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# COMPARISON OF A BOOTH-FREE AUDIOMETER WITH A CONVENTIONAL DEVICE IN TERMS OF IMMUNITY TO NOISE AND SUBJECTIVE COMFORT

Contributions:
A Study design/planning
B Data collection/entry
C Data analysis/statistics
D Data interpretation
E Preparation of manuscript
F Literature analysis/search
G Funds collection

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## Abstract

**Introduction:** This study aimed to evaluate the noise immunity level (NIL) of the booth-free KUDUwave™ audiometer and compare the subjective comfort of its headphones against a conventional screening audiometer under simulated noise conditions, in order to determine its suitability for hearing screening in resource-limited settings.

**Material and methods:** 30 normal-hearing adults (aged 20–25 years) participated in a repeated-measures crossover study. Pure-tone air- and bone-conduction thresholds were obtained under quiet and background noise conditions using the KUDUwave audiometer and a conventional audiometer from Interacoustics. Three types of noise were presented: broadband noise (BBN), speech-shaped noise (SSN), and eight-talker babble (8-TB). In addition, the subjective comfort associated with each audiometer's headset was evaluated.

**Results:** Baseline air-conduction (AC) thresholds were comparable between the two audiometers, whereas bone-conduction (BC) thresholds were significantly lower with the KUDUwave, likely due to the occlusion effect. Across all noise conditions, the KUDUwave demonstrated higher NILs than the conventional audiometer, indicating greater resistance to ambient noise. In AC testing, NILs were lowest at low frequencies and highest at mid frequencies, with 8-TB producing greater masking effects than BBN and SSN. However, participants reported lower comfort with the KUDUwave headset compared to the conventional audiometer.

**Conclusions:** The KUDUwave audiometer demonstrated greater noise immunity than the conventional device, indicating enhanced resistance to ambient noise. These findings suggest its potential suitability for hearing screening in non–sound-treated, community-based environments. However, its real-world utility and practical advantages in such settings need to be further validated through field-based studies.

**Keywords:** pure-tone audiometry • ambient noise • noise immunity • hearing screening • user comfort

# PORÓWNANIE DZIAŁANIA AUDIOMETRU NIEWYMAGAJĄCEGO KABINY AUDIOMETRYCZNEJ I AUDIOMETRU KONWENCJONALNEGO POD WZGLĘDEM ODPORNOŚCI NA HAŁAS OTOCZENIA ORAZ SUBIEKTYWNEGO KOMFORTU UŻYTKOWANIA

## Streszczenie

**Wprowadzenie:** Celem badania była ocena odporności na hałas otoczenia (NIL) bezkabinowego audiometru KUDUwave™ oraz porównanie subiektywnego komfortu użytkowania jego słuchawek z komfortem zapewnianym przez konwencjonalny audiometr przesiewowy w warunkach symulowanego hałasu. Badanie miało na celu określenie przydatności tego urządzenia do prowadzenia badań przesiewowych słuchu w warunkach pozbawionych specjalistycznego zaplecza diagnostycznego.

**Materiał i metody:** W badaniu typu *crossover* z powtarzanymi pomiarami uczestniczyło 30 dorosłych osób z prawidłowym słuchem (w wieku 20–25 lat). Progi słyszenia dla przewodnictwa powietrznego (AC) i przewodnictwa kostnego (BC) wyznaczano w warunkach ciszy oraz w warunkach szumu tła z wykorzystaniem audiometru KUDUwave i konwencjonalnego audiometru firmy Interacoustics. Zastosowano trzy rodzaje szumu: 1) szerokopasmowy (BBN); 2) o widmie mowy (SSN) oraz 3) gwar ośmiu rozmówców (8-TB). Dodatkowo oceniono subiektywny komfort użytkowania zestawów słuchawkowych obu audiometrów.

**Wyniki:** Wyjściowe progi słyszenia dla przewodnictwa powietrznego były porównywalne w przypadku obu audiometrów, natomiast progi dla przewodnictwa kostnego były istotnie niższe w przypadku audiometru KUDUwave, co prawdopodobnie wynikało z efektu okluzji. W badaniach uwzględniających trzy rodzaje szumu audiometr KUDUwave wykazywał wyższy poziom odporności na hałas (NIL) niż audiometr konwencjonalny, co wskazuje na jego większą odporność na zakłócenia pochodzące z otoczenia. W badaniach przewodnictwa powietrznego wartości NIL były najniższe dla niskich częstotliwości, a najwyższe – dla średnich. Spośród zastosowanych rodzajów szumu największy efekt maskowania powodował gwar ośmiu rozmówców (8-TB) w porównaniu z hałasem szerokopasmowym (BBN) i hałasem o widmie mowy (SSN). Jednak uczestnicy badania ocenili komfort użytkowania zestawu słuchawkowego KUDUwave jako niższy niż komfort związany z używaniem słuchawek audiometru konwencjonalnego.

**Wnioski:** Audiometr KUDUwave wykazał większą odporność na hałas otoczenia niż urządzenie konwencjonalne, co wskazuje na jego większą skuteczność w ograniczaniu wpływu zakłóceń akustycznych podczas badania słuchu. Wyniki sugerują, że urządzenie to może być przydatne do prowadzenia przesiewowych badań słuchu poza kabiną audiometryczną – w warunkach terenowych, niespełniających standardów wyciszenia akustycznego. Konieczne są jednak dalsze badania terenowe w celu potwierdzenia jego użyteczności klinicznej oraz przewag praktycznych w rzeczywistych warunkach użytkowania.

**Słowa kluczowe:** audiometria tonalna • hałas otoczenia • odporność na hałas • przesiewowe badania słuchu • komfort użytkownika

| Key to abbreviations | |
|---|---|
| 8-TB | eight-talker babble |
| AC | air-conduction |
| BBN | broadband noise |
| BC | bone-conduction |
| NIL | noise immunity level |
| PTA | pure tone averages |
| SSN | speech-shaped noise |

## Introduction

Hearing loss is a global health concern that impairs communication, social interactions, and quality of life for millions worldwide. According to the World Health Organization, over 5% of the world's population (approximately 466 million people) suffer from disabling hearing loss, with projections indicating this number could rise to over 900 million by 2050 [1]. Early detection and intervention are critical to minimize the adverse effects of hearing loss and to improve the quality of life for those affected [2]. Given the demand for early identification and intervention, technologies that facilitate accurate detection of hearing loss by reducing false positives and retaining high specificity are critical. Booth-free audiometers are gaining traction as a cost-effective strategy to minimize referral rates and reduce the overall burden on healthcare systems [3].

Traditional hearing assessments typically use audiometric booths to minimize background noise and provide a controlled environment for accurate hearing threshold measurements. These booths, however, are expensive, bulky, and require significant space, making them impractical for use in low-resource settings, remote areas, or mobile hearing screening programs [4]. Additionally, the setup and maintenance of these booths can be challenging [5].

Innovative solutions such as booth-free audiometers have been developed to address these challenges. These systems are compact and portable, enabling audiometric testing in diverse settings, including remote areas and in patients' homes [6]. Advanced noise-cancellation technologies allow them to be used in environments with higher ambient noise, permitting reliable hearing assessment outside controlled clinical settings [7–9]. In addition, booth-free audiometers reduce the cost and complexity of sound-treated rooms, making hearing assessments more feasible for clinics with limited resources. Their quick and simple setup also promotes efficient workflows in busy clinics [5,8].

Several booth-free audiometry systems are currently available, including the KUDUwave™ boothless audiometer (GeoAxon Technologies, South Africa), PC-based audiometers (MedRx Inc., USA), mobile or tablet-based audiometers (HearX Group, USA), and virtual booth technologies such as the Wireless Automated Hearing Test System (Edare Inc., Lebanon). Previous studies have demonstrated the reliability of the KUDUwave for hearing assessment. For instance, Storey et al. [10] compared automated hearing assessments obtained using the KUDUwave and the GSI 61 clinical audiometer under different noise conditions. Their results showed that 89% of thresholds obtained using the KUDUwave in quiet and 92% obtained in background noise were within ±5 dB of those measured using a clinical audiometer. Similarly, Swanepoel et al. [11] reported that air- and bone-conduction thresholds obtained remotely using the KUDUwave closely matched in-person measurements within a quiet sound booth, with 96% of thresholds falling within a 10 dB range. Maclennan-Smith et al. [12] further demonstrated that KUDUwave's manual mode produced accurate hearing thresholds in background noise (47–54 dBA), with 95% of air-conduction (AC) and 86% of bone-conduction (BC) thresholds falling within ±5 dB of those obtained in a sound booth.

While previous studies have investigated the effectiveness of booth-free audiometers in continuous noise environments, a direct comparison of noise immunity level between conventional audiometers and the KUDUwave is lacking. Furthermore, validation of this technology is necessary to address challenges posed by multi-talker babble noise, which more closely resembles the auditory conditions encountered in community screening settings. Unlike continuous or steady-state noise, speech babble shares cognitive and linguistic characteristics with the target speech, making it more representative of real-world listening environments. This results in greater informational masking, as listeners must distinguish between acoustically and linguistically similar signals. Research has consistently shown that, due to this linguistic similarity, speech perception is more adversely affected by speech maskers than by non-speech noise [13–16]. Eight-talker babble, in particular, closely resembles the auditory conditions found in community screening camps, where multiple simultaneous conversations generate a highly dynamic and cognitively demanding background [17].

To the best of our knowledge, this study is perhaps the first to systematically compare noise immunity level between a booth-free audiometer and a conventional audiometer across multiple ecologically relevant noise conditions, including both steady-state and speech-based maskers.

Additionally, technological advancements in audiometry have primarily emphasized improvements in diagnostic accuracy and portability; however, user comfort and experience remain important but frequently underreported factors affecting clinical adoption and long-term usability. Discomfort or poor headset fit during audiometric testing can affect participant cooperation, concentration, and the reliability of threshold measurements [18]. Therefore, as well as assessing the diagnostic efficacy of booth-free audiometers it is equally important to evaluate user comfort.

Therefore, the current study compared the efficacy of the KUDUwave and a conventional audiometer in mitigating the adverse effects of ambient noise during audiometric testing. This was achieved by comparing the NIL obtained from both audiometers in the presence of three different types of noise: broadband noise (BBN), speech-shaped noise (SSN), and eight-talker babble (8-TB). Additionally, the study assessed participants' subjective perceptions of the comfort of both devices, focusing on attributes such as headset comfort, noise attenuation, pain, isolation, and ear blockage.

## Material and methods

### Participants

For this single-group repeated measures study, we randomly selected 30 normal-hearing individuals (14 males and 16 females, aged 20–25 years) with PTAs less than 15 dB HL and interaural asymmetry of less than 10 dB. All volunteered for the study, and written informed consent was obtained. The subjects had no present or past complaints of ear pain, ear discharge, recent change in hearing or balance, outer ear blockage as determined by otoscopic examination, or middle-ear dysfunction as determined by tympanometry. All experimental procedures adhered to the guidelines of the Institutional Ethical Committee for Bio--Behavioural Research Involving Human Subjects at the All India Institute of Speech and Hearing, Mysuru, India (approval SH/IRB/M.1/14//2024-25, dated 27.07.2024).

Young adults present an ideal study cohort because they typically exhibit a relatively homogeneous profile in terms of auditory function and overall health, which minimizes the presence of age-related hearing loss, degenerative changes, and chronic conditions that could otherwise confound audiometric measurements. This homogeneity enabled us to establish a reliable baseline of hearing thresholds and NIL. In addition, individuals in this age range are less likely to have experienced significant cumulative noise exposure, ototoxic medication use, or metabolic changes, thereby reducing potential confounding factors and making it more likely that any observed differences in NIL of KUDUwave were attributable to the device itself rather than underlying variations in hearing status [19,20].

### Procedure

Each run began by estimating the baseline threshold at the test frequency for both AC and BC. We employed the modified Hughson–Westlake procedure [22] to determine thresholds. Once the baseline threshold was established, the respective pure tone was delivered continuously at baseline while a masking noise (broadband, SSN, or 8-TB) was turned on and presented continuously, starting at a level 5 dB below the baseline. After a 5-second acclimatization period, the modified Hughson–Westlake procedure was repeated to estimate the masked threshold. In preliminary data, it was seen that this threshold was the same as the baseline threshold in all participants. The noise level was then increased in 5 dB steps, re-estimating threshold at each noise level.

The NIL was defined as the lowest noise level at which the masked threshold showed a consistent >5 dB elevation from baseline (i.e., two of three ascending–descending trials). NILs were obtained separately for BBN, SSN, and 8-TB across both AC and BC modalities using both audiometers.

Each participant completed all tests in a single session lasting approximately 140–160 minutes, including short breaks. The order of testing conditions comprising audiometer type (conventional, KUDUwave), transducer modality (AC, BC), and noise type (BBN, SSN, 8-TB) was fully counterbalanced across participants to minimize order effects. For each condition, testing duration was approximately 8–10 minutes.

To control for fatigue, participants were provided a 1-minute rest after every five noise-level increments, along with additional short breaks (2–3 minutes) between major test blocks (e.g., between AC and BC testing or between audiometers). Fatigue was monitored informally through participant feedback and observation of response consistency, and testing was paused if participants reported discomfort or showed reduced concentration.

For BC testing with the KUDUwave, the bone vibrator was placed on the forehead while circumaural earcups remained in position, as per device configuration. To minimize response bias, participants were not informed about the study hypotheses or expected device differences. The flow chart of the procedures is shown in **Figure 1**.

### Measurement of noise immunity level

#### *Stimuli and equipment*

Hearing thresholds were measured at octave frequencies from 250 to 8000 Hz using pure tones presented by air and bone conduction. Testing was performed under quiet conditions and in the presence of three noise types: BBN, SSN, and 8-TB. BBN (white noise with a flat power spectral density from 250–8000 Hz) was presented using a diagnostic audiometer (Inventis Piano, Inventis Inc., Italy). SSN simulates the long-term average spectrum of speech

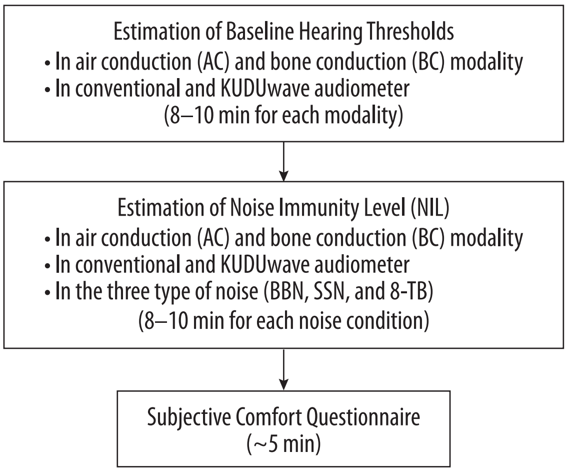


**Figure 1.** Flowchart illustrating the test procedure followed in the study

without linguistic content, whereas 8-TB consists of simultaneous recordings of multiple speakers. The 8-TB used in the study was in Kannada, as all participants were native Kannada speakers. Both SSN and 8-TB were the same as those generated by Kumar and Sandeep [21]. The KUDUwave 5000 (GeoAxon, Pretoria) Type-2 clinical audiometer (IEC 60645-1/2) was used to obtain hearing thresholds in the booth-free setup. The system was operated via eMoyo, a PC-based software platform supporting manual, automated screening, diagnostic pure-tone, and speech audiometry. For AC testing, the KUDUwave utilizes ER-3A insert earphones coupled with circumaural noise-attenuating earcups, while BC testing is performed using a forehead-placed bone vibrator integrated within the headset configuration.

To reduce ambient noise across a broad frequency range the device employs a dual-layer passive noise attenuation system, combining insert earphones with circumaural earcups. Additionally, built-in probe microphones continuously monitor real-time environmental noise levels within the ear canal, allowing the system to pause or flag testing when ambient noise exceeds permissible limits, thereby minimizing contamination of threshold measurements. This integrated approach enhances signal-to-noise ratio and reduces the likelihood of false-positive responses during testing in non-sound-treated environments.

Audiometric hearing thresholds using the conventional setup were obtained with the Interacoustics AD222 Type-2 clinical audiometer (IEC 60645-1), using TDH-39 supra-aural headphones for AC and a B71 bone vibrator for BC. All testing was conducted in a double-walled, sound-treated audiometric room to ensure accurate threshold and noise immunity level measurements. Noise stimuli (BBN, SSN, and 8-TB) were routed through a calibrated sound-field speaker using a separate diagnostic audiometer (Inventis Piano, Inventis Inc., Italy). The sound field speaker was positioned at 0-degree azimuth relative to the participant's ear and 1-m away. The loudspeaker output at ear level was monitored through a sound level meter (B&K 2270).

### *Subjective comfort of headsets*

After completing audiometric testing with both audiometers, participants rated their subjective experiences. Discomfort associated with audiometric testing can affect the accuracy of test outcomes and overall compliance (IEC 60645-1: 2017). From the existing standardized 24 attributes of headsets reported in the literature, five attributes were selected that specifically focused on assessing headphone comfort [23]. They were; comfort, pain caused by the headphones, noise attenuation, sense of acoustic isolation, and sensation of ears being blocked or full – selected as they directly relate to the physical and perceptual experience associated with audiometric headset use. Other attributes in the original framework (e.g., design, brand perception, and sound quality) were not included, as they were not relevant to the objectives of the present study. Each participant rated these attributes on a 5-point Likert-type scale, where 1 indicated the least favourable experience (i.e., very uncomfortable, severe pain, very poor noise attenuation, no sense of acoustic isolation, very strong sensation of ear blockage or fullness) and 5 indicated the most favourable experience (i.e., very comfortable, no pain, excellent noise attenuation, complete sense of isolation, no sense of blockage or fullness).

## Statistical analysis

The noise immunity level with NIL obtained in AC and BC modalities were analyzed across noise conditions and audiometers. A $2 \times 3 \times 6$ factorial repeated-measures ANOVA was conducted for the AC modality, with the factors being audiometer type (conventional, KUDUwave), noise type (BBN, SSN, 8-TB), and frequency (250, 500, 1000, 2000, 4000, and 8000 Hz). Similarly, for the BC modality, a $2 \times 3 \times 5$ repeated-measures ANOVA was performed across 250, 500, 1000, 2000, and 4000 Hz. Post hoc pairwise comparisons were conducted where appropriate, and significance was set at $p < 0.05$.

**Table 1.** Paired *t*-tests at each test frequency comparing baseline air conduction and bone conduction thresholds between the conventional audiometer and the KUDUwave audiometer

| Modality | Test frequency | *df* | Mean difference | SE | *t*-values | *p*-values | Cohen's *d* |
|---|---|---|---|---|---|---|---|
| Air conduction (AC) | 250 | 29 | –0.333 | 4.722 | –0.387 | 0.702 | – |
| | 500 | 29 | –0.667 | 4.686 | –0.779 | 0.442 | – |
| | 1000 | 29 | 0.000 | 4.913 | 0.001 | > 0.999 | – |
| | 2000 | 29 | 0.000 | 4.913 | 0.001 | > 0.999 | – |
| | 4000 | 29 | –0.166 | 4.639 | –0.197 | 0.845 | – |
| | 8000 | 29 | 0.166 | 4.639 | 0.197 | 0.845 | – |
| Bone conduction (BC) | 250 | 29 | 3.500 | 4.939 | 3.881 | 0.001 | 0.71 |
| | 500 | 29 | 4.666 | 5.241 | 4.877 | < 0.001 | 0.89 |
| | 1000 | 29 | 5.000 | 5.085 | 5.385 | < 0.001 | 0.98 |
| | 2000 | 29 | 1.833 | 3.591 | 2.796 | 0.009 | 0.51 |
| | 4000 | 29 | 2.000 | 2.816 | 3.890 | 0.001 | 0.71 |

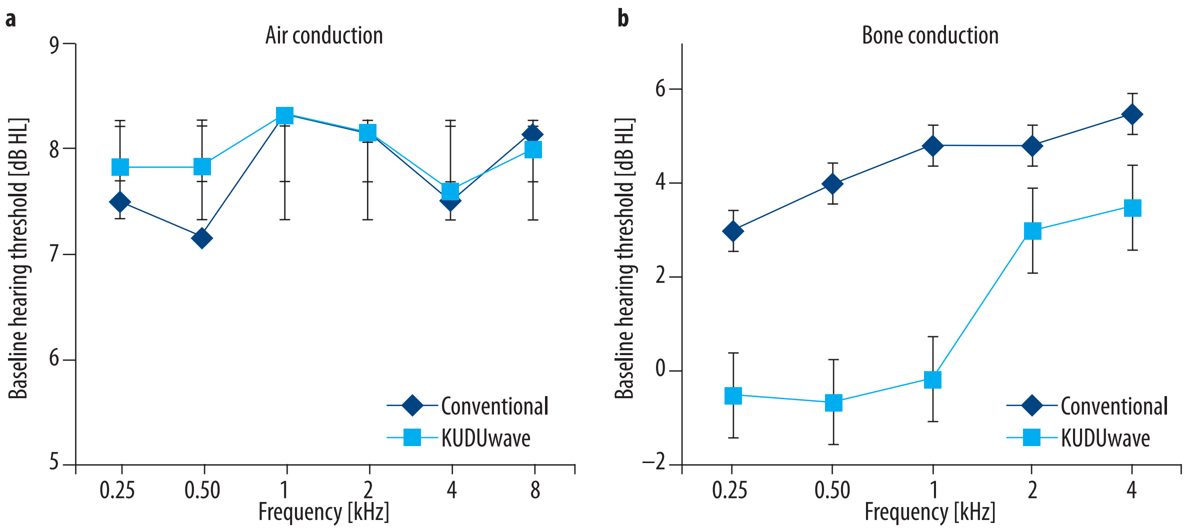


**Figure 2.** Baseline hearing thresholds (mean and standard deviation) for air conduction (**a**) and bone conduction (**b**) obtained using both the conventional and KUDUwave audiometers

## Results

### Noise immunity level

The KUDUwave audiometer consistently yielded lower (better) thresholds than the conventional audiometer. Paired *t*-tests (**Table 1**) showed no significant differences in baseline AC thresholds across all frequencies. However, BC thresholds were significantly lower with the KUDUwave audiometer ($p < 0.001$) at all frequencies, with moderate to large effect sizes (Cohen's $d = 0.51–0.98$). **Figure 2** presents the mean and standard deviation of the thresholds. Mean AC differences were within 5 dB HL across frequencies, whereas BC thresholds showed larger differences, particularly at lower frequencies.

A 2 × 3 × 6 factorial repeated measures ANOVA was conducted for the AC modality across six frequencies, and a similar analysis was performed for the BC modality across five frequencies. **Table 2** presents the main and interaction effects of the repeated-measures ANOVA for AC and BC modalities. In the AC modality, NILs were higher for the KUDUwave audiometer than the conventional audiometer across all noise types (**Figure 3**), with mean differences ranging from 20 to 28 dB HL for AC and standard deviations within 5.6 dB HL at all test frequencies across the three noise conditions.

Across the noise conditions, mean NILs were slightly higher for BBN and SSN compared to 8-TB, with similar values between BBN and SSN. Across frequencies, NILs were highest at mid frequencies (1000–4000 Hz), lower at low

**Table 2.** Results of repeated measures ANOVA for factors audiometer type, noise type, and frequency, and their interaction in AC and BC; the *F*-values, *p*-values, and effect sizes are shown

| Modality | Condition | *F*-values | *p*-values | $\eta p^2$ |
|---|---|---|---|---|
| Air conduction (AC) | Audiometer type | 1192.427 | < 0.001 | 0.976 |
| | Noise type | 31.559 | < 0.001 | 0.521 |
| | Frequency | 47.803 | < 0.001 | 0.622 |
| | Audiometer type / Noise type | 1.031 | 0.363 | – |
| | Audiometer type / Frequency | 44.108 | < 0.001 | 0.603 |
| | Noise type / Frequency | 3.536 | < 0.001 | 0.109 |
| | Audiometer type / Noise type / Frequency | 0.868 | 0.564 | – |
| Bone conduction (BC) | Audiometer type | 12537.467 | < 0.001 | 0.998 |
| | Noise type | 0.352 | 0.705 | – |
| | Frequency | 21.945 | < 0.001 | 0.413 |
| | Audiometer type / Noise type | 0.114 | 0.893 | – |
| | Audiometer type / Frequency | 51.050 | < 0.001 | 0.638 |
| | Noise type / Frequency | 0.824 | 0.582 | – |
| | Audiometer type / Noise type / Frequency | 0.447 | 0.892 | – |

frequencies (250–500 Hz), and lowest at 8000 Hz, irrespective of noise type. A significant main effect of audiometer type, noise type, and frequency was observed, along with a significant audiometer × frequency interaction. However, the audiometer × noise type and three-way interactions were not significant.

In the BC modality and for all three noise types, the mean NILs (**Figure 3**) were higher for the KUDUwave audiometer than for the conventional audiometer, with mean differences ranging from 35 to 42 dB and standard deviations within 4.42 dB for all test frequencies and noise type.

Across noise type and all tested frequencies, mean NILs were consistent across BBN, SSN, and 8-TB. Additionally, in BC mode, NILs decreased as frequency increased, regardless of the noise types. A significant interaction was found between audiometer type and frequency, suggesting that the difference in NILs between audiometers varied across frequencies.

Pairwise comparisons (**Table 3**) showed that in the AC modality, significant differences were observed between SSN and 8-TB, as well as between BBN and 8-TB. However, no significant difference was found between SSN and BBN. The pairwise comparisons across the frequency in AC modality, indicated that the NIL was sigificantly higher at mid frequencies compared to the low (250 Hz) and high (8000 Hz) frequencies. Mean differences in NIL ranged from 1.167 to 4.639. In contrast, in the BC modality, the low frequencies (250 and 500 Hz) exhibited higher NILs with mean differences ranging from 0.833 to 1.861 (detailed statistics are available with the authors and will be published on request).

## Subjective comfort

**Figure 4** depicts the ratings for the five target attributes (comfort, headphone-induced pain, noise attenuation, feeling of complete isolation, and sensation of the ears feeling blocked/full) obtained on the 5-point scale for the two headsets. For the attributes of comfort and headphone-induced pain, most participants rated the conventional audiometer headphones between 4 and 5 (representing comfortable to very comfortable and minimal to no pain, respectively), whereas the KUDUwave headset was commonly rated between 1 and 3 (representing very uncomfortable to neutral and very painful to neutral, respectively). On the contrary, the opposite was obtained for the other three attributes. The Wilcoxon signed-rank test showed a significant difference in all five measured attributes: comfort ($z = 4.767$, $p < 0.001$, $r = 0.870$), pain ($z = 4.627$, $p < 0.001$, $r = 0.844$), noise attenuation ($z = 4.594$, $p < 0.001$, $r = 0.839$), feeling of complete isolation ($z = 4.543$, $p < 0.001$, $r = 0.830$), and sensation of ears feeling blocked/full ($z = 4.780$, $p < 0.001$, $r = 0.873$), showing that participants rated the two audiometers quite differently.

## Discussion

The present study evaluated hearing threshold estimation using a conventional and the KUDUwave audiometer under quiet and noisy conditions involving three noise types: BBN, SSN, and 8-TB, across various frequencies. Baseline AC thresholds obtained using both audiometers were comparable, indicating stable and reliable measurements under quiet conditions.

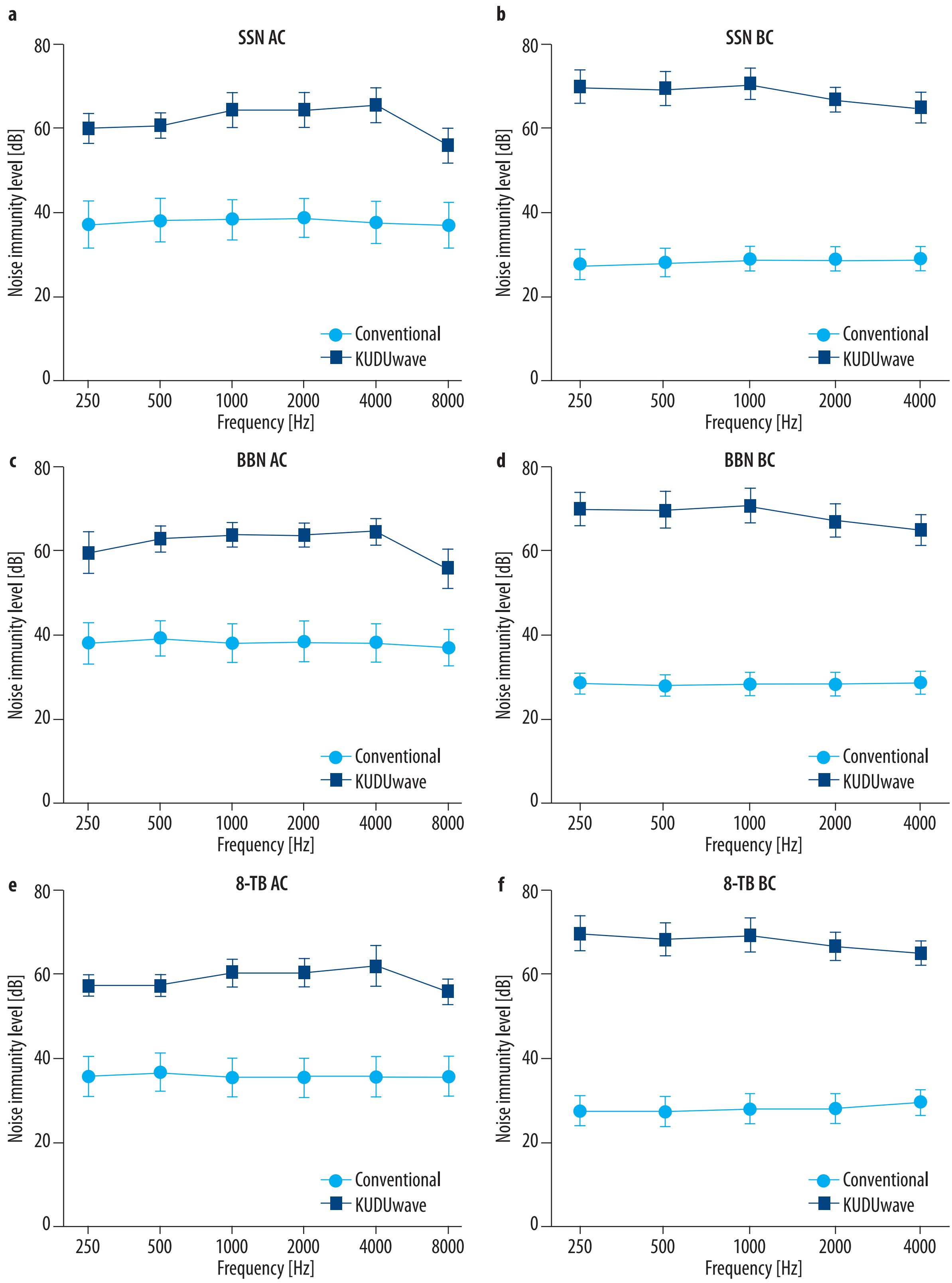


**Figure 3.** Noise immunity level (mean and standard deviation) obtained using the conventional and KUDUwave™ audiometer in air conduction (AC) and bone conduction (BC) modalities across three noise conditions: (**a, b**) speech-shaped noise, SSN; (**c, d**) broad-band noise, BBN; and (**e, f**) eight-talker babble, 8-TB

**Table 3.** Pairwise comparison of noise immunity level (NIL) across frequencies in air conduction and bone conduction; S = significant; NS = not significant

| Modality | Frequency [Hz] | 250 | 500 | 1000 | 2000 | 4000 | 8000 |
|---|---|---|---|---|---|---|---|
| Air conduction | 250 | | S | S | S | S | S |
| | 500 | | | NS | NS | S | S |
| | 1000 | | | | NS | NS | S |
| | 2000 | | | | | NS | S |
| | 4000 | | | | | | S |
| Bone conduction | 250 | | NS | NS | S | S | |
| | 500 | | | S | S | S | |
| | 1000 | | | | S | S | |
| | 2000 | | | | | NS | |

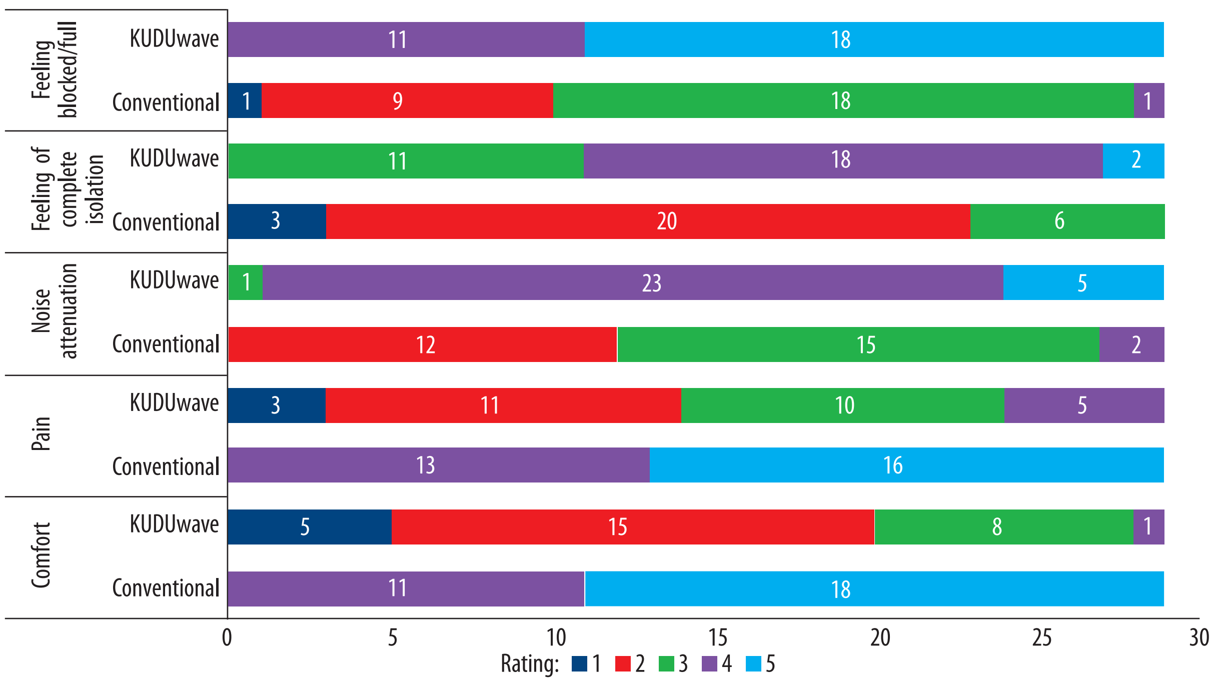


**Figure 4.** Subjective ratings (colour coded 1 to 5) given by 30 participants (the number giving each rating provided on bars) for their experience with the audiometer headphones (conventional and KUDUwave) during hearing threshold estimation. The ratings are for comfort (very uncomfortable to very comfortable), pain caused by the headphones (severe to none), effectiveness of noise attenuation (very poor to excellent), sense of isolation from the environment (none to complete), and sensation of ear blockage or fullness (very strong to none)

BC thresholds measured using the KUDUwave were consistently lower (i.e., better) than those obtained using a conventional audiometer. This difference can be attributed to the occlusion effect introduced by the circumaural headphones of the KUDUwave, which tightly cover both ears (while its bone vibrator is placed on the forehead). The occlusion effect enhances the perception of bone-conducted sound, especially at low frequencies, by trapping vibratory energy within the occluded ear canal. Goldstein and Hayes [24] reported the occlusion effect to be approximately +24 dB at 250 Hz, +20 dB at 500 Hz, and +10 dB at 1000 Hz, diminishing to near 0 dB at 2000 Hz and higher. These frequency-specific differences in occlusion explain the pronounced BC threshold improvements at lower frequencies. Direct comparison of BC thresholds between the two systems should be interpreted cautiously, because the KUDUwave introduces an occlusion effect due to its circumaural earcups, which is absent in conventional BC measurements. Thus, the observed differences are probably attributable to an occlusion effect.

The KUDUwave demonstrated superior performance in noisy environments compared to conventional audiometers, maintaining threshold accuracy even as ambient noise levels increased. It reliably estimated AC thresholds in environments with noise levels up to 50–65 dB SPL and BC thresholds up to 60–75 dB SPL. This enhanced noise immunity is primarily due to the combination of insert earphones and circumaural earcups, which together provide substantial passive attenuation across the frequency range.

Such capability is particularly beneficial for community-based hearing screening programs, where sound-treated environments are unavailable and ambient noise levels are typically high. For instance, Abraham et al. [25] reported ambient noise levels of 58.3 dB SPL in a meditation center, 60.1 dB SPL in a household, and 64.8 dB SPL in a rural panchayat office, levels that exceed the operating threshold of standard audiometers (20–40 dB SPL). In these contexts, the KUDUwave can reduce the rate of false-positive referrals that often arise when testing in noisy environments at the standard 25 dB HL cut-off. Even in such conditions the KUDUwave is capable of reliably detecting hearing losses up to a moderately severe degree [26]. Given that ambient noise poses greater interference for individuals with milder hearing losses [27], the KUDUwave's resistance to noise assists in estimating more accurate thresholds.

Across all noise types and frequencies, inter-subject variability in NILs was minimal, with standard deviations consistently below 6 dB. This indicates a good degree of test–retest reliability.

The significant interaction between noise and frequency in the AC modality indicates that masking effects varied with the spectral characteristics of the stimuli (BBN, SSN, and 8-TB). NILs were lower at low frequencies (250–500 Hz), likely due to stronger energetic masking from dominant low-frequency ambient noise, and highest at mid frequencies (1000–4000 Hz), indicating greater resistance to masking. Slightly reduced noise immunity at 8000 Hz may reflect limitations in transducer attenuation and residual masking effects. These findings align with those of Storey et al. [10], who reported reduced accuracy at 250 and 8000 Hz. Despite this variation, NIL differences across frequencies were within 10 dB, and performance remained robust at the key screening frequencies of 0.5, 1, 2, and 4 kHz recommended by WHO [1].

When comparing noise types, the KUDUwave exhibited greater immunity to BBN and SSN than to 8-TB. The 8-TB condition produced lower NILs, indicating a higher masking effect, likely due to both energetic and informational masking. As speech babble simulates more realistic and cognitively demanding listening environments, it poses greater challenges for threshold determination. Thus, NILs obtained under 8-TB conditions may serve as the most conservative and realistic reference values for noise immunity in field applications. In contrast, BC thresholds remained stable across noise types, likely because bone-conducted signals bypass the outer and middle ear and are less affected by environmental noise. This highlights the device's relative advantage in BC testing in adverse conditions. However, a limitation of this study is the inclusion of only young adults with normal hearing, limiting generalization of the findings to children and older adults with normal hearing and to individuals with hearing loss. We do not expect that the other participant groups will have different levels of immunity to ambient noise. However, it needs to be scientifically validated.

Despite its technical advantages, user feedback highlighted notable discomfort with the KUDUwave headset, particularly the weight and pressure of its circumaural earcups. Participants reported sensations of ear fullness and pressure, possibly exacerbated by extended testing durations. Similar observations have been made by Liu et al. [28], who noted that increased attenuation from circumaural configurations may lead to physical discomfort during prolonged use.

In this study, both AC and BC thresholds were measured, resulting in longer test sessions. However, in typical screening camps where only AC thresholds are assessed, the duration will be considerably shorter, perhaps mitigating the reported discomfort issue. To maintain user comfort, future research should explore preferred session durations for different age groups, particularly pediatric and geriatric populations.

The findings point to the suitability of the KUDUwave audiometer for use in community screening settings, particularly where the acoustic environment is uncontrolled. Its ability to maintain accurate thresholds in ambient noise up to 65 dB SPL and its robustness against noise-induced variability make it a promising tool for large-scale outreach initiatives. However, the trade-off between comfort and attenuation must be carefully considered, noting that community screenings will prioritize short test sessions.

It is important to note that the present study did not directly evaluate screening outcomes (e.g., referral rates or diagnostic accuracy) in real-world contexts. Therefore, while the findings indicate robustness to ambient noise, their applicability to actual community screening settings warrants further validation.

## Conclusions

We found that the KUDUwave boothless audiometer demonstrated reliable noise immunity up to 65 dB HL, supporting its suitability for community-based hearing screening in acoustically uncontrolled environments. Accurate thresholds were maintained even in the presence of challenging speech babble noise, an advantage for hearing assessment in community-based settings. However, concerns about user comfort particularly headset weight and pressure during prolonged testing highlight the need for an improved ergonomic design. However, in general, the KUDUwave audiometer is a promising solution for expanding access to reliable hearing screening in resource-limited and noisy settings.

## Limitations and future work

The present study has some limitations. First, the sample consisted exclusively of young adults with normal hearing, which limits the generalizability of the results to pediatric, geriatric, and hearing-impaired populations, who may exhibit different susceptibility to ambient noise and variability in threshold estimation. Second, the study did not directly evaluate real-world screening outcomes such as referral rates, sensitivity, specificity, or diagnostic accuracy in community settings; therefore, the implications for large-scale screening programs remain uncertain. Third, discrepancies in bone conduction thresholds between the audiometer were affected by the occlusion effect inherent to the KUDUwave headset, limiting comparisons with conventional audiometer. Additionally, user-reported discomfort related to the weight and pressure of the circumaural earcups is an ergonomic limitation, particularly for prolonged testing. Future research should include diverse age groups and individuals with varying degrees and types of hearing loss, assess performance in real-world community screening environments, and examine clinical outcomes such as false-positive and false-negative rates. Further studies should also explore optimization of test duration and ergonomic improvements in headset design to enhance user comfort, especially for pediatric and older populations.

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## Supplementary material

**Supplement 1.** Mean noise immunity level [dB HL] across frequencies and noise types in air conduction (AC) and bone conduction (BC) modality

| Modality | Frequency [Hz] | Conventional audiometer | | | KUDUwave audiometer | | |
|---|---|---|---|---|---|---|---|
| | | BBN | SSN | 8-TB | BBN | SSN | 8-TB |
| Air conduction (AC) | 250 | 37.83 | 37 | 35.5 | 59.5 | 59.83 | 57.17 |
| | 500 | 39.00 | 38 | 36.5 | 62.67 | 60.5 | 57.17 |
| | 1000 | 37.83 | 38.17 | 35.33 | 63.67 | 64.17 | 60.17 |
| | 2000 | 38.16 | 38.5 | 35.33 | 63.66 | 64.16 | 60.16 |
| | 4000 | 38 | 37.5 | 35.5 | 64.5 | 65.33 | 61.83 |
| | 8000 | 36.83 | 36.83 | 35.5 | 55.66 | 55.83 | 55.66 |
| Bone conduction (BC) | 250 | 28.16 | 27.33 | 27.33 | 69.66 | 69.83 | 69.66 |
| | 500 | 27.66 | 27.83 | 27.16 | 69.5 | 69.33 | 68.33 |
| | 1000 | 28 | 28.66 | 27.83 | 70.5 | 70.5 | 69.33 |
| | 2000 | 28 | 28.66 | 27.83 | 67 | 66.66 | 66.66 |
| | 4000 | 28.33 | 28.66 | 29.83 | 64.66 | 64.83 | 65 |

**Supplement 2.** Pairwise comparisons of noise immunity level (NIL) across frequencies in air conduction (AC) modality

| Compared frequency pairs [Hz] | Mean difference | *p* |
|---|---|---|
| 250 vs 500 | –1.167 | < 0.001 |
| 250 vs 1000 | –2.083 | 0.002 |
| 250 vs 2000 | –2.194 | 0.001 |
| 250 vs 4000 | –2.639 | < 0.001 |
| 250 vs 8000 | 2.0 | > 0.001 |
| 500 vs 1000 | –0.917 | 0.409 |
| 500 vs 2000 | –1.028 | 0.259 |
| 500 vs 4000 | –1.472 | < 0.001 |
| 500 vs 8000 | 3.167 | < 0.001 |
| 1000 vs 2000 | –0.111 | > 0.999 |
| 1000 vs 4000 | –0.556 | 0.824 |
| 1000 vs 8000 | 4.083 | < 0.001 |
| 2000 vs 4000 | –0.444 | > 0.999 |
| 2000 vs 8000 | 4.194 | < 0.001 |
| 4000 vs 8000 | 4.639 | < 0.001 |

**Supplement 3.** Pairwise comparisons of noise immunity level (NIL) across frequencies in bone conduction (BC) modality

| Compared frequency pairs [Hz] | Mean difference | *p* |
|---|---|---|
| 250 vs 500 | 0.361 | > 0.999 |
| 250 vs 1000 | –0.472 | 0.269 |
| 250 vs 2000 | 1.194 | 0.001 |
| 250 vs 4000 | 1.861 | < 0.001 |
| 500 vs 1000 | –0.833 | 0.012 |
| 500 vs 2000 | 0.833 | 0.023 |
| 500 vs 4000 | 1.500 | 0.002 |
| 1000 vs 2000 | 1.667 | < 0.001 |
| 1000 vs 4000 | 2.333 | < 0.001 |
| 2000 vs 4000 | 0.667 | 0.194 |

**Supplement 4.** Questionnaire for Subjective Comfort with Headphones of Audiometer

**Participant's Demographic Details**

**Name:**

**Age:**

**Gender:**

**Occupation:**

**Informed consent**

'I have been informed about the purpose and procedure of the questionnaire. I declare that my participation in this study is entirely voluntary and that I may withdraw at any time without incurring a penalty or without being obligated to provide a reason. I understand that my participation in the study will not adversely affect me in any way and that confidentiality will be maintained about my identity at all times. I also understand that the information given by me will be used only for the purpose of the study. I do not have any financial or non-financial benefits from this study. I hereby give my consent to participate.'

Date: Name:

Place: Signature:

**Instructions to Participants**

The questionnaire consists of five items assessing headset experience on a 5-point scale across the following attributes: overall comfort, pain caused by the headphones, effectiveness of noise attenuation, sense of complete isolation from the environment, and sensation of ear blockage or fullness.

You will be asked to rate your experience with the two audiometer headsets used during testing (KUDUwave™ and the conventional headphones). Please read each item carefully and indicate your response based on your personal experience with each headset. There are no right or wrong answers; kindly select the option that best reflects your perception.

| No. | Attributes | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|---|
| 1. | Overall comfort while wearing the headphones | very uncomfortable | uncomfortable | neutral | comfortable | very comfortable |
| 2. | Pain caused by the headphones | severe pain | moderate pain | mild pain | minimal pain | no pain |
| 3. | Effectiveness of noise attenuation | very poor | poor | moderate | good | excellent |
| 4. | Sense of acoustic isolation from the environment | none | slight | moderate | good | complete |
| 5. | Sensation of ear blockage or fullness | very strong | strong | moderate | slight | none |