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EVALUATION OF A NOVEL SOUND ENHANCING CONNECTING TUBE APPARATUS FOR IMPROVING SOUND LOCALIZATION OF OCCLUDED EARS

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ABSTRACT

Noise-induced hearing loss (NIHL) poses a serious risk to individuals exposed to high-intensity sounds, particularly military personnel and industrial workers. While hearing protection devices (HPDs) like foam earplugs mitigate NIHL, they often impair sound localization and speech intelligibility. This study investigates the sound-enhancing-connection-tube (SECT), a prototype perforated tube connected to the opening of two vented earplugs, designed to adjust attenuation across frequencies for improving sound localization while preserving protective benefits. Using head-related transfer functions (HRTF) to measure sound pressure at the position of the eardrum, the study evaluated SECT effects on the 1–4 kHz range, critical for speech and environmental sounds.
The research involved three experiments: HRTF-based optimization of SECT design using a head-and-torso-simulator (HATS) and two human trials to assess localization performance. HATS results demonstrated up to 15 dB less attenuation for frequencies above 800 Hz when the SECT was used with vented earplugs compared to just earplugs. However, human trials showed no significant localization improvement. Differences may stem from how the human brain processes complex auditory cues, bone and tissue conduction effects absent in HATS, and potential sound loss through SECT connectors. Future research should prioritize live-subject guided training to address these limitations.

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Keywords: *hearing protection, sound source localization, noise induced hearing loss*

1. INTRODUCTION

Noise-induced hearing loss (NIHL) results from exposure to high-intensity sound, with prolonged noise above 85 dB posing significant risks [1]. Military personnel are especially vulnerable due to exposure to loud engine noise, gunfire, and explosions [2; 3]. Other at-risk populations include construction workers and factory laborers. NIHL can develop gradually, impairing communication and necessitating assistive devices like hearing aids [4; 5].
Hearing protection devices (HPDs) help mitigate NIHL by attenuating harmful noise levels. Linear HPDs, such as foam earplugs, reduce sound evenly across frequencies but may impair speech intelligibility and sound localization [6; 7]. Non-linear HPDs, in contrast, adjust attenuation based on intensity, allowing softer sounds to pass through while blocking louder noises [8]. However, even non-linear HPDs can interfere with localization cues by altering ear acoustics or blocking pinna effects, leading to degraded spatial hearing and increased cognitive effort for speech comprehension [9; 10; 11].
To address these limitations, this study examines a prototype sound-enhancing connection tube (SECT), designed to improve localization while maintaining noise attenuation. The SECT consists of a perforated tube

integrated with non-linear earplugs, allowing controlled attenuation similar to a woodwind instrument. Pilot studies [12; 13; 14] suggest SECT may improve speech intelligibility while retaining noise-blocking properties, though optimal design parameters remain unclear.

A head-related transfer function (HRTF) was used to assess how SECT impacts sound transmission. Initial HRTF measurements on a head and torso simulator (HATS) established baseline effects of occlusion. This study aims to determine SECT parameters that minimize attenuation in the 1-4 kHz range, critical for speech and firearm sounds.

This study's objectives were:

1. To determine which combination of SECT parameters, such as the number and spacing of perforations, leads to a significant difference in the HRTF with an earplug with the tube compared to an earplug without the tube.
2. To test whether individuals demonstrate improved sound localization when using the SECT with a non-linear HPD compared to using the non-linear HPD alone.

We hypothesized that

1. The HRTF measurements for ears occluded with the SECT will show less attenuation in the 1-4 kHz range compared to the occluded condition without the SECT.
2. Individuals using the SECT in combination with two perforated earplugs will show improved sound localization compared to the perforated earplugs alone but will still perform worse than in the unoccluded condition.

Study Overview

The research consists of three experiments:

- Experiment 1: HRTF measurements to analyze SECT design variations.
- Experiment 2: Wideband sound localization tests.
- Experiment 3: Narrowband sound localization tests.

Results will be discussed with implications for future HPD development.

2. EXPERIMENT 1

2.1 Introduction

A HATS is a system designed to replicate the acoustic properties of the human head, torso, and ear canals. It consists of an artificial head and torso with microphones embedded at the eardrum position, allowing researchers to analyze how sound is perceived in different conditions. HATS are widely used in audio research, particularly for testing hearing protection devices (HPDs) [15].

This experiment aimed to optimize the design of the SECT by identifying a configuration that minimizes attenuation in the critical 1-4 kHz frequency range. This range is important for speech perception and identifying key sounds such as rifle fire. Using a HATS setup, we tested various SECT designs to determine the combination of perforation spacing that would allow the best preservation of these frequencies.

2.2 Method

2.2.1 Tools

The experiment was conducted using a GRAS 45BC KEMAR HATS equipped with GRAS 46BD ¼" microphones at the ear canal positions. The HATS was powered by a GRAS 12AX 4-Channel CCP Power Module. Sound was generated using Sinus Samurai software and transmitted through an RCF Ayra 5 monitor, while measurements were analyzed using the same software. A GRAS 146AE rugged ½" reference microphone was placed near the tragus to record the original signal before it reached the ear.

2.2.2 Process

A pure tone sweep (100-12,800 Hz) was played from a monitor positioned 1 meter in front of the HATS at 0° azimuth. The sound level was set to 54 dB[A] at the reference microphone. The sound pressure level (SPL) recorded by the eardrum microphones was compared to the reference microphone to calculate the HRTF. This process was repeated using different SECT designs, with variations in perforation spacing, until a configuration was identified that minimized attenuation in the 1-4 kHz range. The setup we used for this stage of the study can be seen in Figure 1.

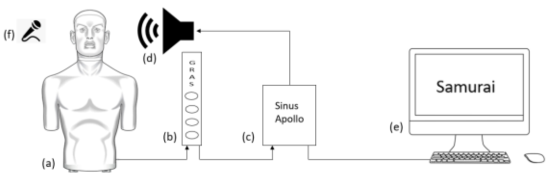

Figure 1. The setup used in Experiment One consisted of (a) KEMAR HATS with embedded microphones in ear canals, (b) Power module (c) Sinus Apollo Light, (d) monitor, (e) laptop with Sinus Samurai software, (f) reference microphone.

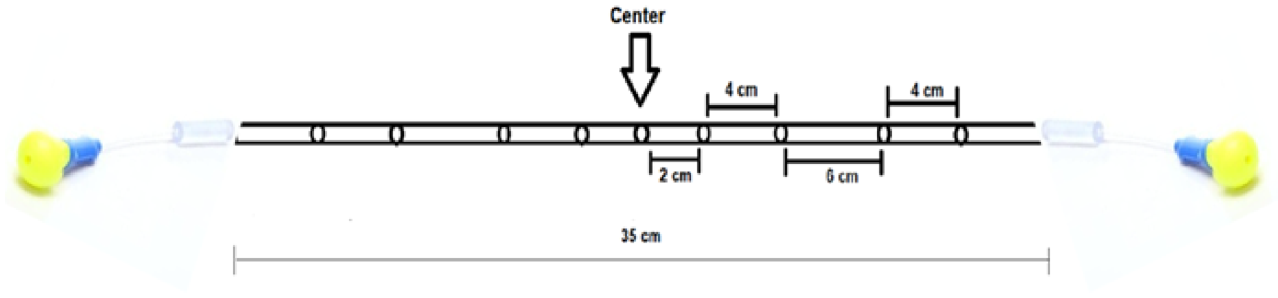

Figure 2. An illustration of the dimensions of the final SECT design used in this study. Earplugs are attached to either side of the SECT

2.3 Results

The optimal SECT design was determined by evaluating the effects of perforation spacing across three prototype tubes (2 cm, 4 cm, and 6 cm spacing). Each design produced frequency-specific attenuation reductions, with the 6 cm spacing showing the least attenuation at 1200 Hz, the 4 cm spacing at 2000 Hz, and the 2 cm spacing at 3000 and 5000 Hz. To incorporate the benefits of all three designs, a final SECT model was developed with perforations at progressively increasing distances from the tube's center (2 cm, 4 cm, and 6 cm), as seen in Figure 2.

2.4 Discussion

The results indicate that incorporating a perforated tube into earplugs alters the HRTF in a way that may enhance sound localization. By reducing attenuation in the 1-4 kHz range, the SECT allows more auditory cues to reach the ear, potentially improving the perception of speech and other critical sounds. This suggests that a properly configured SECT could provide a balance between hearing protection and environmental awareness. This hypothesis was further tested in subsequent human experiments, which assessed whether these modifications led to actual improvements in sound localization performance.

Figure 3. The SECT affixed to a helmet and connected to earplugs.

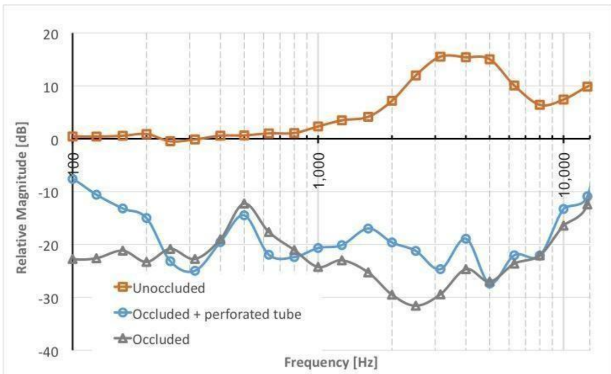

Figure 4. HRTF of the unoccluded condition (orange squares), the occluded condition (gray triangles) and the occluded + perforated tube (blue circles) condition.

3. EXPERIMENT 2

3.1 Introduction

Following the selection of the final SECT design, the next phase of the study tested its effect on human sound localization ability. Soldiers frequently report avoiding the use of HPDs in combat due to their negative impact on localizing sounds such as gunfire and spoken commands [16; 17]. To address this issue, we assessed localization performance using stimuli relevant to combat scenarios. It was hypothesized that the SECT would improve localization compared to standard push-in earplugs but would still perform worse than an unoccluded condition.

3.2 Method

3.2.1 Participants

Fourteen university-aged participants (9 female, 5 male; aged 21–29, mean = 23.9) took part in the study. All had normal hearing and no history of learning or attention disorders. Participants were compensated either monetarily or with course credit.

3.2.2 Tools

Sound stimuli were presented through eight RCF Ayra 5 monitors arranged in a circle around a central chair at a 1.8-meter radius. The speakers were positioned at azimuths of 22.5º, 67.5º, 112.5º, 157.5º, 202.5º, 247.5º, 292.5º, and 337.5º, with 0º representing directly in front of the participant. Responses were recorded via a touchscreen tablet displaying a circular interface, where participants tapped their perceived sound source location. More information about the tools can be found in Fostick and Fink (2021) [10].

3.2.3 Stimuli

Four stimuli were used: the Hebrew word "esh" (fire), a pink noise burst, a single M16 rifle shot, and three M16 shots fired in quick succession. All stimuli were presented at 75 dB SPL.

3.2.4 Procedure

Each participant sat in the center of the speaker array with a tablet on their lap. Each stimulus was presented ten times per speaker for a total of 320 trials (4 stimuli × 8 speakers × 10 repetitions). Stimulus order and speaker presentation were randomized. Each participant completed the experiment under three conditions:

1. Unoccluded (no HPD)
2. Occluded (3M™ E-A-R™ Push-Ins™ Earplugs)
3. SECT condition (SECT attached to 3M™ E-A-R™ Push-Ins™ Probed Test Plugs)

The order of conditions was randomized to prevent fatigue or learning effects. After each stimulus, participants tapped on the tablet to indicate the perceived sound source location. Regular breaks were provided. The research protocol was approved by the university's ethical review board. All participants signed an informed consent before beginning the experiment.

3.3 Results

Root Mean Square Error (RMSE) was used to assess localization accuracy by measuring the difference between perceived and actual sound azimuths. A three-way ANOVA revealed a significant main effect for condition (unoccluded, occluded, occluded + SECT) ($F(2, 26) = 27.06$, $p < 0.001$, $\eta^2 = 0.675$), stimulus type ($F(3, 39) = 3.38$, $p = 0.028$, $\eta^2 = 0.206$), and speaker position ($F(1.49, 19.33) = 21.06$, $p < 0.001$, $\eta^2 = 0.618$).

Post hoc comparisons revealed that localization accuracy was best in the unoccluded condition, followed by the occluded condition, with the SECT condition yielding the highest RMSE (poorest localization). No significant differences were found between stimuli. RMSE was highest for stimuli from the rear (157.5° and 202.5°) and lowest for front-hemifield locations (22.5° and 337.5°).

A significant interaction was found for condition × speaker position ($F(14, 182) = 8.518$, $p < 0.001$, $\eta^2 = 0.396$) (Figure 5), but no significant interactions were observed for condition × stimulus ($p = 0.072$) or stimulus × speaker ($p = 0.179$).

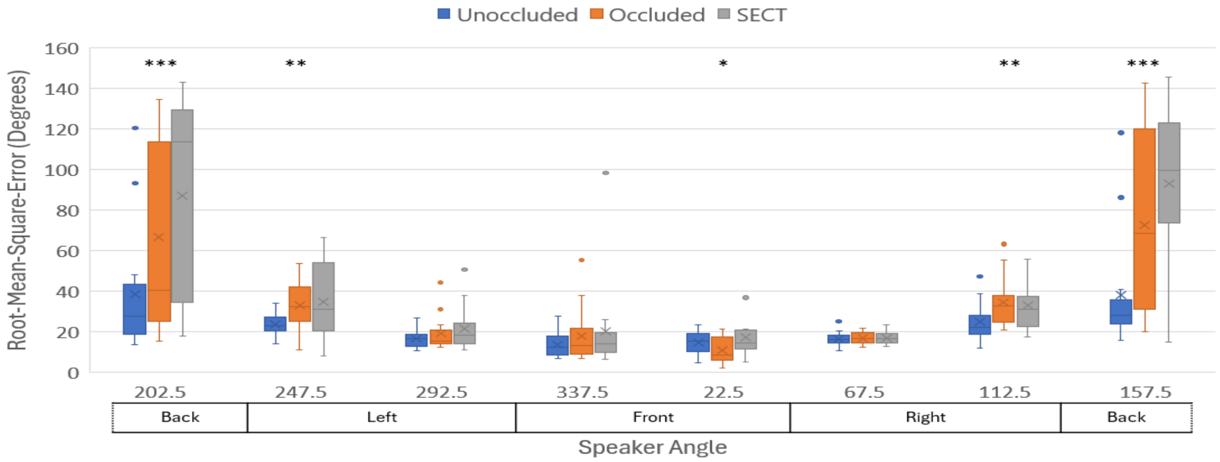

Figure 5. Interaction between condition and speaker angle for RMSE. **p*<0.05 between (unoccluded, occluded); (occluded, SECT). ***p*<0.05 between (unoccluded, occluded); (unoccluded, SECT). ****p*<0.05 between (unoccluded, occluded); (unoccluded, SECT); (occluded, SECT).

3.4 Discussion

After testing 14 participants, data analysis revealed no localization advantage for the SECT over standard occluded conditions. While speaker angle effects were consistent with previous findings [10], the SECT failed to enhance localization across the tested stimuli.

One possible explanation is the complexity of the stimuli's frequency content. The SECT was designed to reduce attenuation in the 100–250 Hz and 900–5000 Hz ranges, but its performance was initially measured at a 0° angle. Given that the localization task involved stimuli from multiple angles, SECT's effectiveness may not have translated across all directions, leading to its underperformance compared to expectations.

4. EXPERIMENT 3

4.1 Introduction

Experiment 3 aimed to simplify the stimuli from Experiment 2 in order to more accurately assess the SECT's effectiveness. Additional HRTF measurements were taken from a wider range of sound source angles (22.5°, 67.5°, 112.5°, and 157.5°) to identify which frequencies would most benefit from the SECT apparatus. Based on these measurements, two narrow-band stimuli were selected: a low-frequency stimulus (500-600 Hz) and a higher-frequency stimulus (1200-1600 Hz). These new stimuli are represented visually in Figure 6. The hypothesis was that the SECT would improve sound localization performance for the higher-frequency stimulus, but not for the lower-frequency stimulus. It was also expected that the unoccluded condition would outperform the other conditions for both stimuli.

4.2 Methods

4.2.1 *Participants*

Twenty participants (10 female, 10 male, aged 21-32, mean age 25.7) were recruited for this experiment, with inclusion and exclusion criteria identical to Experiment 2.

4.2.2 *Tools*

The same equipment used in Experiment 2 was employed for this stage of the study.

4.2.3 *Stimuli*

Two narrow-band noise bursts were used as stimuli: a low-frequency stimulus (500-600 Hz) and a high-frequency stimulus (1200-1600 Hz). Each burst lasted 250 ms and was presented at 75 dB SPL. The stimuli were delivered from 8 speakers at randomized positions around the participant.

4.2.4 *Procedure*

The experiment followed the same procedure as Experiment 2, with participants seated in front of 8 monitors. Each stimulus was presented 10 times from each speaker, totalling 160 presentations. The experiment included the same three conditions: unoccluded, occluded, and SECT. The research protocol was approved by the university's ethical review board. All participants signed an informed consent before beginning the experiment.

4.2.5 *Data Analysis*

A three-way ANOVA was performed to assess the effects of condition, stimulus, and speaker on Root Mean Square Error (RMSE). Main effects and interactions were analyzed to determine how these variables influenced sound localization accuracy.

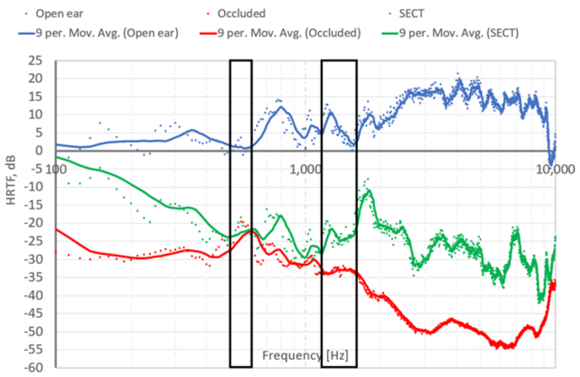

Figure 6. HRTF measurements averaged for stimuli presented from angles of 22.5º, 67.5º, 112.5º, and 157.5º for the unoccluded (blue), occluded (orange), and occluded with SECT (green) conditions. The areas encompassed by the black rectangles indicate the frequency ranges contained in the low-frequency narrow-band stimulus (500-600 Hz) and the high-frequency narrow-band stimulus (1200-1600 Hz) that were used to derive the two narrow sound burst stimuli for Experiment 3.

4.3 Results

A three-way ANOVA revealed significant main effects for both the condition (F(2, 38) = 42.3, $p < 0.001$, $\eta^2 = 0.69$) and speaker (F(1.8, 34.18) = 41.14, $p < 0.001$, $\eta^2 = 0.684$). There were also significant interactions between condition and stimulus (F(2, 38) = 4.493, $p = 0.018$, $\eta^2 = 0.191$), condition and speaker (F(3.442, 65.39) = 10.867, $p < 0.001$, $\eta^2 = 0.364$) (Figure 7), and stimulus and speaker (F(3.905, 74.187) = 2.906, $p = 0.028$, $\eta^2 = 0.133$). These results highlight that the experimental condition, speaker position, and stimulus type all influenced the RMSE in sound localization accuracy.

4.4 Discussion

The results from Experiment 3 showed that altering the stimuli to focus on low- and high-frequency ranges did not improve performance with the SECT, as hypothesized. While the high-frequency stimulus was expected to benefit from the SECT, no significant difference was found between the SECT and occluded conditions. These findings diverged from those of Villian & Cement (2020) [12], who observed better localization performance with SECT designs compared to standard earplugs. The discrepancy may be due to differences in earplug types used between the two studies (3M Ear Classic vs. 3M™ E-A-R™ Push-In™), and the different methods of performance analysis (RMSE vs. average angle error).

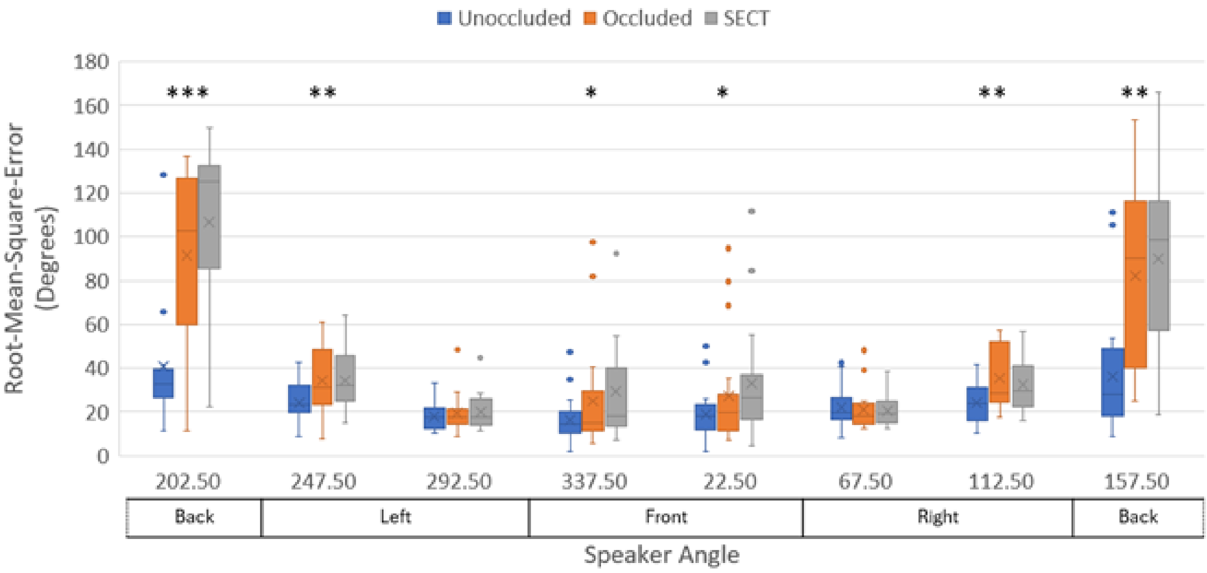

Figure 7. Interaction between condition and speaker angle for RMSE. *$p<0.05$ between (unoccluded, SECT). **$p<0.05$ between (unoccluded, occluded); (unoccluded, SECT). ***$p<0.05$ between (unoccluded, occluded); (unoccluded, SECT); (occluded, SECT).

5. GENERAL DISCUSSION

This study was conducted to create the SECT, a perforated air tube connected to two non-linear perforated earplugs, that would allow for improved sound localization abilities when compared to standard Push-Ins earplugs. HRTF measurements were performed on a HATS to determine which tube parameters allowed for the least amount of attenuation at the 1-4 kHz frequency range, chosen for its inclusion in spoken language as well as dominance in gunfire sound. This design was then tested on human subjects in a sound localization task. Upon analyzing the results, we found no significant statistical difference between the occluded condition and the SECT condition, contrary to our hypothesis. However, as predicted, the unoccluded condition displayed better performance than both occluded conditions.

There are several possible explanations for the discrepancy between the HATS results and the results received in experiments with human subjects. One possibility is based on how the human brain processes and interprets incoming stimuli. Whereas none of these occur within the HATS, typically, the brain processes two sound signals, one reaching each ear, and uses the interaural time and intensity differences to aid in localization, as well as acoustic factors such as the pinna effect [18]. However, the addition of the SECT introduces numerous sound signals to both ears through each of the perforations along the length of the SECT. The arrival of multiple similar stimuli simultaneously may inhibit the brain's ability to differentiate between them effectively [19]. Supervised training using the SECT followed by retesting the sound localization capabilities may lead to improved results. Indeed, Casali & Robinette (2015) [20] showed that training sessions can lead to improved performance in sound source localization tasks while wearing HPDs.

It is also possible that the passage of sound waves through the T-connectors and into the thinner probe tubes located within the perforated ear plugs may weaken sound levels at certain frequencies that would otherwise provide critical information.

Another possible cause for this study's results is the impact of bone and tissue conduction (BTC). The HRTF measurements obtained in the first stage of this study possess only air conduction pathway capabilities. However, the human cochlea also receives sound waves that propagate to the cochlea through the subject's body tissues and bones, which are not measured on the HATS. When HPDs are used, such as those used in conjunction with the SECT, sounds arriving through air conduction are attenuated, thus allowing BTC sounds to dominate the auditory experience. Thus, it may be necessary to reconsider the way in which the SECT's final design was created. Instead of using a HATS, the HRTF measurements should be performed on a human subject so that the influence of the BTC can be taken into consideration.

6. CONCLUSIONS, LIMITATIONS AND FURTHER RESEARCH

In conclusion, this study explored the potential of the SECT, a perforated air tube connected to non-linear earplugs, to improve sound localization while providing adequate noise attenuation. The SECT design was based on HRTF measurements obtained from a HATS, with the goal of preserving frequencies essential for speech recognition and sound localization in the 1-4 kHz range. However, human trials did not confirm a significant improvement in localization with the SECT compared to standard occluded conditions, despite successful attenuation characteristics in HATS testing. This suggests that while the SECT concept is feasible, the current design may require further optimization to align with natural hearing cues and individual auditory processing mechanisms.

A few limitations may have influenced these outcomes. The study relied on HATS for initial HRTF measurements, which, while precise for acoustic modeling, cannot fully replicate the nuances of human auditory processing. Specifically, the HATS cannot simulate binaural processing and other brain functions that aid in sound localization, such as interaural time differences and the pinna effect. Moreover, the SECT design might introduce competing sound signals due to its perforations, potentially causing interference that limits sound source differentiation. Another important factor is the effect of BTC on hearing perception, which the HATS model does not capture. Human listeners experience BTC in conjunction with air-conducted sound, and the lack of BTC in testing could mean that significant aspects of sound transmission and localization were overlooked.

Future research could benefit from HRTF measurements conducted directly on human subjects to incorporate BTC effects, as well as from additional training protocols to help participants adapt to the SECT's unique signal presentation. These adaptations may enhance the SECT's effectiveness and provide clearer insights into its potential benefits for hearing protection and sound localization.

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