FlexEar-Tips: Shape-Adjustable Ear Tips Using Pressure Control

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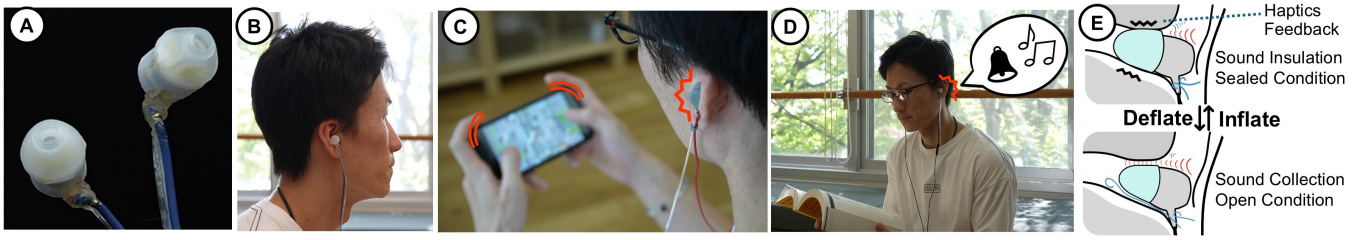


Figure 1: FlexEar-Tips overview and application examples. A: FlexEar-Tips, an ear tip system for hearables that allows shape adjustment through pressure control, B: user wearing the device, C: haptics features during gameplay, D: music listening experience enhancement and notification features, E: an image of ear tip status transitions.

Abstract

We introduce FlexEar-Tips, a dynamic ear tip system designed for the next-generation hearables. The ear tips are controlled by an air pump and solenoid valves, enabling size adjustments for comfort and functionality. FlexEar-Tips includes an air pressure sensor to monitor ear tip size, allowing it to adapt to environmental conditions and user needs. In the evaluation, we conducted a preliminary investigation of the size control accuracy and the minimum amount of variability of haptic perception in the user's ear. We then evaluated the user's ability to identify patterns in the haptic notification system, the impact on the music listening experience, the relationship between the size of the ear tips and the sound localization ability, and the impact on the reduction of humidity in the ear using a model. We proposed new interaction modalities for adaptive hearables and discussed health monitoring, immersive auditory experiences, haptics notifications, biofeedback, and sensing.

CCS Concepts

• **Human-centered computing** → **Mobile devices**.

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Keywords

Hearables, Earables, Pneumatics, Inflatable Interface, Haptics, Tactile

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1 INTRODUCTION

Earphone-type wearable devices (hearables) are expected to be used not only for music listening and calls but also for sensing the user's state [28, 30], monitoring the user's physiological state (such as heart rate [10], blood oxygen levels [4], and respiration [19]), and communicating with AI agents [32]. Various research and development efforts are underway in these areas. As hearables evolve into advanced information terminals, they are expected to be used in various situations, with longer wearing times. However, such extensive usage raises several concerns, including user safety, health risks, and information overload.

The prevailing approach to information presentation for hearables relies on audio. This raises the issue of interference from audio notifications during conversations or listening to music, which can hinder effective hearing. To address audio interference, alternative information presentation methods such as thermal [26] and vibration [23] feedback have been proposed. However, the speed of information switching remains a challenge, and the haptic presentation

sensations that can be added are limited. Moreover, mainstream canal-type hearables, which tightly seal the ear tips against the outer ear, can block out important ambient sounds like approaching vehicles or spoken communication, thus increasing traffic risks and hindering interpersonal interactions. Additionally, long-term use can raise the humidity inside the ear, increasing the risk of health issues such as ear infections [59]. Solutions such as an ambient sound awareness feature, which captures environmental sounds through an external microphone and plays them back to the user, or a system that alerts users after extended use, could be considered to mitigate these risks. However, the former does not fully reproduce the natural auditory experience [50], and the latter requires the user to stop using the device. Using open-ear type devices [38, 47], which do not block the ears, is also one solution. However, these devices do not have noise-cancelling functions and are inferior to in-ear devices in terms of sound quality and insulation.

In response to these challenges, we propose the FlexEar-Tips, a hearables ear tip system designed to provide various interactions to the user (Fig. 1). FlexEar-Tips are equipped with an ear tip connected to an air pump, enabling dynamic control of the ear tip's size. By exhausting air, the size of the ear tip can be reduced, thereby increasing the space between the ear tip and the outer ear. This adjustment allows for better air circulation within the ear, thus reducing humidity and improving the wearer's ability to hear ambient sounds (Fig. 1E). Furthermore, the shape change of the ear tip can add a haptic modality to the information presentation method in hearables, which has previously relied on the audio modality. Since providing visual feedback when a device is worn on the ear is difficult, the haptic is expected to be an effective method for extending hearables that do not rely on audio.

In this study, we designed the hardware configuration and control mechanisms for FlexEar-Tips. We then performed usability tests and evaluation experiments, ensuring the reliability and effectiveness of our proposed system, and thoroughly discussed potential use cases. The contributions of this research are as follows.

- We propose FlexEar-Tips, a system that enables interaction through the physical transformation of the ear tips.
- We conducted user experiments on information presentation, focusing on notification/enhancing the auditory experience. The results of the notification experiment demonstrated that the haptics method exhibited a higher left-right discrimination sensitivity than the sound method. Additionally, the results of the auditory experience experiment indicated that users preferred sound presentation with haptic feedback for certain sounds.
- We conducted user experiments to evaluate changes in sound localization ability. The results demonstrated an improvement in the front-back misrecognition rate by 6.6 points.
- By discussing the results of the experiment and the application of FlexEar-Tips, we provided future insights into the advancement of shape-changing interfaces and hearables.

2 RELATED WORK

2.1 A Study on Information Presentation Modalities for Hearables

Auditory modalities have traditionally been the dominant method for information presentation in hearables. Extensive research has been conducted on synthetic speech [36, 43], spatial audio reproduction [9, 40], and its application system [3, 12, 45]. Beyond auditory modalities, for instance, Nasser et al. [26] have developed devices that deliver thermal feedback to the auricle and conducted comprehensive studies on user perception. Tamaki et al. [42] incorporated projectors into headphone-type devices to present visual information in the user's forward field of view.

We introduce haptic feedback through the inflation and deflation of ear tips as a new method for information presentation, directly stimulating the ear canal. Our method provides a sensory experience that existing techniques cannot achieve and allows information presentation while minimizing interference with the user's music appreciation. Additionally, while previous methods were limited to information presentation, FlexEar-Tips expands the functionality of hearables, offering new capabilities for physical interaction and sensing.

2.2 Feedback Methods for Auditory Enhancement and Auditory Perception

There has been extensive research into methods of improving the musical experience [16, 39, 54] and expanding auditory perception [20, 31, 52] using audio and vibration feedback in relation to hearing.

2.2.1 Auditory Enhancement. Alice et al. [17] proposed a system that maps the characteristics of music rhythm and melody to haptic stimulation. They implemented the stimulation system in an arm-type device and demonstrated its effectiveness in improving music appreciation. Yamazaki et al. [51] developed the necklace-type haptic device "Hapbeat", and clarified the superiority of using the device in navigation systems as well as improving the music experience. Mirzaei et al. [23] used an earphone-type device that provides vibratory feedback to the ear as a guidance system for the visually impaired.

In contrast to these methods, our method achieves a haptic feedback system by dynamically adjusting the size of the ear tip. This approach enables haptic stimulation inside the ear, and in addition, it enables music appreciation with the same earphone-type device. Our method allows haptic stimulation to be presented at the closest possible location to the auditory stimulus, potentially providing a music experience distinct from previous approaches. While this study remains a fundamental investigation, we obtained positive evaluations regarding music appreciation. In the future, we anticipate further enhancement of the listening experience through haptic stimulation designed for specific scenarios.

2.2.2 Auditory Perception Augmentation. Watanabe et al. [49] proposed a framework that allows users to manipulate auditory input in real time by altering the frequencies of the sounds captured by the device. Tajadura-Jiménez et al. [41] demonstrated that modified walking sounds can alter a person's perceived body weight, leading

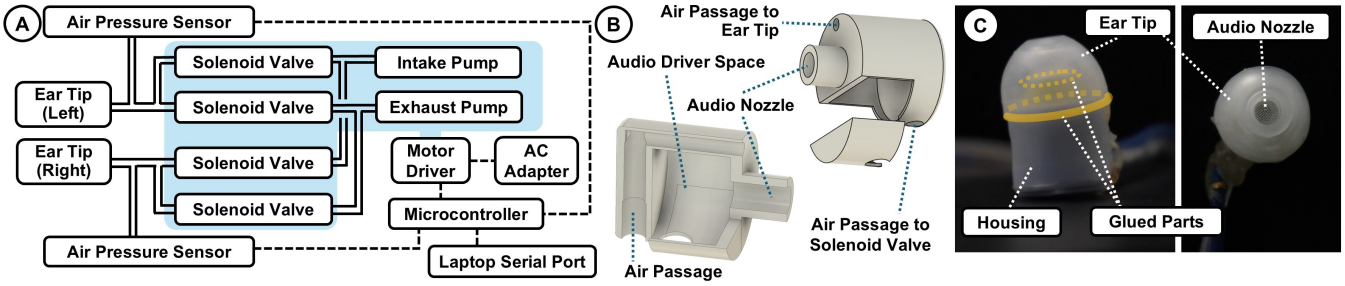


Figure 2: Overview of FlexEar-Tips. A: device configuration (all light blue shaded areas are connected to the motor driver for power supply and control), B: 3D model of the housing, C: actual device (left: side view, right: top view).

to corresponding changes in their gait pattern. Veluri et al. [46] implemented a neural network-based sound extraction system in a commercially available hearable and evaluated its effectiveness. These approaches represent auditory perception augmentation through sound processing software. On the other hand, Shirota et al. [37] proposed a wearable device with an adjustable pinna orientation, attempting to alter the user's hearing capability physically. Their experiments investigated the effects on auditory characteristics.

Our method modifies the device's physical characteristics by altering the shape of the ear tip, thereby changing its auditory characteristics.

2.3 Inflatable Technology

Many studies have been proposed on wearable devices, sensing, fabrication, robots, and interaction using inflating technology [6, 11, 13, 14, 18, 24, 27, 34, 35, 48, 53, 55, 56, 58]. In particular, wearable devices and interaction methods are gaining attention as comfortable, well-fitting interfaces due to their characteristics of flexibility and adaptability. Zhuoming et al. [57] introduced a pneumatic input-output interface with haptic feedback for smartphones and evaluated its effectiveness. Vazquez et al. [44] proposed a pneumatic haptic display by embedding airbags inside a jacket. Park et al. [29] developed an inflatable input-output interface to evaluate its practicality and effectiveness in long-distance communication between couples. Aryan et al. [33] presented "PneuMa", a wearable system that utilizes pneumatic technology for body augmentation. Their experiments included a case study on ear movement and a field study to evaluate its usability.

Our approach aims to enhance the functionality of hearables by proposing shape-adjustable ear tips, which differ from previous research. In this study, we explored and discussed the potential applications of FlexEar-Tips technology. Through evaluation experiments, we investigated pneumatic haptic feedback within the ear canal, changes in auditory characteristics, and humidity control inside the ear.

3 FLEXEAR-TIPS

Fig. 2 illustrates an overview of the FlexEar-Tips. The device comprises commercial silicone ear tips (SpinFit/CP100+ L: base diameter 13.3 mm), housing, a microcontroller (Adafruit/ESP32 Feather Board), a motor driver (Adafruit/Assembled DC Motor + Stepper FeatherWingAdd-on), an air pump (MERCURY MOTOR/AP030-060), solenoid valves (uxcell), an air pressure sensor (METRODYNE MICROSYSTEM CORP./MIS-2503-015G), a music driver (audio-technica/ATH-CKR30iS), air tubing (PISCO HQ/UB01810-10), and AC adapter (5V/2.0A output). Fig. 2A illustrates the device configuration for air pressure control within the ear tips. Solenoid valves, which manage the connections, are placed between the exhaust/intake pump and each ear tip. An air pressure sensor is placed in front of the solenoid valve so that the internal air pressure can be measured when sealed state. The device was connected to a laptop computer, and operation commands and data were sent and received via serial communication.

3.1 Housing

Fig. 2B shows the 3D model of the housing. The housing comprises a space for accommodating the audio driver, an audio nozzle, and a pipe section that channels air to the ear tip. The space for the audio driver and the pipe are separated, ensuring that the air and audio transmission paths remain independent. The housing was manufactured using a stereolithography (SLA) printer (HOTTY POLYMER inc. /Smapri Sonic 4K LL/XY resolution: 50 µm) and high-strength resin (Okamura Tech Co., Ltd./HS-5000-W) as a material. Fig. 2C shows the actual device. After installing the driver within the housing, the unit was sealed. Subsequently, the ear tip was attached to the housing in a sealed manner. By sealing the glued parts shown in Fig. 2C, the inside of the ear tip is isolated from the audio driver space and external.

3.2 Internal Pressure and Ear Tip Shape

Our system measures the size of the ear tip by using the internal air pressure. The internal pressure P of an ear tip depends on the enclosed volume V, the air molecule count n, and the temperature T, following the ideal gas law:

$$P = \frac{n \cdot R \cdot T}{V}$$

where R is the universal gas constant. As shown in the equation, when the air in the ear tip is exhausted by the pump, the number of air molecules decreases, so the internal pressure decreases. Fig. 3A shows the shape of the ear tip when the internal pressure is changed. The internal pressure was approximately −10 kPa in gauge pressure, which corresponds to 91.3 kPa in absolute pressure when the solenoid was released and then closed again without the

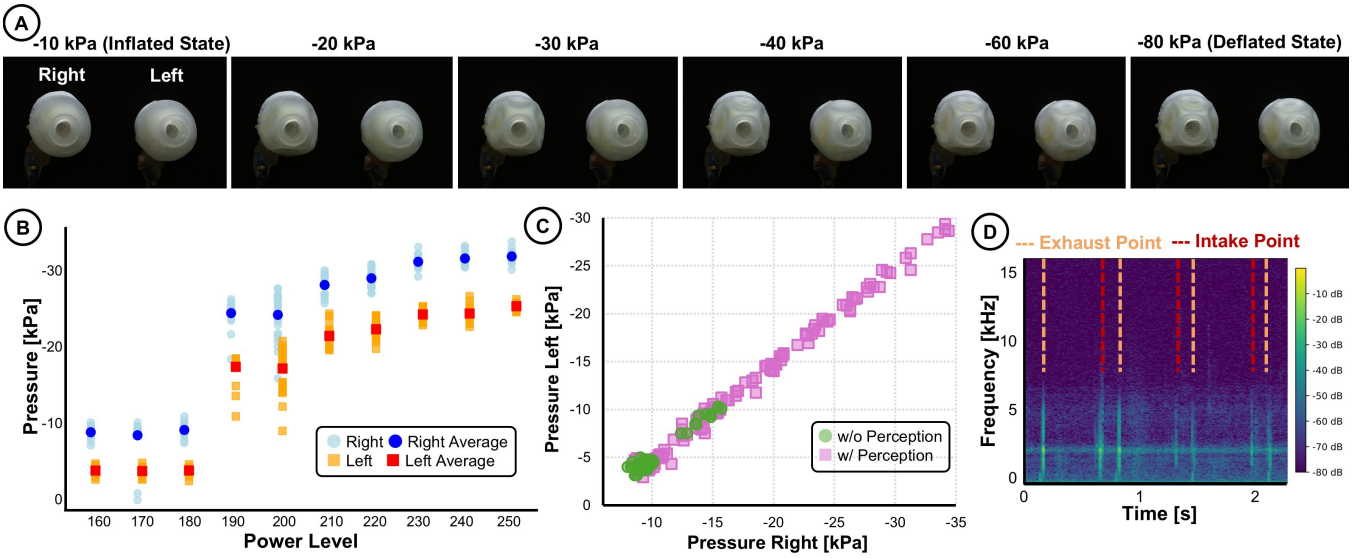


Figure 3: Eartip shape and air pressure. A: eartip shape for each air pressure value, B: air pressure distribution for each power level, C: The user's haptics perception results during size-shape change, D: the spectrogram of the sound inside the ear during repeated inflation and deflation of the ear tip.

pump operating. In this paper, gauge pressure is employed. At this time, the ear tip is approximately in a non-pressurized state and is at its maximum size. This state of the ear tip is referred to as the inflated state. Next, the shape of the ear tip deforms so that its volume becomes smaller due to exhaust air from the pump. The internal pressure at the exhaust limit was approximately -80kPa. This state of the ear tip is referred to as the deflated state.

Notably, significant shape changes occurred between −20 kPa and −30 kPa. This is likely due to the elastic properties of the silicone, which are strongly affected by external pressure within this range. Because it was challenging to measure the volume of the ear tip directly, the pressure sensor readings are used in this study as a proxy for the size of the eartip. In this study, inflation was achieved at a sufficient speed using natural intake, so an intake pump was not used. Additionally, due to the rigidity of the ear tip, even with pump-assisted intake, the pressure did not decrease below −10 kPa.

3.3 Sizing Ear Tips with Air Pressure Sensors

In this study, voltage was applied to the air pump and solenoid valve using PWM (pulse width modulation) signals from a microcontroller. Due to the nature of PWM signal-based voltage control, there is a slight discrepancy between the theoretical value and the actual applied voltage. Therefore, we investigated how PWM signal voltage application affects size control errors. Specifically, we measured the internal air pressure of the sealed ear tip after applying the PWM signal, starting from the inflated state. The power level of the exhaust pump was increased from 160 in increments of 10, with 30 measurements taken at each power level. The application duration was set to 100 milliseconds. Fig. 3B shows the internal air pressure at each power level and the corresponding average. The difference in the air pressure between the left and right ear tips is due to initial volume variations caused by device fabrication discrepancies. The investigation revealed that the internal air pressure of the ear tips increased when the power level was 190 or higher. At power levels of 190 or above, the standard deviation of air pressure changes at the same power level averaged −24.0 kPa for the right ear and −17.1 kPa for the left ear. At power levels of 200 and 240, the average pressure was higher than at 190 and 230, indicating that the air pressure change did not follow a linear relationship with the power level. Therefore, implementing haptic presentations with varying intensities requires adjustments in this system, such as setting power levels at least 30 units apart.

3.4 Haptic Perception and Ear Tip Size

The relationship between the amount of size change of the ear tip and the user's haptic perception is not yet fully understood. To conduct haptic testing, it is necessary to understand the minimum amount of change in earplug size required for human perception. This preliminary study, which involved six participants (4 males and 2 females, average age 27.7 years, $SD = 7.61$), aims to provide initial insights. Of the six participants, three reported that the device fit them properly, and the other three reported that it was large. In this experiment, participants wore the device while the ear tip was randomly reduced in size from an inflated state. They were then asked to indicate whether they felt any haptic feedback. Each participant completed five measurements per round across three rounds, with the device being removed and reattached between rounds.

Fig. 3C shows the size change amounts and whether they were perceived. In this experiment, the amount of size change was adjusted by tuning the PWM signal strength and application time. As a result of the experiment, the maximum size change without perception was when the right ear was −15.73 kPa and the left ear

was −10.04 kPa. In addition, it should be noted that some sound is generated by the compression of the ear tip and its friction with the ear canal during haptic feedback. Fig. 3D shows the spectrogram of the sound produced inside the ear during repeated inflation and deflation of the ear tip. The sound was recorded by attaching the device to an ear model, with a microphone placed at the eardrum to capture the audio. The sounds generated during the deformation of the ear tip were primarily distributed in the 0 to 7 kHz range, and the main components were the silicone's deformation noise and the solenoid's operating noise.

4 EVALUATION

In this study, we investigated information notifications, haptics, changes in auditory characteristics, and changes in ear canal humidity.

4.1 Information Notification Tests

We implemented a haptic notification system using the proposed device and investigated the pattern recognition rate and usability.

4.1.1 Experimental Setup. We generated a total of 12 haptic patterns by combining three factors: presentation position (both ears, right ear, left ear), number of pulses (one, two), and intensity (strong, weak). A single haptic presentation involves compressing the ear tip from an inflated state to reduce its size and then returning it to the inflated state. In the future use of our method, it is expected that ear tips will be tailored to different sizes according to the fitting preferences of the user, the environment, and the purpose of use. In this study, the starting point from the inflated state, which is considered to be the most frequently used, was investigated. The transition time from the inflated state to the deflated state was approximately 0.27 s, and vice versa was approximately 0.33 s. In setting the parameters for the intensity, it is necessary to avoid confusing the pressure changes that occur when applying a strong signal and a weak signal. On the other hand, if the power level is increased and extra air pressure changes are generated, the haptic presentation will become too strong, and usability will be impaired. In this study, based on Section 3.3, we determined the settings that are assumed not to confuse the distribution of pressure changes. Specifically, we set the signals to 190 (weak) and 230 (strong), respectively, and the application time to 100 milliseconds.

We used an audio-based notification system as a comparison method. In the audio-based notifications, pitch (high or low) was used instead of haptic intensity. The tones used were 2000 Hz for high and 600 Hz for low, with a signal duration of one second and a volume set to approximately 50 dB. We adopted a change in frequency in this study because intensity based on volume is expected to be highly sensitive to individual hearing thresholds and environmental factors (external noise, music, and speech).

4.1.2 Data Collection. A total of 16 participants (7 males and 9 females, average age 30.1 years, $SD = 12.6$) participated in the experiment, all participating in both methods. Of the 16 participants, eight reported that the device fit them properly (well-fit), and the other eight reported that it was large (non-well-fit). As the ear tip size was predetermined to be large, no participants reported it as small. The experiment began with an explanation of each presentation pattern, followed by an opportunity for participants to experience each pattern to familiarize themselves with the sensations. Afterward, participants listened to the device's music (piano and rock music) while randomly receiving one of the haptic patterns. Participants were asked to respond to the perceived pattern by pointing to the corresponding options on a sheet in front of them, and the experimenter recorded their responses. The presentation was given at random times. No subsequent notifications were presented for 10 seconds after each notification to provide sufficient answer time. Additionally, the next notification was set to occur within 40 seconds to gather enough samples. In total, 231 responses were collected for the haptic method and 235 for the audio method, resulting in a total of 466 responses. The experiment was designed counterbalancing to avoid any order effects on the results.

After each method, participants answered eight usability-related questions (notification understandability, no music interference, perceived response speed to notification, music focus retention, no stress from notification, adaptability across contexts, attention-grabbing, and overall satisfaction) using a five-point Likert scale (strongly agree, agree, neutral, disagree, strongly disagree). They were also invited to provide open-ended feedback. This experiment was approved by the ethical board at the author's institution, and informed consent was obtained from the participants.

4.1.3 Comparison of Haptics and Audio Methods. The upper section of Fig. 4A summarizes the results of correct answers overall and for each factor for the entire group. The overall pattern recognition rate was 74.9% for the haptic method and 86.8% for the audio method. For individual factor recognition rates, the haptic method showed higher recognition rates for presentation position compared to the audio method, while the audio method showed higher recognition rates for the count and intensity compared to the haptic method. A Wilcoxon signed-rank test on overall recognition showed a significant difference ($W = 25.0, p = 0.046$). For position recognition, a Wilcoxon signed-rank test revealed a significant difference between audio and haptic recognition ($W = 3.0, p = 0.007$). Similarly, significant differences were found in the recognition of count/intensity between the audio and haptic methods ($W = 1.5, p = 0.021$/$W = 1.0, p = 0.003$).

Fig. 4B presents the ratio of each score from the questionnaire results. In all items, higher scores indicate better outcomes. The results of the Wilcoxon signed-rank test showed that p-values for all results were above 0.05, indicating no significant differences. This suggests that both methods were effective to some extent, with varying preferences among users. When comparing the number of responses with scores of 4 or higher, the haptic method had more responses for *no interference with music*, *no stress from notification*, and *satisfaction*, while the audio method had more responses for *notification understandability* and *attention-grabbing*.

4.1.4 Comparison of Results Based on Fitting. The accuracy in the non-well-fit group (61.2%) for the haptic method was significantly lower compared to the well-fit group (88.6%). A t-test revealed a statistically significant difference between the two groups ($t(14) = 3.25, p = 0.006$). This was attributed to the low accuracy in the count identification rates. The identification rates in the non-well-fit group (79.4%) were significantly lower compared to

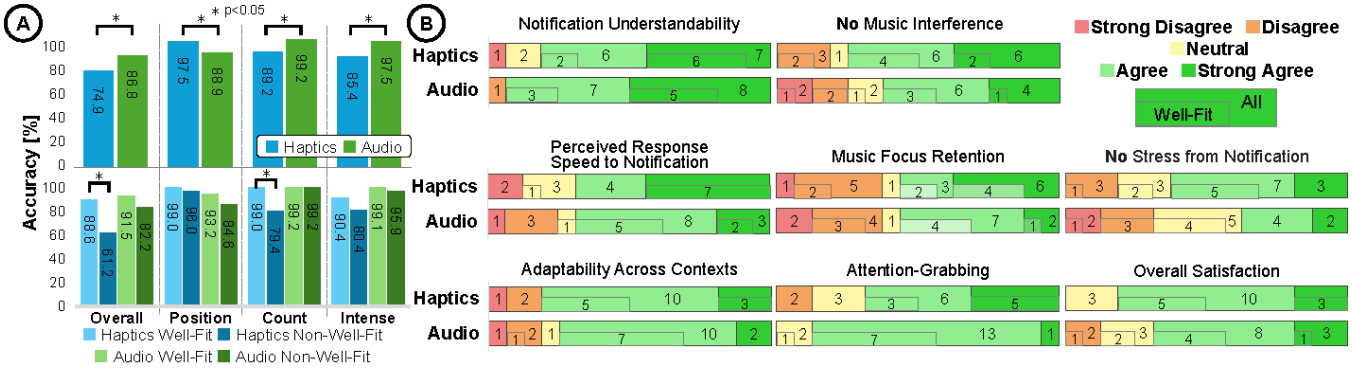


Figure 4: Results of the information notification test; A: the upper section displays the overall results, and each factor result for the entire group. The lower section displays the results for the well-fit group (where the device size was properly) and the non-well-fit group (where the device size was large), B: aggregate results of subjective evaluation. The well-fit user's response is shown inside.

the well-fit group (99.0%), as determined by a Mann–Whitney U test ($U = 54.0, p = 0.013$). The questionnaire results also showed significant differences in the items of notification understandability, adaptability, perceived response speed, and overall satisfaction. A Mann–Whitney U test indicated significant differences for notification understandability ($U = 9.0, p = 0.011$), adaptability ($U = 12.5, p = 0.021$), perceived response speed ($U = 5.0, p = 0.003$), and overall satisfaction ($U = 12.5, p = 0.021$).

4.2 Impact on Auditory Experience

We investigated how haptic feedback, achieved by varying the ear tip size, affects the experience of listening to music and sound effects.

4.2.1 Experimental Setup. Seven types of audio sources, including music and sound effects, were selected for this study. For the music sources, we selected three tracks, the electric guitar, piano, and drums being the main instruments. We selected explosion sounds, gunfire (machine gun), footsteps, and drinking sounds for the sound effects. Fig. 5A shows the spectrogram and haptics point for each sound source data. The cycle of a single haptic presentation is the same as described in Section 4.1.1. The feedback was synchronized with the guitar strokes, piano bass notes, and the high-tom/cymbal of the drums. The explosion sound was paired with one haptic feedback at the start of the sound. For the gunfire, five haptic presentations at equal intervals were given in response to the continuous firing sounds. The drinking sound was accompanied by four haptic presentations synchronized with the swallowing sounds. The intensity of the PWM signal for each presentation was adjusted by the experimenter.

4.2.2 Data Collection. A total of 16 participants (7 males and 9 females, average age 30.1 years, $SD = 12.6$) participated in the experiment, listening to the audio sources with and without haptic feedback. Of the 16 participants, eight reported that the device fit them properly, and the other eight reported that it was large. As the ear tip size was predetermined to be large, no participants reported it to be small. They rated the impact of the haptic feedback on their experience (enhancement of immersion, harmonization with the sound, and comfortability for haptics) using a five-point Likert scale (strongly agree, agree, neutral, disagree, strongly disagree). They also indicated whether they preferred the audio with or without haptic feedback, with a neutral option available. The experiment was designed counterbalancing to avoid any order effects on the results. This experiment was approved by the ethical board at the author's institution, and informed consent was obtained from the participants.

4.2.3 Experimental Results. Fig. 5B shows the questionnaire results for each audio source. Higher scores indicate a more positive impact of the haptic feedback. Regarding the results related to the impact, for all sound sources except the piano, the number of responses with a score of 4 or higher exceeded those with a score of 2 or lower. Regarding preferences, more users preferred haptic feedback for all sound sources other than the piano.

The impact scores on a 5-point Likert scale averaged 4.1 for the well-fit group and 3.4 for the non-well-fit group. Similarly, the preference scores on a 3-point Likert scale averaged 2.4 for the well-fit group and 1.9 for the non-well-fit group.

4.3 Sound Localization Test

4.3.1 Experimental Setup. We investigated the change in sound localization ability according to the size of the ear tip. Two types of tests were conducted to investigate sound localization ability. Fig. 6A illustrates the speaker placement and the direction participants face for each test. In the Direction 1 (D1) test, speakers were positioned at equal intervals of 30 degrees over a 180-degree arc in front of the participant, assessing left-right localization ability. In the Direction 2 (D2) test, speakers were positioned at equal intervals of 30 degrees over a 180-degree arc to the participant's right, assessing front-back localization ability. For each test, participants were asked to predict and respond to the direction from which white noise was randomly played through the speakers. The white noise signal lasted 3 seconds. The audio files were played through speakers (Creative: Creative Pebble V2) using a PC (ASUS: ROGFLOW X13) via an audio interface (Roland: OCTA-CAPTURE).

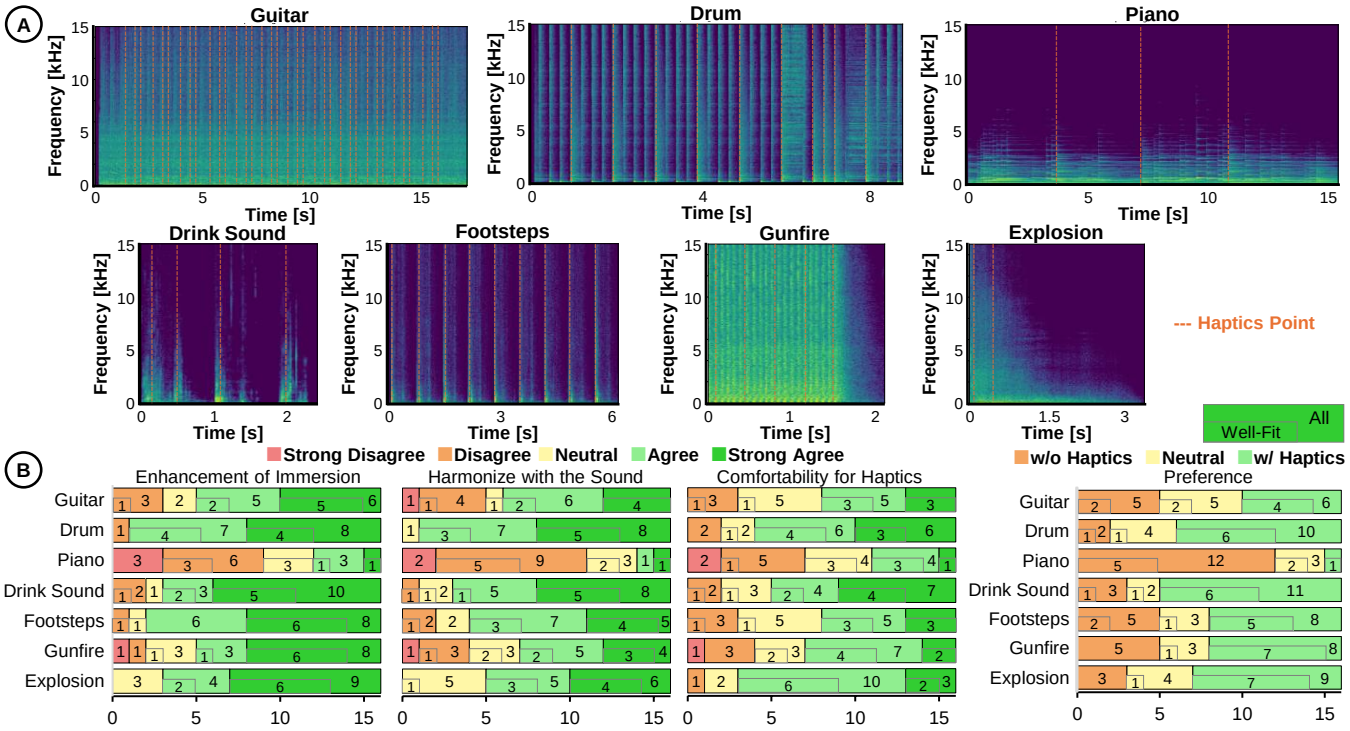


Figure 5: A: Spectrogram and haptics point for each sound source data. The vertical orange line indicates the position of the haptics presentation, B: Subjective evaluation and preferences for each sound source. The well-fit user's response is shown inside.

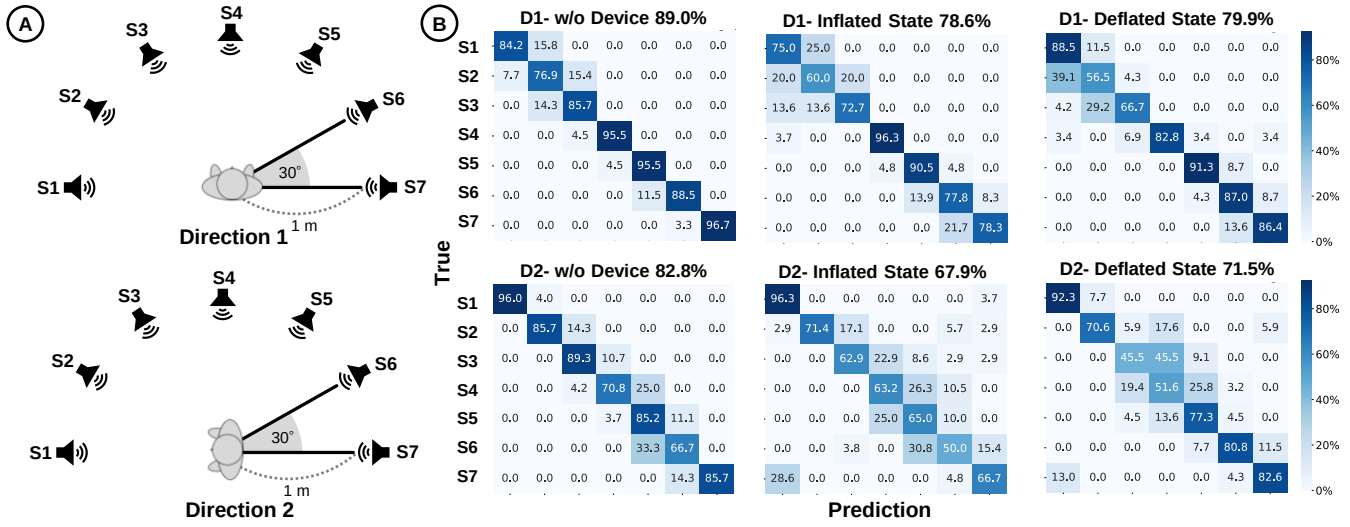


Figure 6: Speaker placement and experimental results for the localization test. A: the speaker placement and the direction participants face, B: the confusion matrix for each condition.

4.3.2 Data Collection. A total of 10 participants (9 males and one female, average age 25.8 years, $SD = 6.36$) participated, with 20 trials conducted under each condition. These measurements were performed under three wearing conditions: with the ear tip in the inflated state, with the ear tip in the deflated state, and without the device (w/o device). The experiment was conducted in a laboratory, where a table with a height of 1 m was placed in the center of a 4 m square space, and the speakers were arranged on the table.

During the experiment, participants sat on a chair with a height of 50 cm. The ambient noise level was approximately 40 dB, and the signal volume was set to approximately 60 dB. This experiment was approved by the ethical board at the author's institution, and informed consent was obtained from the participants.

4.3.3 Experimental Results. Fig. 6B shows the results for each condition. The accuracy rates were 89.0% (D1 - w/o device), 78.6% (D1 - inflated state), 79.9% (D1 - deflated state), 82.8% (D2 - w/o device), 67.9% (D2 - inflated state), and 71.5% (D2 - deflated state). The Friedman test found significant differences in accuracy between the wearing conditions in both the D1 and D2 tests ($\chi^2 = 20.52$, p = 0.015 for D1; $\chi^2 = 23.57, p = 0.005$ for D2). However, no significant differences were observed in any comparisons in the post-hoc tests after Bonferroni correction. On the other hand, the rate of front-back confusion (e.g., presenting sound from S7 being perceived as coming from S2) was 11.7% when inflated, which was higher than when deflated (5.14%). Therefore, when it is necessary to be aware of the surrounding environment, using the device in the deflated state may provide a certain level of safety. However, front-back confusion still occurred, indicating that further improvements are necessary.

4.4 Humidity Changes

We investigated the relationship between ear tip size and changes in humidity inside the ear.

4.4.1 Experimental Setup and Data Collection. In this experiment, a humidity sensor (SANWA DIRECT: UNI-01-C003) was placed inside a plastic ear model (Nihon 3B Scientific Inc.: Equilibrium organ, transparent model) to measure the humidity inside the ear canal (Fig. 7A). We used a humidifier to raise the humidity inside the ear canal to 80% and then measured the decrease in humidity until it reached 65%. This measurement was conducted under four different conditions: inflated state, deflated state, without the device, and airflow mode. Airflow mode is the inflated and deflated states alternated for every 0.6 s, aimed at accelerating humidity reduction through airflow generation. Each condition was measured nine times. The average room humidity during the measurements was 53.97% (SD = 2.88).

4.4.2 Experimental Results. Fig. 7B shows the time required for the humidity to decrease to 75%, 70%, and 65%. The results showed that the time required for the humidity to decrease to 65% was 441.7 s (inflated state), 394.5 s (deflated state), 404.7 s (airflow mode), and 222.3 s (without the device). Compared to the without-device condition, the time to reduce humidity was longer in other conditions. However, compared to the inflated state, the deflated state and airflow mode reduced the time by 10.7% and 8.4%, respectively. The results of Dunn's Multiple Comparison Test showed a statistically significant difference ($p < 0.05$) in the time required to reach each humidity level between the condition without the device and the other three conditions (inflated state, deflated state, and airflow mode). The effect sizes (Cohen's d) for the comparisons between deflated state-inflated state and airflow mode-inflated state were 0.454 and 0.439, respectively, indicating a moderate effect, though these were not statistically significant ($p > 0.05$). Although statistical significance was not observed between the three conditions, the effect size suggests a moderate difference between the inflated and deflated states and between the inflated state and airflow mode. Further detailed evaluations—such as flow visualization experiments using a smoke generator and usability tests—are needed to determine whether the performance is sufficient for practical use.

5 Applications

In this section, we discuss the potential applications of FlexEar-Tips. Fig. 8 illustrates the application scenarios for FlexEar-Tips. We categorize three application domains (information presentation, physical effects, sensing), although these categories are not strictly defined, and the boundaries between them are not always clear.

5.1 Information Presentation

5.1.1 Notifications. In commercial hearables, the predominant modality for notifications is audio. This poses a usability challenge, particularly when users want to listen to music or take calls simultaneously, as the audio notifications either interrupt or overlap with other sounds. FlexEar-Tips can control the contact area between the ear tip and the ear canal, allowing for the reproduction of various haptic patterns by adjusting the size, speed of transitions, and left-right presentation patterns. This haptic information presentation enables notifications for emails or tasks without compromising the user's auditory experience (Fig. 8a).

5.1.2 Enhancing the Auditory Experience. Enhancements to the auditory experience have been widely explored by incorporating haptic modalities to create a more immersive experience [16, 39, 51, 54]. FlexEar-Tips can offer a new music listening experience by combining haptic feedback with the pressure of the ear tip against the outer ear, aligning with the auditory content. This is not limited to music listening but is expected to be combined with game playing or video content (Fig. 8b).

5.1.3 Virtual Reality and Biofeedback. The ear canal is a sensitive organ, partly due to the concentration of the vagus nerve, which offers the potential for enhancing virtual reality (VR) experiences. For example, FlexEar-Tips could simulate sensations like ear-picking, potentially reducing excessive ear-picking behaviors by delivering a similar haptic experience. VR therapy for anxiety and stress could leverage gentle haptic feedback near the ear to stimulate the vagus nerve, mimicking calming effects akin to ear acupressure. This approach may support relaxation and meditation-based VR applications aimed at reducing anxiety and improving mental well-being. Additionally, previous research has proposed methods to influence the cardiac system by stimulating the vagus nerve in the ear [25], and the haptic feedback of FlexEar-Tips may replicate similar effects (Fig. 8c).

5.2 Physical Effects

5.2.1 Auditory Characteristics. Canal-type hearables provide high sound insulation but reduce awareness of surrounding sounds, while in-ear types offer better ventilation at the cost of sound insulation. FlexEar-Tips allows flexible adjustment of the eartip condition, allowing the user to switch between characteristics similar to those of these device types. In situations where it is necessary to be aware of the danger, such as an approaching car, it is assumed that

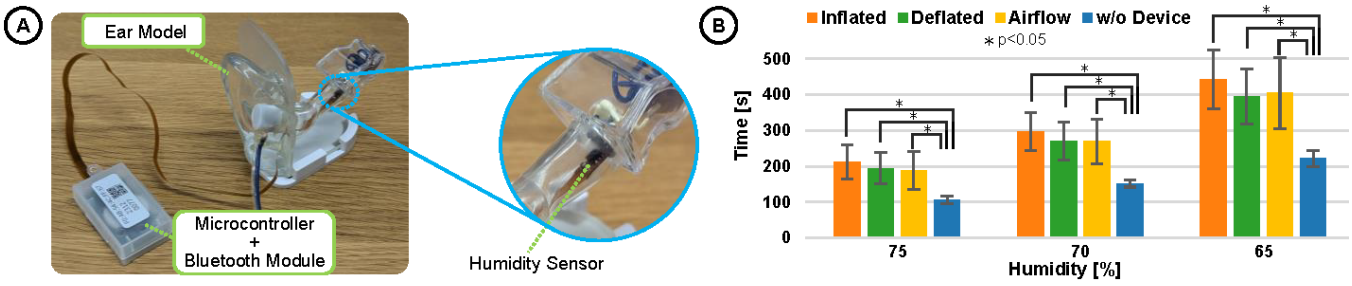


Figure 7: A: Measured environment for humidity change test, B: time required for humidity decrease.

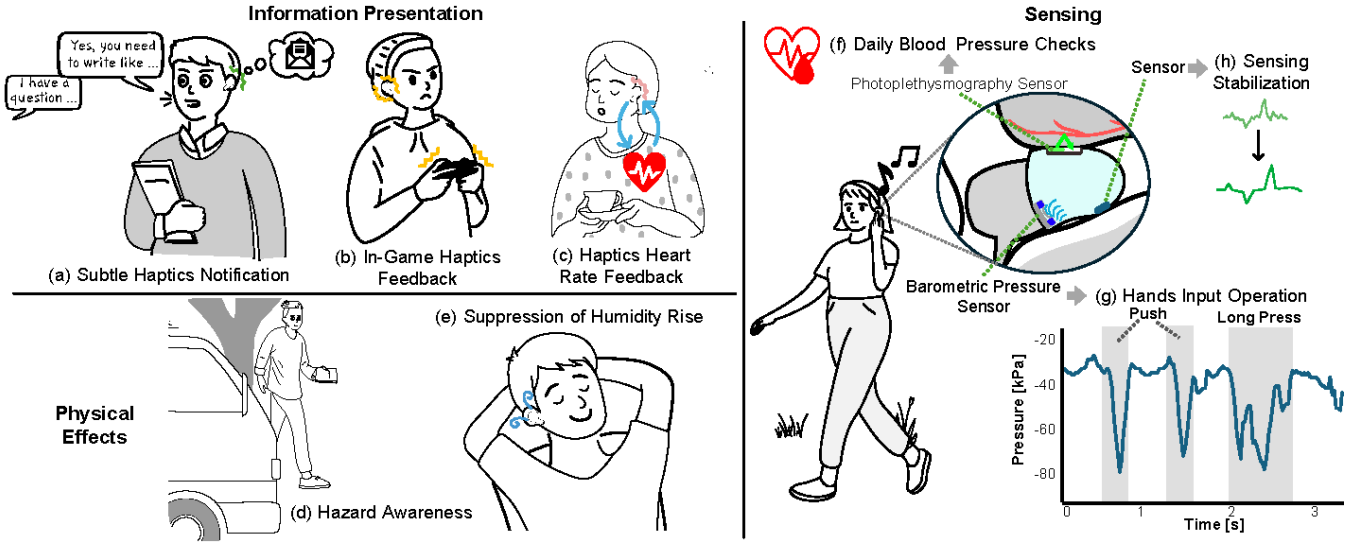


Figure 8: Three application domains and example scenarios for FlexEar-Tips.

the ear tips will be used in a smaller size to improve the hearing of surrounding sounds (Fig. 8d).

5.2.2 Humidity Control. The long-term use of hearables can increase ear humidity, raising health concerns, especially with canal-type devices due to their close contact with the ear canal [59]. FlexEar-Tips mitigates this issue by adjusting the ear tip size to control ventilation and reduce humidity buildup, promoting ear health. For instance, if a user falls asleep while wearing hearables, the device can automatically shrink the ear tips to prevent humidity increase (Fig. 8e). However, this application requires an internal ear microphone for sleep detection [15], which is not currently supported by the FlexEar-Tips setup.

5.2.3 Fitting Control. Commercial hearables typically offer ear tips in a few fixed sizes to achieve a proper fit, which is essential for sound quality and insulation. However, fine adjustments are difficult with these fixed-size options. While LIGHTFORM [21] molds ear tips to the user's ear shape using photo-curable polymers, the resulting ear tips cannot be adjusted after molding. In contrast, FlexEar-Tips leverages solenoids and air pumps to dynamically adjust ear tip size, offering a customizable fit that can be modified as needed. However, as fitting adjustments can alter internal acoustic characteristics, a dynamic equalization function is also necessary.

5.3 Sensing

5.3.1 Blood Pressure Measurement. Nam et al. [5] measured blood pressure using tightly fitting balloon-like ear tips. FlexEar-Tips might achieve similar results by integrating a PPG sensor for snug fitting within the ear canal. This approach could enable daily blood pressure monitoring, significantly contributing to healthier lifestyles (Fig. 8f). However, this study did not experimentally validate the concept, as the current FlexEar-Tips lacks a PPG sensor.

5.3.2 Ear Tip Deformation. FlexEar-Tips controls ear tip size by measuring internal air pressure, which changes as the ear tip deforms in its sealed state. This principle could be applied to detect hands-on device inputs or facial recognition (Fig. 8g). Similar to the method by Ando et al. [2], which measures ear canal pressure changes during facial expressions, FlexEar-Tips instead focuses on pressure changes within the ear tip itself. The graph in Fig. 8g shows the change in internal air pressure when the housing is pressed with the index finger when the device is actually worn. In the future, we need to measure data in real-world environments

with a large number of people and explore the possibility of using it for device operation.

5.3.3 Adjustment of Sensor Positions. Ear tips exhibit high adhesion to the skin, and the ear canal is minimally affected by external light and sound. Additionally, the ear canal's shape deforms with facial expressions and varies by individual, making it a suitable site for sensor placement in applications like facial expression recognition and personal authentication [7, 8, 22]. However, sensing accuracy in these methods is heavily influenced by sensor positioning, requiring measures to minimize misalignment caused by user movement [1]. FlexEar-Tips, with its shape adjustment and fitting control, may help stabilize measurements by enabling fine adjustments to sensor placement within the ear tip (Fig. 8h).

6 DISCUSSION

6.1 Haptic Feedback

6.1.1 Notification Test. In our notification test, the recognition rate for identifying the number of pulses and the intensity of the haptic was lower compared to the sound presentation. In the interview, seven participants (six non-well-fit users and one well-fit user) commented that it was challenging to distinguish the number of pulses, and three non-well-fit users reported difficulty differentiating between strong and weak intensities. In addition, there was a large difference in accuracy between the well-fit group and the non-well-fit group, which clearly indicates that fitting substantially impacts performance. All users in the non-well-fit group reported the device size as too large, which likely prevented deep insertion of the ear tips and proper transmission of haptic feedback. In the future, we will need to investigate how accuracy can be improved by adjusting the size of the ear tips. One participant mentioned delayed responses due to the novelty of the haptic experience, while another highlighted potential confusion between haptic notifications and unintended device movements caused by user motions. These observations highlight the need for future investigations into the effects of user habituation for haptic feedback systems and changes in perceptual characteristics during motion.

Conversely, haptic feedback provided higher recognition rates for the presentation position compared to audio feedback. Seven participants reported difficulty distinguishing between audio signals played from both ears and those played from the left or right in the audio method. This difficulty may stem from a lack of distinct spatial cues, such as intensity or timing differences, and overlapping frequency components. Haptic feedback showed effectiveness for notifications requiring clear left-right directionality, making it a promising approach for applications such as guidance systems or visual aids. Building on these findings, we plan to investigate the effectiveness of haptic feedback in various information presentation scenarios. Additionally, given its effectiveness in indicating left and right directions, we aim to explore potential synergistic effects when combining spatial audio with haptic feedback.

6.1.2 Auditory Experience. Haptic feedback had a generally positive effect on the auditory experience. In particular, it significantly enhanced the sense of immersion, and feedback from interviews suggested that it could provide new experiences in contexts such as movie watching. Drink sound was preferred with haptic feedback. This is thought to be because the haptic feedback in the ear was effective for the physical movement of the throat, which occurs close to the ear. In addition, the sounds of drums and explosions were also preferred. Users who preferred the haptic feedback for these sound sources commented that haptic feedback was well-matched to intense sounds. This result was similar to user feedback on the experience of listening to music when vibration feedback was given to the arm [17]. It has been confirmed that haptic stimulation in the ear canal can produce effects similar to those on the arm, marking an initial step toward enhancing music experiences with an integrated device.

However, participants rated the combination of piano sounds with haptic feedback negatively. We believe this is because the music was a gentle piece in a minor key, incompatible with haptic feedback. Furthermore, some participants felt that haptic feedback was distracting when their primary intention was to enjoy the music itself. For the comment on the gunfire, two participants responded that the number of haptics was too few, and two participants pointed out the discomfort of the timing gap. On the other hand, there was also one participant who responded that the number of haptics was too many. In related research, the effect of the gap in presentation timing and the number of presentations on usability has not been investigated. From the results of this study, it has become clear that it is necessary to clarify the design of the timing and number of presentations when the sound is repeated continuously.

While this study only investigated seven types of sounds, we aim to specify the characteristics of sound sources (frequency distribution, timbre, and sound quality) well-suited to haptic feedback by examining the compatibility with a wider range of sounds. In addition, the evaluation is expected to extend beyond auditory experiences to include the effects of haptic feedback in conjunction with visual presentations or user actions, such as eating or exercising. Additionally, it is important to compare haptic feedback methods with approaches involving thermal perception or vibration. Since each method provides different sensory stimuli, their effects are expected to be different.

As the prototype device was made using a large-sized ear tip, all participants reported that the size was proper or large. However, some users might find the device too small. We assume that the device can be adjusted to fit by identifying the size that all users perceive as either proper or large and then refining the fit by reducing only the ear tip size. However, it is unclear how a device that is too large will affect users with small ears. It is also unclear how the current prototype device will feel to users who feel that the device is small. We plan to identify a universally comfortable size through user feedback and adjust the device accordingly in future iterations.

6.2 Limitation

In this study, all experiments were completed using a single prototype device. Although not rigorously measured, the device withstood thousands of inflating and deflating cycles throughout the experiment process, demonstrating its durability. Future work will need to evaluate the durability of the ear tips under a higher number of cycles and long-term use.

The current prototype requires solenoids and pumps, making it neither wearable nor power-efficient. Miniaturization and power optimization are needed, along with usability studies in real-world settings. Feedback from notification tests showed changes in sound quality due to ear tip shape, but the prototype can not tune the sound, limiting this study. Future work will optimize the setup, including driver selection and housing design, to evaluate the impact of ear tip shape on sound quality and implement automatic equalization to compensate for variations.

6.3 Implications

In contrast to previous shape-changing interfaces, the ear tip is characterized by its small size. In addition, it is assumed that control of minute size changes will be required to realize some of the applications proposed in Section 5. On the other hand, there was variation in the air pressure changes in the device setup of this study. In the future, it will be necessary to devise unique hardware and ear tip designs to achieve more delicate and flexible ear tip control. Minute shape changes have the potential to provide higher resolution information presentation and finer expression not only for our method but also for different shape change interfaces.

By utilizing the sensitive area of the ear canal, our method opens up the possibility of designing multi-modal experiences that integrate auditory and haptic sensations. Examples of such applications suggest a path for shape-changing technology to develop from simple interaction aids to the core technology for user-centered, personalized experiences. In addition, there are individual differences in ear canal shape and many unknown aspects of haptic properties. Therefore, we believe that more detailed research will continue to be important.

In terms of the development of hearables, by focusing on ear tips, we have shown the potential for solving the issues with hearables and for expanding new interactions. We believe that this shows a new research direction for hearables research, which has been dominated by technological interventions in housing.

7 CONCLUSION

In this study, we proposed FlexEar-Tips, which offers a novel solution to improve the usability of hearables by dynamically adjusting ear tip size. The result from our test demonstrated that by controlling the ear tip size, we can improve ambient sound awareness and auditory experiences, and manage internal ear humidity. We explored the potential for technological intervention in ear tips by developing and discussing use cases for FlexEar-Tips. We hope that this research serves as a foundation for hearables to evolve into advanced information terminals by addressing both modality expansion and physical challenges.

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