acceptance

1. Introduction

1.1. Background

Sound plays an important role in daily life, entertainment, and construction sites, among other areas. However, people with hearing impairments face challenges in accessing the world of sound. Specifically, they struggle to identify the direction of sound sources and perceive sound types such as pitch, loudness, and timbre. This issue directly affects their safety and communication in daily life. There are various types of hearing impairments, including congenital and acquired, conductive hearing loss, sensorineural hearing loss, and mixed hearing loss. While conductive hearing loss may be improved with treatment or hearing aids, sensorineural hearing loss often cannot be adequately addressed with hearing aids [1]. Additionally, Unilateral hearing loss in children is often detected late. Unilateral hearing loss has frequently been underestimated as a disability [2]. Traditional treatments and surgeries for these hearing impairments are invasive, placing significant physical and financial burdens on patients, and not all sensorineural hearing loss cases can be improved through surgery. There are also CROS hearing aids and bone conduction hearing aids that can be attached to glasses for people with unilateral hearing loss [3]. Nevertheless, the challenge of identifying the direction of sound sources remains unresolved [4].

Thus, one of the challenges faced by individuals with hearing impairments is the difficulty of identifying sound directions and distinguishing sound sources, making it hard for them to perceive sound sensory-wise.

The difficulty in sound localization can lead to an inability to respond appropriately to warning sounds, putting individuals at risk. Additionally, the challenge of identifying sound sources increases the time required to distinguish between warning sounds and general noises or calls from others.

A popular approach to alleviating these problems is sensory substitution, which compensates for impaired senses using other remaining senses [5]. In sensory substitution for hearing, vision [6] and touch [7] [8] have been utilized. However, it is difficult to live daily life while wearing a head-mounted display, and to the best of our knowledge, no studies simultaneously address sound localization and sound source identification using vibration.

Therefore, this study proposes a device that can assist

APMAR'24: The 16th Asia-Pacific Workshop on Mixed and Augmented Reality, Nov. 29-30, 2024, Kyoto, Japan
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with both sound localization and sound source identification using vibration stimuli, designed to accommodate various types of hearing impairments.

2. Related Research

2.1. Degree of Hearing Impairment

In the case of hearing impairment in both ears, the degree of physical disability is classified into Levels 2, 3, 4, and 6 according to the "Degree of Physical Disability Classification Table" in the Enforcement Regulations of the Act on Welfare of Physically Disabled Persons [9]. At Level 2, both ears have a hearing level of 100 decibels or more (complete deafness in both ears). At Levels 3, 4, and 6, the hearing level decreases by 10 dB for each grade.

2.2. A wearable device that transmits sound vibrations to the body

A device developed for hearing-impaired individuals is Fujitsu's Ontenna (in Japanese) [7]. Ontenna converts sounds from 60 to 90 dB into 256 vibration and light intensity levels, allowing users to perceive sound characteristics such as rhythm, pattern, and volume. However, since it consists of only one device, it is unsuitable for sound localization. Additionally, it is not ideal for sound source identification because it only presents vibration intensity.

The support device proposed by Yumiba et al., which focuses on the sound localization issues of individuals with unilateral hearing loss (in Japanese) [8], provides two distinct vibrations for dangerous sounds and communication sounds. The device has four vibrators placed on the left and right, front and back of the shoulders, allowing for a five-directional sound presentation when the rear vibrators on both sides activate simultaneously. While this study demonstrated usefulness in the sound localization task, the device is designed for unilateral hearing loss. Therefore, it does not provide a system for presenting sound characteristics like volume or rhythm, which is a limitation.

2.3. Sensation

2.3.1. Hearing frequency range

The range of frequencies that can be perceived as sound is called the audible frequency range. Humans perceive variations in air pressure as sound through the sensory organ known as the ear. Even with the same energy fluctuations in pressure, the perceived loudness of sound is not consistent across different frequencies. Generally, for healthy young people, the audible frequency range is from 20 Hz to 20,000 Hz, and hearing, particularly in the higher frequency range, tends to decline with age. Figure 1 shows the equal-loudness contour [10]. The equal-loudness contour represents the sound pressure levels at various frequencies that are perceived to have the same loudness. This is regarded as one of the most fundamental characteristics of human hearing. According to Figure 1, human hearing is most sensitive to frequencies between approximately 2,000 Hz and 4,000 Hz.

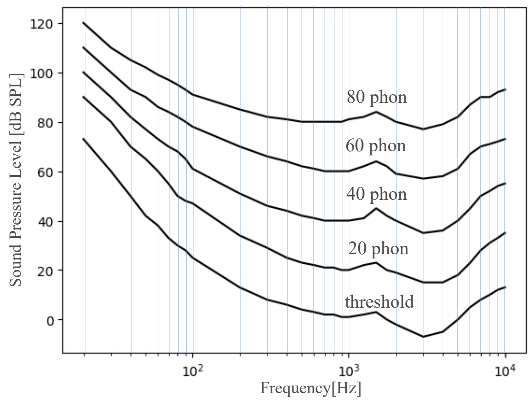

Figure 1: Equal loudness level curve (taken from [10])

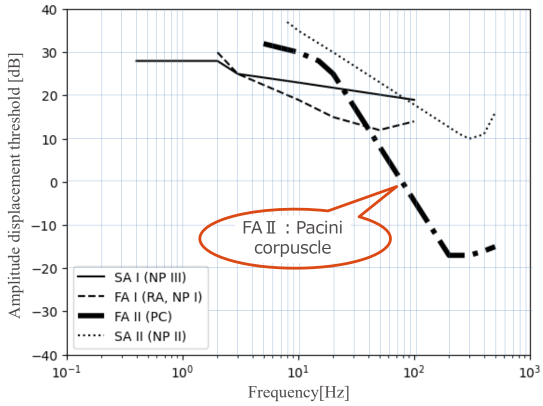

Figure 2: Vibration detection threshold curve (taken from [11])

2.3.2. Tactile frequency range

Skin sensory receptors are classified into mechanoreceptors, thermoreceptors, and nociceptors. Mechanoreceptors are responsible for sensing touch and pressure and include Merkel cells, Pacinian corpuscles, and Meissner's corpuscles [12]. Figure 2 shows the vibration detection threshold curve, illustrating the sensitivity of different skin receptors to various frequencies [11]. In this study, we focus on the curve related to Pacinian corpuscles, the receptors that detect vibrations in human skin. According to Figure 2, human skin can perceive vibrations in the range of approximately 5 Hz to 500 Hz, with the highest sensitivity between 200 Hz and 400 Hz.

3. Proposed system

3.1. System requirements

In this section, we define the fundamental requirements that the proposed system must meet. The key requirements include sound localization, sound source identification, and form factor. We explain below how achieving these requirements contributes to realizing the system's goals.

3.1.1. Requirements for sound localization

Deaf and hard-of-hearing individuals may have difficulty or be unable to perceive the direction of sound sources. This can lead to dangerous situations, especially if they cannot notice sounds coming from outside their field of vision. Therefore, at a minimum, it is necessary to be able to identify the sound source positions from the left and right rear. Additionally, being able to identify sound sources from the left and right front would further enhance safety.

3.1.2. Requirements for sound source identification

For deaf and hard-of-hearing individuals, it is extremely difficult to distinguish between different types of sound sources, such as human voices, warning sounds (e.g., sirens), and general environmental sounds. For example, they may not be able to recognize the difference in urgency between an ambulance and a police car siren or notice a car horn from behind. Being able to perceive all sounds as they are, similar to people with normal hearing, would likely improve safety and enhance the quality of daily life.

3.1.3. Requirements for form factor

The appearance, size, and shape of the system must match the environment in which it is used, its social acceptability, and the needs of the user. Considering long-term use in daily life, the device should be designed to be lightweight, easy to wear, and not cause embarrassment. As possible designs that meet these criteria, we considered headphone-type and Beret-type devices.

3.2. Sound localization

To achieve sound localization, a small microphone array, a microcontroller, and small vibrators are used. The sound source direction is communicated by activating the vibrator corresponding to the detected sound source direction from the microphone array.

3.3. Sound source identification

We will present not only the direction of the sound source but also "what kind of sound is being made" to convey various information contained in sound. Vibration stimuli will convey sound characteristics such as pitch and loudness, and we will explore methods to convert sound information into vibration stimuli.

In summary, for the three main elements of sound: loudness will be represented by the strength of the vibration, pitch by the speed of the vibration, and timbre by a combination of frequencies.

3.3.1. Conversion Function from Sound to Vibration

As shown in Section 2.3, the frequency characteristics of human perception differ significantly between auditory perception and tactile perception (skin sensation). Therefore, it is necessary to convert frequency ranges that are easily heard by the human ear into frequency ranges that are more easily perceived as vibrations on the skin. When examining the equal-loudness curve from 0 Hz to 4000 Hz and the Pacinian corpuscle curve from 0 Hz to 500 Hz, we found that the curves exhibit a very similar trend. Therefore, for simplicity, this study adopts a linear conversion. The equation is shown below:

$$V_f = S_f \frac{V_{\max} - V_{\min}}{S_{\max} - S_{\min}}$$

Where:

V_f: is the vibration frequency, S_f: is the sound frequency, $V_{\max}$: is the maximum value of the vibration frequency range, $V_{\min}$: is the minimum value of the vibration frequency range, $S_{\max}$: is the maximum value of the sound frequency range, and $S_{\min}$: is the minimum value of the sound frequency range. In this study, $V_{\max}$ is set to 500 Hz, $S_{\max}$ to 4000 Hz, and both $V_{\min}$ and $S_{\min}$ are set to 0 Hz. For example, when the sound frequency S_f is 1000 Hz, the vibration frequency V_f is converted to 125 Hz.

4. Implementation

4.1. Sound localization device

4.1.1. Headphone type device

Figure 3 shows the appearance of the prototype headphone-type device. The total weight of this device is 238 grams. The components used are the headphone body, two disk-shaped vibration motors (DVM150), an M5StickC Plus, and a sound direction sensor board (CRESCENT-031). During the development process, the control program for the device was created using Arduino IDE. The sound direction sensor board is equipped with four microphones that detect the time difference of sound arrival and calculate the direction of the sound source based on it, outputting angle information. When viewed from above, the front (forehead side) is defined as 0 degrees, and the back (occipital side) as 180 degrees. Accordingly, vibrators were installed in the ear pads of the headphones. If the detected sound direction from the top view of the head is $0 \leq \theta < 180$, the right-side vibrator is activated, and if $180 \leq \theta < 360$, the left-side vibrator is activated.

4.1.2. Beret type device

Figure 4 shows the appearance of the prototype beret-type device. This device weighs 353 grams in total, with the built-in battery alone weighing 130 grams. The components used include a beret, six disk-shaped vibration motors (DVM150), an Arduino UNO, and a sound direction sensor board (CRESCENT-031). The control program for the device was also developed using Arduino IDE.

The beret-type device can convey the direction of sound sources in six directions. The vibrators are arranged, when viewed from above, at 0 degrees (forehead), 60 degrees (right front), 120 degrees (right rear), 180 degrees (back), 240 degrees (left rear), and 300 degrees (left front). Depending on the detected sound source direction, the corresponding vibrator is activated. For example, if the sound source is detected from the front at an angle of $0 \leq \theta < 30$ or $330 \leq \theta < 360$, the forehead vibrator is activated. Similarly, for angles $30 \leq \theta < 90$, the right-front vibrator operates; for $90 \leq \theta < 150$, the right-rear vibrator; for $150 \leq \theta < 210$, the back vibrator; for $210 \leq \theta < 270$, the left-rear vibrator; and for $270 \leq \theta < 330$, the left-front vibrator.

4.2. Sound source identification system

The frequency conversion from sound to vibration is achieved through the following steps:

1. Detect sound using a microphone
2. Perform Fourier Transform (FFT) on the detected data

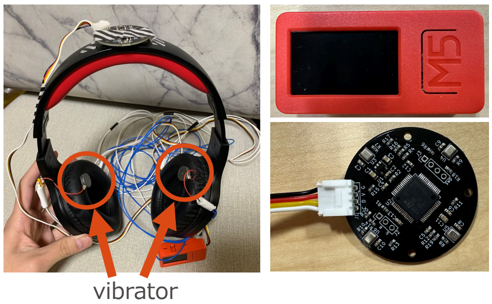

Figure 3: Headphone-type device (left), appearance (top right), microcontroller (bottom right), and microphone array

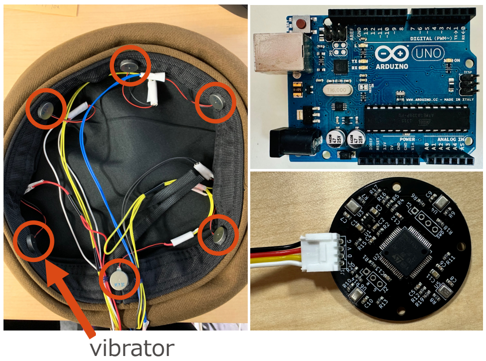

Figure 4: Beret-type device (left), appearance (top right), microcontroller (bottom right), and microphone array

3. Convert the frequency using the conversion function
4. Apply Inverse Fourier Transform (IFFT) to the converted data
5. Output the transformed data to the vibrator

This method is similar to that used in real-time voice changers.

In these steps, we prepared audio data in advance and confirmed the operation of the Haptuator by converting this audio source. For the implementation, we used a Haptuator (TactileLabs / TL002-14R), a computer (MacBook), an audio amplifier, and a stabilized DC power supply.

First, we downloaded "Ambulance Siren 1" from Sound Effect Lab [13]. The audio file was divided into 0.1-second segments, and Fourier Transform (FFT) was applied to each segment to analyze the frequency spectrum. The frequency data for each segment was then mapped. Next, we performed Inverse Fourier Transform (IFFT) on the mapped frequency data to reconstruct the signal in the time domain. Finally, the segments were reassembled to generate the continuous audio signal after processing. Figure 5 shows the frequency conversion diagram of the ambulance siren.

We also applied the conversion to human speech (female saying "Konnichiwa")[14]. For human speech, the optimal range for formant analysis is said to be 0.02 to 0.04 seconds. Therefore, for human speech, we performed Fourier Transform at 0.02-second intervals. Figure 6 shows the frequency conversion diagram of the human (female) voice.

4.3. System Combining Sound Localization and Sound Source Identification

In this section, we describe a system that enables both sound localization and sound source identification by building upon the beret-type device for sound localization introduced in Section 4.1 . The system replaces the disk-shaped vibration motors used for sound source identification, discussed in Section 4.2, with vibrators called Haptuators, allowing for simultaneous sound localization and sound source identification.

The components used include two Arduino UNO boards, a sound direction sensor board, six Haptuators, two 8-channel relay modules, a PC (MacBook), an audio amplifier, six speakers, and three AUX cables. An experimental implementation was conducted using 15 types of sound source data.

4.3.1. Creation of Sound Source Data

As the first step, we prepared 15 different sound source data. These sounds were collected by category from those we commonly hear in daily life [15]. The categories include siren, car engine sound, horn, bicycle, phone ringtone, and human voice. These categories are listed in Table 1.

These sounds underwent frequency conversion following the method described in Section 4.2.

Table 1
Types of Sound Source Data

Category	Sound Source	Count
Siren	Ambulance	2 types
	Police car	1 type
Engine	Car engine	1 type
Horn	Car horn	2 types
Bell	Bicycle bell	3 types
Ringtone	Landline phone	1 type
	Rotary phone	1 type
	Mobile phone	1 type
Human Voice	Female	2 types
	Male	1 type

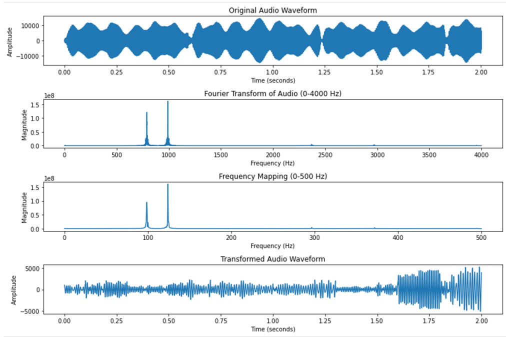

Figure 5: Frequency Conversion of Ambulance Siren

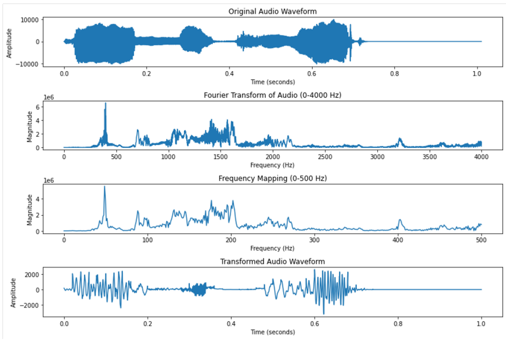

Figure 6: Frequency Conversion of Human (Female) Voice

4.3.2. Speaker Output of Sound Source Data

The audio data output from the R (right) side of the amplifier was directed to any selected speaker using a relay module and an Arduino UNO. To enable output to a specific speaker, a push-button switch was incorporated for switching between speakers. A tactile switch was used as the push-button, and it was controlled by the Arduino UNO.

4.3.3. Implementation of Sound Localization

The audio data output from the L (left) side of the amplifier was directed to the Haptuator corresponding to the detected sound direction using a relay module, an Arduino UNO, and a sound direction sensor board.

The mechanism for outputting to the Haptuator follows the same design as the Beret-type device described in Section 4.1.2. The implementation, which combines the methods discussed in Sections 4.3.2 and 4.3.3, is shown in Figure 7.

5. Preliminary Investigation

5.1. Interviews and Surveys at Schools for the Deaf

With the cooperation of the Nara Prefectural School for the Deaf, we conducted a trial session for the prototype device. We received the following feedback:

Regarding the Headphone-Type Device (Figure 3)

- "The ear pads are soft and comfortable to wear."
- "Vibrations may become stressful if multiple people speak at once."
- "Prolonged use could cause discomfort or pain."
- "Walking while wearing headphones may raise concerns about etiquette."

Regarding the Beret-Type Device (Figure 4)

- "It is excellent that sounds from behind can be detected."
- "The weight of the battery is noticeable."
- "The device might fall off if the head is moved quickly."
- "It is unclear if the proximity of vibrators allows for detailed perception."
- "It is easier to use than the headphone-type device."

Additionally, participants shared a general observation about both devices: apart from the Ontenna, they had not encountered any other devices that allow users to perceive sounds through vibrations. Many expressed interest in using such a device if it could help differentiate between various sounds and types.

5.2. Exhibits at Visitor Experience-Type Events

Based on feedback from the School for the Deaf, we decided to adopt the beret-type device. We then presented this device at the Innovation Stream KANSAI 6.0, held on February 21–22, 2023. Below are some of the main comments and questions received during the exhibition:

- "As a driver, it is often difficult to interact safely with individuals with hearing impairments, leading to potentially dangerous situations. This device could enhance safety for both parties."
- "I have seen visually impaired individuals appear anxious when crossing intersections with sound cues, as they cannot always determine the direction. This device might also be useful in such situations."

The feedback from this academic exhibition reaffirmed the high potential value of sound localization for various applications.

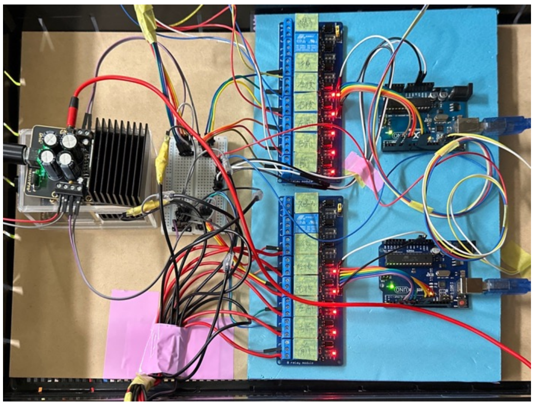

Figure 7: Combined Implementation

6. Experiment

6.1. Purpose of the Experiment

The purpose of this experiment is to verify whether the device improves the ability to localize sound sources and identify sound types.

Hypothesis 1 Sound Localization Accuracy via Vibration: Using this device will allow users to identify the direction of sound sources more accurately compared to without assistance.

Hypothesis 2 Sound Source Identification Accuracy via Vibration: Providing frequency-converted vibrations will enable users to identify sound types more effectively compared to without assistance.

6.2. Experimental Method

6.2.1. Experiment Participants

This experiment targeted hearing-impaired individuals aged 20 to 40. The scope of hearing impairment was defined as Levels 2, 3, and 4 under the Act on Welfare of Physically Disabled Persons. Participants were recruited through the Nara Prefecture Hearing Impairment Support Center, with approximately 300 individuals invited to participate.

The participants included one person with Level 3 hearing impairment and two with Level 2, totaling three participants (two males and one female).

6.2.2. Experimental System

The experiment used the Beret-type device developed in Section 4.3, which can simultaneously perform sound localization and sound source identification. The device presents different vibration patterns on the head, depending on the direction and type of the sound source. Sound source directions were output from six directions: 0 degrees (forehead), 60 degrees (right front), 120 degrees (right rear), 180 degrees (back of the head), 240 degrees (left rear), and 300 degrees (left front). Six speakers were used as sound sources, with only one speaker playing sound at a time. The number of vibrators matched the number of speakers.

Fifteen types of sound sources were prepared, as shown in Table 1. These sounds were selected from those commonly encountered in daily life, where sound localization is required, referring to "Nijiiro Hearing Aids – Types of Everyday Sounds" [15].

6.2.3. Evaluation Metrics

The evaluation metrics included the accuracy rate of sound localization and the accuracy rate of sound source identification. In addition, a self-report questionnaire (using a 7-point Likert scale) was used to evaluate the user experience of the device.

6.2.4. Experimental Environment

The experiment was conducted in the 3rd meeting room on the 6th floor of the Nara Prefecture Comprehensive Social Welfare Center. The experimental environment was an indoor space where external sounds were difficult to hear and unlikely to escape. A sign language interpreter was also present to facilitate communication with the participants. The experiment setup is shown in Figure 8.

Figure 8: Experiment

The sound sources used were the 15 types listed in Table 1, which were played randomly in both directions and types. Using the device developed in Section 4.3, the frequency-converted sound sources were output to the vibrators, while the original sound sources were played through the speakers.

6.2.5. Experimental Procedure

The experiment was conducted in two conditions: with the Beret-type device worn and without it. The experiment followed the steps below and took approximately 60 minutes.

1. Explanation of the experiment
2. Five to ten minutes of vibration training
3. Random presentation of sound source positions and types
4. Completion of the questionnaire

During vibration training, each type of sound source was explained through a sign language interpreter. In this practice, each sound was played, allowing participants to feel the corresponding vibrations and understand what each sound represented through sign language interpretation. For example, while the sound of a siren was played, participants could feel the vibration pattern of the siren, and the interpreter conveyed that it was an ambulance siren. In this training, participants experienced all types of sound sources prepared for the experiment. The test consisted of 12 questions per set, and the device was worn or removed between each set. A total of four sets were conducted.

7. Results and Discussion

7.1. Number of Correct Answers

The scores for the number of correct answers for sound source direction and type, with and without the device, are shown in Figures 9 and 10. The number of questions was 24 for both conditions (with and without the device). Assuming a normal distribution of the scores out of 24 points, a t-test was conducted.

The results showed no significant difference in the sound localization task between the two conditions ($t(2) = -0.277, p = 0.808, d = -0.204$).

For the sound source identification task, while a clear significant difference was not observed, a trend toward significance was found ($t(2) = 3.90, p = 0.0599, d = 3.00$). However, given the relatively small p-value and the large effect size, it is suggested that increasing the number of participants may yield a significant difference.

7.2. Questionnaire

7.2.1. About Participants' Disabilities

The participants included two individuals with Level 2 hearing impairment and one with Level 3. Regarding the age at which their hearing impairment was discovered, one participant reported it was immediately after birth, and two reported it was between the ages of 1 and 5.

Table 2
User Experience with the Device

Likert Scale Score	Bad	1	2	3	4	5	6	7	Good
Q1. Weight of the device	Heavy			1	1		1		Light
Q2. Sensation of vibration	Unpleasant	1			1	1			Pleasant
Q3. Confidence in sound-to-vibration conversion	Low	1				1	1		High
Q4. Fatigue during use	Present				1	1	1		Absent
Q5. Discomfort during use	Present	1		1		1			Absent
Q6. Ability to use all day	No	1				2			Yes
Q7. Willingness to use in daily life	No	1				1	1		Yes

The questionnaire on challenges faced in daily life revealed the following responses:

"I have difficulty communicating and cannot hear any surrounding sounds. It can be troublesome when I can't grasp sounds when needed."

"I can't recognize sounds during emergencies."

"Even if I hear a sound, I sometimes struggle to understand what it is."

Figure 9: Number of Correct Answers for the Sound Localization Task

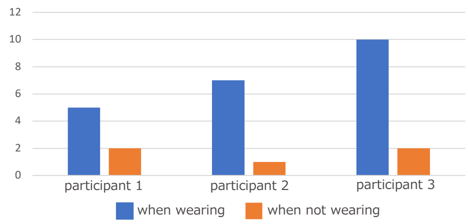

Figure 10: Number of Correct Answers for the Sound Source Identification Task

7.2.2. User Experience with the Device

We conducted a survey using seven questions (Table 2) on a 7-point Likert scale. The results for Q1 and Q4 were relatively positive, but one participant gave low ratings for Q2 and Q3. This participant also had fewer correct answers for sound source identification compared to the other participants.

7.3. Summary of Experimental Results

This study examined whether the device we developed can facilitate sound localization and sound source identification for hearing-impaired individuals in daily life. The following key points were identified from the results:

Regarding the accuracy of sound localization and sound source identification, no significant difference was found for sound localization between the conditions with and without the device. However, a trend toward significance was observed for sound source identification. Due to the small sample size of three participants, further experiments with a larger participant pool are necessary. Additionally, the results for the sound localization task may have been influenced by malfunctions of the sound direction sensor and the room's echo.

Regarding user experience with the device, participants reported little fatigue during use. However, opinions varied concerning the sensation of vibration, confidence in the sound-to-vibration conversion, and willingness to use the device in daily life.

8. Conclusion

We proposed a device capable of simultaneously performing sound localization and sound source identification, addressing the challenges that hearing-impaired individuals face in these areas. The results showed no significant difference in the sound localization task. However, in the sound source identification task, a large effect size was observed, indicating a trend toward significance even with a small number of participants.

Future challenges include conducting experiments with a larger participant pool and further miniaturizing the device.

Acknowledgments

We would like to express our sincere gratitude to the Nara Prefecture Hearing Impairment Support Center, the Nara Prefecture Comprehensive Social Welfare Center, and the sign language interpreters for their invaluable support. Their contributions include providing essential data and information related to this study, assisting with the recruitment of participants, and supporting the experiment.

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