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SOUND ATTENUATION WITH DOUBLE HEARING PROTECTION: A COMPARISON OF REAL-EAR AND BEHAVIORAL HEARING THRESHOLD MEASUREMENTS

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ABSTRACT

This study explores the relationship between objective sound measurements and subjective hearing thresholds under double hearing protection. Both Real-Ear Measurement (REM) and subjective testing were used to examine attenuation with EasyView Otoblock earplugs and Optime 105 earmuff. Stimuli were delivered from a fixed frontal source (0° azimuth) across a frequency range of 500 to 12,000 Hz, allowing observation of attenuation patterns at both low and high frequencies.
Descriptive analysis suggested consistent trends across participants. At higher frequencies (above 4 kHz), subjective results indicated more attenuation than objective REM values, whereas the opposite was observed at lower frequencies (below 4 kHz), where REM showed more attenuation. These patterns may reflect the contribution of bone conduction (BC) when air conduction (AC) is significantly reduced.
While the sample size limits statistical generalization, the findings highlight the value of integrating subjective data alongside objective measurements in evaluating hearing protection performance. The use of a realistic protection configuration and fixed sound direction offers practical insights into how auditory information is transmitted under high-attenuation conditions. These insights may support the development of more effective hearing protection devices for environments with hazardous noise exposure.

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1. INTRODUCTION

1.1 Air Conduction and Bone Conduction Hearing

Hearing occurs through air conduction (AC), bone conduction (BC), and to a lesser extent, body conduction - which is often considered a subset of BC due to its indistinct boundaries [1]. AC is the dominant auditory pathway, transmitting sound via the ear canal, eardrum, and ossicles to the cochlea. In contrast, BC transmits sound through skull vibrations directly to the cochlea, bypassing the outer and middle ear entirely [2-3]. Under typical listening conditions, AC predominates, but when AC is obstructed,such as through the use of double hearing protection when combining insert earplugs and an earmuff,BC becomes increasingly relevant in auditory perception [4].
The AC pathway depends on the integrity and openness of the outer and middle ear structures. When these are sealed off by hearing protection, the transmission of sound via AC is significantly reduced. BC, however, is relatively unaffected by such occlusion and can become the primary pathway through which sound is perceived, particularly at lower frequencies (<1 kHz). This increased contribution of BC under occluded conditions is known as the occlusion effect, and it leads to measurable differences between physical (objective) and perceptual (subjective) assessments of sound attenuation [5].

These discrepancies are especially evident when comparing results from Real-Ear Measurement (REM) systems, used to objectively quantify sound levels in the ear canal, with behavioral threshold testing, which reflects the listener's perceptual experience. Under double hearing protection, where the AC path is highly attenuated, REM results tend to overestimate attenuation at low frequencies, while subjective tests reveal residual perception via BC [6].

In this study, we examine sound attenuation under a single, fixed condition of double hearing protection, using EasyView Otoblock earplugs in combination with Optime 105 earmuff. All sound stimuli were presented from the frontal direction (0° azimuth) to ensure consistent spatial input and to eliminate directional variability. This controlled setup allows us to focus specifically on how sound is conducted and perceived under maximum realistic occlusion, providing insight into the interplay between AC and BC under these conditions.

By understanding how the auditory system responds when AC is relatively blocked and BC dominates, especially in the context of real-world double hearing protection,we can better interpret the limitations of standard objective testing and develop more effective hearing protection strategies for high-noise environments.

AC is the most commonly utilized hearing pathway but is significantly reduced when hearing protection is applied. BC offers an alternative route, transmitting sound through bone and soft tissue [2]. Under double hearing protection, where both earplugs and earmuff are used, the attenuation of AC is high, and thus, the relative contribution of BC becomes more prominent. Understanding this shift in auditory pathways is essential for interpreting attenuation outcomes under such conditions.

1.2 Sound Attenuation Under Double Hearing Protection

Earplugs and earmuffs have different frequency-specific attenuation profiles, and their combination (i.e., double hearing protection) increases overall attenuation, particularly in the mid-to-high frequencies. However, the gains in attenuation are limited at low frequencies due to BC transmission, typically plateauing around 40–60 dB [4]. In this study, only the double protection configuration was evaluated using both objective and subjective measurements to assess how AC and BC interact under realistic high-attenuation conditions.

Subjective tests, which are based on perceptual thresholds, provide insight into the listener's experience and are influenced by BC. In contrast, objective methods such as REM offer consistent measurement of sound pressure levels in the ear canal but may underestimate BC effects [5]. This study compares both approaches to provide a more comprehensive eexplanation of attenuation under double protection.

1.3 Objective vs. Subjective Measures

Objective measures (e.g., REM) quantify sound levels in the ear canal using probe microphones, offering repeatable data that reflects the performance of the protection device [7]. However, they overlook the contribution of BC. Subjective thresholds, while more variable across individuals, are sensitive to BC influence. This study integrates both methods to evaluate the perceptual and physical aspects of attenuation under double protection and frontal sound presentation (0°).

1.4 Current Study Focus

This study investigates how double hearing protection affects auditory thresholds via both AC and BC, using a combination of objective (REM) and subjective (behavioral threshold of hearing) methods. The goal is to clarify the extent to which BC contributes to residual auditory perception when AC is substantially attenuated.

By focusing on a realistic protection configuration, earplugs combined with earmuff, the study enables a controlled and focused evaluation of auditory processing under high-attenuation conditions. This approach reduces variability related to directional hearing and protection level, allowing for a detailed analysis of the interaction between frequency, measurement modality, and the dominance of BC versus AC.

Through this design, the study aims to assess how effectively current measurement techniques capture attenuation, and to provide practical insights into the real-world performance of double hearing protection in high-noise environments.

1.5 Research Questions

1. How do objective real-ear measurements compare with subjective behavioral hearing thresholds when attenuation is assessed under double hearing protection?
2. Does the discrepancy between objective and subjective attenuation vary across frequencies?

1.6 Hypotheses

1. Subjective hearing thresholds will demonstrate less attenuation than objective REM measurements at low frequencies due to the contribution of BC pathways.
2. The gap between the subjective level of attenuation and the objective one will be most pronounced at low frequencies and will decrease at higher frequencies.

2. METHODS

2.1 Participants

Ten participants (6 female, 4 male), aged 18 to 28, with confirmed normal hearing, took part in the study. Testing was conducted at the Acoustics and Noise Research Laboratory at Ariel University. Inclusion criteria was air-conduction hearing thresholds of ≤20 dB HL between 500 and 8000 Hz. Exclusion criteria included any history of hearing loss, prolonged exposure to loud noise, or the use of ototoxic medications. The research protocol was approved by the university's ethical review board. All participants signed an informed consent before beginning the experiment.

2.2 Stimuli and Equipment

All measurements were conducted using the Interacoustics Affinity Compact system.

Objective measurements were carried out using Real-Ear Measurement (REM) module with 90 dB SPL pure-tone sweeps ranging from 250 Hz to 16,000 Hz. Sound pressure levels were recorded at the eardrum using a probe tube microphone.

Subjective hearing thresholds were obtained with the audiometer module using warble tones at 500, 1000, 2000, and 4000 Hz, as well as 1/12-octave intervals from 4000 to 12,000 Hz. Participants responded by pressing a button.

Calibration of all equipment was performed using a Brüel & Kjær Type 2250 Sound Level Meter.

All testing was performed in unoccluded condition and under double hearing protection, consisting of EasyView Otoblock earplugs and Optime 105 earmuff (see Figure 1).
Attenuation was calculated by comparing the protected condition to an unoccluded baseline for each participant, using both objective and subjective data.

Figure 1. EasyView Otoblocks by PHONAK, used as insert earplugs (left side), and Optime 105 earmuff by 3M (right side), comprising the double hearing protection configuration evaluated in the study.

2.3 Procedure

Participants completed both objective and subjective tests in a single session lasting approximately 1.5 to 2 hours. REM measurements were passive and required no response from the participant. During subjective testing, participants responded when they heard a tone, and thresholds were established using a manual audiometry protocol.
All stimuli for both objective and subjective tests were presented from a fixed sound source at 0° azimuth, positioned 50 cm infront of the participant's head.
Only the right ear was tested, while in the subjective testing, the left ear was masked at 50 dB HL using narrowband noise to eliminate cross-hearing.

2.4 Data Analysis

Due to the limited sample size, only descriptive statistical analysis was conducted. Attenuation (in dB) was examined across frequency and measurement method (objective vs. subjective). The analysis focused on identifying trends and patterns reflecting the contribution of BC under conditions of significant AC attenuation.

3. RESULTS

Mean attenuation values were analyzed across the tested frequency range, comparing objective measurements obtained through REM with subjective auditory hearing thresholds. The results depicted in Figure 2 revealed clear frequency-dependent patterns in both measurement methods, as well as systematic differences between them. Objective attenuation measurements peaked at approximately 36 dB near 3000 Hz, then gradually declined with increasing frequency, reaching a minimum of 18 dB at 12,000 Hz. Subjective attenuation showed a slightly deeper peak of around 38 dB near 4000 Hz, followed by a decrease in attenuation to 33-40 dB at the upper end of the frequency range. At frequencies below 3000 Hz, objective attenuation exceeded subjective attenuation, whereas at higher frequencies, this pattern reversed, and subjective attenuation became greater.

This crossover pattern suggests that while objective measurements capture the attenuation of AC sound effectively, they may underestimate the perceptual influence of BC sound, particularly at higher frequencies. The divergence in attenuation levels between methods above 3000 Hz likely reflects the perceptual contributions of BC and the interaction with individual auditory sensitivity and occlusion effects.

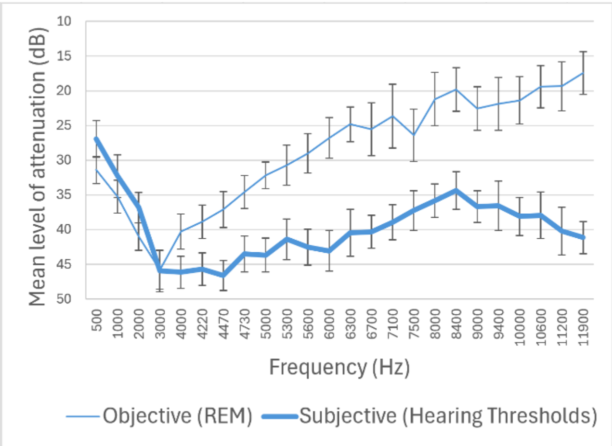

Figure 2. Mean attenuation (in dB) across frequencies, comparing objective REM (thin line) and subjective hearing thresholds (thick line). Measurements were conducted under double hearing protection. Error bars represent standard errors of the mean for each data point. (n=10)

4. DISCUSSION

The results of this study demonstrate clear differences between objective and subjective measurements of sound attenuation, with distinct frequency-dependent patterns. Objective attenuation levels peaked around 3000 Hz and decreased at higher frequencies, while subjective attenuation remained elevated beyond that frequency. This crossover at 3000 Hz may reflect the combined contributions of AC and BC to auditory perception under occluded conditions and aligns with earlier findings [4] showing that the limits of attenuation are set by the BC pathway even under maximal occlusion.

4.1 Dominant Sound Conduction Pathway

In conditions of high attenuation, such as those created by double hearing protection, the AC pathway is substantially reduced, allowing BC to play a more dominant role in perception. While objective REM primarily capture sound pressure levels in the ear canal and are largely AC-dependent [7], subjective thresholds reflect the listener's full perceptual experience, including the effects of BC transmission [23-]. The relatively higher objective attenuation at low frequencies, as compared to the lower subjective thresholds, supports the interpretation that BC continues to transmit sound effectively in this range. These findings are consistent with previous work showing that sound transmission via BC becomes the primary pathway under occluded conditions [3]. At higher frequencies, where subjective attenuation surpasses objective values, individual variability in skull vibration transmission or the auditory system's non-linear characteristics may contribute to perceptual differences not captured by physical measurements [2].

Moreover, it is well established that REM may underestimate BC influence, particularly under conditions involving strong occlusion and internal physiological noise [5]. This limitation underscores the value of using both objective and subjective measures to fully characterize hearing protection performance.

4.2 Stimulus Type Effects

The observed discrepancies between measurement modalities may also stem from differences in stimulus characteristics. Warble tones, used for subjective testing, minimize standing wave formation and provide a more perceptually stable signal, whereas the pure-tone frequency sweeps used in REM are more prone to standing waves and acoustic leakage artifacts [6]. These differences may partly explain the crossover effect between objective and subjective data observed in the present study.

Similar concerns have been raised in clinical hearing aid studies, where REM did not always predict perceptual performance, particularly when complex acoustic interactions were present [7]. Aligning the acoustic properties of the stimuli used in both measurement methods could help isolate the effect of stimulus type on attenuation results and improve the comparability between modalities in future work.

4.3 Limitations and Future Work

As a preliminary study, several limitations should be acknowledged. The sample size was modest, limiting the generalizability of the findings. Additionally, while the study design intentionally focused on a single hearing protection configuration and a fixed sound source direction to allow for controlled analysis, this necessarily reduced ecological variability. Future research should expand the sample population, explore additional hearing protection configurations, and investigate multiple azimuth angles to better simulate real-world listening environments. It is also recommended to further investigate the separate contributions of AC and BC. Finally, standardizing the stimulus type across both objective and subjective measurements could reduce methodological variance and improve the comparability of findings across modalities.

5. CONCLUSION

This study demonstrated clear, frequency-dependent differences between objective (REM) and subjective (threshold-based) measurements of sound attenuation under occluded conditions. A crossover pattern was observed around 3000 Hz, where objective attenuation peaked and then declined, while subjective attenuation remained elevated. These findings highlight the dominant role of bone conduction when air conduction is suppressed and underscore the limitations of relying solely on objective physical measures. Differences in stimulus type also contributed to the divergence between methods, reinforcing the need for methodological alignment. Overall, the integration of both objective and subjective assessments is essential for accurately evaluating hearing protection performance in high-attenuation environments.

6. ACKNOWLEDGMENTS

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