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ORIGINAL ARTICLE

Automated pure-tone audiometry using true wireless stereo earbuds with active noise control

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ABSTRACT

Objective: Automated pure-tone audiometry (PTA) conducted outside a sound booth is heavily affected by environmental noise. This study aims to evaluate the performance of an automated PTA system, employing commercially available true wireless stereo earbuds with active noise cancellation (ANC) in noisy environments.

Design: The electroacoustic characteristics of earbuds are thoroughly evaluated. Hearing thresholds were measured by ANC earbuds and TDH-39 in three noise levels and two types of noise.

Study sample: 21 normal-hearing participants for calibration and 22 participants below mild hearing loss for evaluation experiments.

Results: The average absolute differences between hearing thresholds measured via the standard manual audiometer in quiet and the automated PTA in various noise conditions, across octave frequencies ranging from 125 to 8000 Hz, were as follows: 5.2 (quiet environment without ANC), 5.4 (40 dBA pink noise with ANC), and 9.3 dB (55 dBA pink noise with ANC).

Conclusion: ANC can mitigate the impact of low-frequency noise (below 1000 Hz) on the accuracy of hearing level measurements, aligning with trends observed in objective experimental results. However, the influence of ANC on output levels warrants serious consideration in further practices.

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KEYWORDS
Automated audiometry; active noise control; hearing healthcare; TWS earbuds; hearing screening

Introduction

According to the most recent *World Report on Hearing*, more than 1.5 billion individuals suffer from hearing loss, affecting one-fifth of the global population (World Health Organization 2021). Pure-tone audiometry (PTA) is widely regarded as the gold standard for hearing screening in individuals aged four years and older (Bright & Pallawela 2016; Oremule et al. 2024). However, manual PTA, which is typically conducted individually in sound booths by audiologists, faces notable efficiency limitations (Brennan-Jones et al. 2016). Shortages of professional audiologists, suitable space, and necessary equipment in certain regions exacerbate this issue (Margolis & Morgan 2008; Rahim et al. 2023).

With the development of mobile devices, a large number of automated audiometry programs have emerged, offering potential solutions to some limitations of conventional audiometry. Chen et al. (2021) reviewed 25 studies of smartphone-based audiometry and pointed out that some of them can offer diagnostic accuracy comparable to conventional methods. However, factors including patient age and equipment may affect reliability. Almufarrij et al. (2023) reviewed 187 web- and app-based hearing assessment tools and compared the features of different testing methods, including speech, tone, and mixed methods. The review highlighted the lack of accuracy and reliability in most tools. Besides, automation and machine learning technologies have been integrated into hearing assessments to reduce the time of screening and enhance the reliability of the results (Wasmann et al. 2022). These developments collectively improve the accessibility, accuracy, and applicability of hearing assessments in diverse environments.

While the majority of the automated PTA methods used standard PTA earphones, such as Telephonic TDH-39, it has been demonstrated that true wireless stereo (TWS) earbuds can also serve as acceptable transducers for conducting automated PTA within sound booth settings (Guo et al. 2021). By adapting commercially available earphones for audiometric purposes, the broader public is granted the capability to evaluate and monitor their individual hearing thresholds.

PTA outside the sound booth is particularly sensitive to ambient noise, which is a challenge that hinders the broad implementation of automated PTA. To mitigate the impact of ambient noise, Berger & Killion (1989) compared the performance of three pairs of earphones: ER-3A insert earphones, TDH-50P supra-aural headphones, and Audiocups circumaural headphones, in the context of PTA testing. Their investigation revealed the superior noise insulation capabilities of ER-3A, followed by Audiocups. Both circumaural headphones TDH-50P and Audiocups proved ineffective in attenuating low-frequency noise, a limitation shared by many earphones (Frank 2000; Lankford et al. 1999). Circumaural headphones were commonly used as transducers for automated audiometry outside the sound booth (Bean et al. 2022; Margolis et al. 2022; Storey et al. 2014).

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TWS earbuds are more compact and lightweight than circumaural headphones, yet they may be more vulnerable to the influence of noise.

Active noise cancellation (ANC) technology has the capability to address low-frequency noise, providing a potential method for mitigating low-frequency noise interference. A novel approach in prior studies employed ANC headphones to attenuate ambient noise while delivering the PTA stimuli through standard insert earphones. One study demonstrated better accuracy in the presence of noise with levels of 30 and 40 dB when conducting PTA using ANC headphones (Bose Active X) covering insert earphones (Bromwich et al. 2008). In another study, the performance of two commercial PTA software programs (EarTrumpet and ShoeBOX) was evaluated, also using ER 3 A insert audiometric earphones covered by ANC circumaural headphones (Noisebuster PA4000; Saliba et al. 2017). However, these studies require expensive standard PTA earphones, which are rarely available for home use, prompting an exploration of the direct integration of ANC and PTA. Lo and McPherson (2013) integrated ANC headphones (Sennheiser PXC450) into automated PTA for screening the hearing thresholds of schoolchildren in classrooms and found ANC headphones obtained a more than 10% lower referral rate than TDH-39 in the screening at 500 Hz. Similarly, a test involving pre-school children employed Bose QuietComfort 15 ANC headphones in classrooms with ambient noise levels ranging from 40 to 51 dBA (Kam et al. 2014). Both studies utilised ANC headphones for noise reduction and PTA playback simultaneously and resulted in a lower failure rate than TDH-39 when conducting hearing threshold screening in school classrooms.

In addition to conducting PTA with ANC earphones, some researchers have designed dedicated ANC algorithms for PTA testing. A self-designed noise reduction system developed for automated PTA with audiometric earphones achieved comparable results to manual PTA at ambient noise levels lower than 45 dB (Sun et al. 2019). Another study reported a reduced threshold deviation at 250 Hz when using a self-designed ANC system in comparison to traditional TDH-39 or Audiocups earphones for narrowband noise with levels lower than 45 dB HL (Chang et al. 2019). They also explored the noise-attenuation capabilities of ANC earphones and TDH-39, confirming the superior noise-reduction capabilities of ANC earphones. These two studies evaluated ANC algorithms, but the automated PTA was still conducted with standard audiometric earphones rather than commercially available earphones.

The aim of this study was to conduct a comprehensive assessment of the performance of commercially available TWS earbuds equipped with ANC in noisy environments. ANC-capable TWS earbuds (Huawei FreeBuds Pro, referred to hereafter as the earbuds) were combined with a previously developed automated PTA program (Guo et al. 2021).

The first experiment focused on objective electroacoustic measurements, assessing the sound output performance and noise attenuation capabilities of the earbuds. The second experiment involved a behavioural evaluation, beginning with the calibration of the earbuds, and proceeding to a comparative analysis between the automated audiometry utilising ANC earbuds and manual audiometry employing the TDH-39 earphones.

Objective measurement

Method

The objective measurements included assessments of the noise-attenuation performance of the earbuds across various conditions, including different noise directions, noise intensities, and the activation or deactivation of the ANC function. The harmonic distortion, linearity of pure-tone output, and wearing repeatability of the earbuds were also assessed.

The entire objective measurements were conducted within a soundproof room, maintaining a background noise level of 21 dBA (octave noise levels were shown in Table 1; the level was measured using a Brüel & Kjær type 2250 sound level metre). A loudspeaker (Genelec 8010 A) connected with a sound card (RME Fireface UC) served as the primary noise source. The results were recorded utilising a KEMAR manikin equipped with pinnae, ear canal, and ear simulator. The centre of head was situated at 1.7 m from the loudspeaker. Both the centre of the loudspeaker and the ears of the manikin were 1.2 m above the floor. The testing methodology used in this study was based on ISO 4869-3:2007 (2007; Acoustic Test Fixture, ATF method).

Wide-band pink noise with different levels spanning from 46.3 to 76.3 dB SPL in a step of 10 dB (measured at the centre position of the dummy head when the head was removed) was used as the noise source. Given that ANC systems may perform differently when subjected to noise located in various directions (Liebich et al. 2018), noise from five distinct directions was used (0, 45, 90, 135, and 180°, where 0 and 90° correspond to frontal and left-facing directions, respectively; see the left panel of Figure 1). To account for potential variations in ANC performance resulting from different noise types, two additional noise types, babble noise and impulse trains of pink noise, were used. The aforementioned three variables (noise level, direction, and type) were assessed separately, compared to a reference condition of pink noise at 56.3 dB SPL from 0°. The detailed results can be found in *Supplemental Material.*

Both the noise attenuation performances of earbuds with ANC activated and deactivated were measured. For comparison, the noise attenuation capabilities of three additional earphones, namely TDH-39 (standard earphones for audiometers), Sennheiser HDA200 (out of production now), and Apple Airpods Pro (another TWS earbuds with ANC), were also evaluated in the reference condition (i.e. pink noise at a level of 56.3 dB SPL from 0°).

The linearity of output was evaluated by recording the actual level of pure tone when adjusting the digital level. The wearing repeatability was evaluated by the differences in output levels between two-times wearing of earbuds. Detailed procedures and results can be found in *Supplemental Material.*

Given that ANC can influence the output characteristics of earphones (Clark et al. 2017), the pure-tone output and harmonic distortion of the earbuds at the seven frequencies (125, 250, 500, 1000, 2000, 4000, and 8000 Hz) were compared when the ANC function was activated. The digital levels were varied at four levels with a 10 dB step for each frequency. The pure tone was played at a relatively high level to ensure a high signal-to-noise ratio.

Table 1. The octave-band analysis of background noise of the sound proof room, sound booth, and the pink and babble noise used in behavioural measurement. The last line shows the overall noise attenuation of earbuds with ANC (Figure 2).

	Leq / dB SPL						
Frequency/Hz	125	250	500	1000	2000	4000	8000
Sound proof room	29.5	22.3	16.7	11.3	9.8	11.9	13.0
Sound booth	27.3	13.2	13.2	16.9	15.7	15.8	18.4
40-pink	30.3	27.8	27.9	28.9	30.8	34.5	35.7
55-pink	42.3	42.6	42.7	43.6	45.7	49.4	50.6
55-babble	48.3	54.8	51.2	46.9	46.9	47.0	42.5
Attenuation of earbuds	18.7	17.5	12.9	11.1	24.7	22.1	17.4

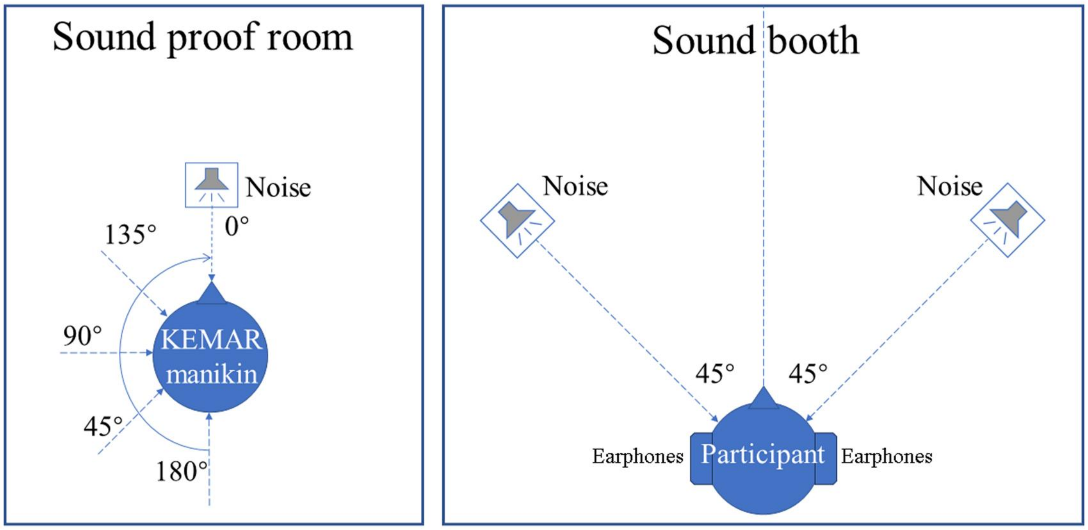

Figure 1. Setups for the objective measurements (left) and the behavioural measurement (right). Left: The KMEAR was rotated to change the direction of the noise. The dotted lines represent the relative noise directions. Right: The signals were played through the earphones worn by the participants.

The sound levels and harmonic distortion of earbuds with ANC activated were then calculated using the received signals of KMEAR.

Results

Noise attenuation performance

Figure 2 compares the pink noise attenuation of the four earphones in the reference condition. The noise attenuation was defined as the difference between the sound levels received by the manikin with and without the earphones.

As shown in Figure 2, the earbuds (Freebuds Pro) with ANC presented superior noise attenuation at low frequencies (lower than 1000 Hz) but less noise attenuation at middle and high frequencies (1000 Hz and higher) than TDH-39 and HDA200. At frequencies below 1000 Hz, earbuds equipped with ANC exhibited better noise attenuation than their non-ANC counterparts or TDH-39. At frequencies above 1000 Hz, the earbuds and the TDH-39 produced similar noise attenuation performance. However, for one study of TDH-39, namely TDH-39-Arlinger (1986) in Figure 2, observed higher attenuation values of TDH-39 compared with the results in the present study. The study of Arlinger (1986) shows better high-frequency (4000 and 8000 Hz) attenuation than two kinds of earbuds (Freebuds Pro and Airpods Pro). ANC and non-ANC earbuds typically yielded similar outcomes at 2000 Hz and higher frequencies. When comparing two ANC TWS earbuds, the Airpods Pro had better attenuation than the Freebuds Pro earbuds at all frequencies except 4000 and 8000 Hz, albeit two earbuds shared the same general trend.

Influence of ANC on pure tone output

When ANC was activated, the output levels increased by 12.4, 7.3, and 0.9 dB at 125, 250, and 4000 Hz, respectively; and decreased by 0.8, 3.7, 0.7, and 0.4 dB at 500, 1000, 2000, and 8000 Hz, respectively. The changed output levels caused by ANC were consistent across different setting digital levels for a certain frequency ($\leq$ 0.1 dB). Therefore, the earbuds could maintain a good linearity with ANC-on. The maximum total harmonic distortion was 0.3% among all the recorded pure tone outputs with ANC-on. In summary, the ANC function led to increased output levels at 125 and 250 Hz, while conversely resulting in decreased output levels at 1000 Hz.

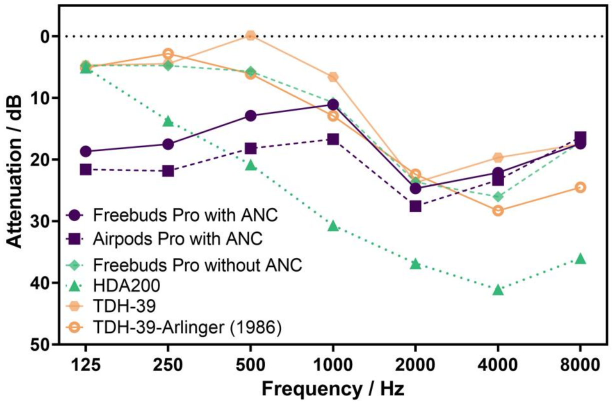

Figure 2. Noise attenuation values of four earphones. The line TDH-39 shows measured results in this study, the line TDH-39-Arlinger (1986) is the mean attenuation values tested by Arlinger (1986).

Discussion

Noise attenuation

The noise attenuation performance of the earbuds tested in this study align with earlier findings, demonstrating effective ANC at low frequencies (125 and 250 Hz) but decreased performance at 500 Hz. The earbuds provided nearly 20 dB attenuation across most frequencies (octave frequencies from 125 to 8000 Hz) except at 500 and 1000 Hz, where it dropped to 13 and 11 dB, respectively. Given that low-frequency noise predominates in indoor environments (Bean et al. 2022; Lo & McPherson 2013), the low-frequency attenuation provided by ANC is beneficial for hearing screenings in real-world settings.

Clark et al. (2017) reported results of Bose QuietComfort 15 circumaural headphones, which are comparable to those of the present study. The headphones provided attenuation of 20 dB or more at most frequencies between 250 and 4000 Hz but dropped to 13 and 14 dB at 1000 and 6000 Hz, respectively. Bromwich et al. (2008) used insert earphones that offered substantial passive attenuation at high frequencies and circumaural ANC headphones (Bose Aviation X) that provided extra active noise attenuation of 20 dB at low frequencies, resulting in impressive overall noise attenuation. The ANC headphone's attenuation also decreased at 500 Hz and above in their study. Sennheiser PXC450 headphones, as studied by Lo & McPherson (2013), gave attenuation around 10 dB at low frequencies (125 to 500 Hz). The attenuation increased to 20 dB at 1000 and 2000 Hz and reached 30 dB at 4000 and 8000 Hz.

For PTA in higher-noise environments, better attenuation of medium and high frequencies than the earbuds in this study is required. Attenuation at medium and high frequencies primarily relies on passive isolation; hence, circumaural headphones usually outperform earbuds at these frequencies. Variations in passive attenuation can be influenced by the design and shape of the earphones (Meinke & Martin 2023). However, it is difficult to reduce low-frequency noise by only passive isolation. The active attenuation capabilities for low frequencies (125 and 250 Hz) of the earbuds were either comparable to or greater than those reported in the aforementioned studies.

It's worth noting that a custom ANC algorithm developed by Chang et al. (2019) demonstrated a different pattern of noise attenuation. In their study, the attenuation of the earphones increased from 10 dB at 125 Hz to 40 dB at 4000 Hz. Furthermore, ANC remained effective even at 2000 Hz. Their study shows the potential for improving the accuracy of automated PTA in noise using specially designed ANC algorithms.

The impact of ANC on output levels is a crucial aspect that requires careful examination. In this study, we observed consistent variations in the output levels for each frequency when ANC was switched on and off. These influences could be effectively compensated by implementing specific adjustments in the reference equivalent threshold sound pressure level (RETSPL, not performed in this study). Other aspects of the study, including assessments of linearity and wearing repeatability, established the availability of the earbuds for PTA testing.

Limitations and future work

The objective measurements were inadequate in some aspects: the test of output signals did not cover the whole range of measurement levels of PTA, and the attenuation measurements were only conducted by a dummy head rather than a real ear, as suggested by Meinke & Martin (2023) to conduct laboratory real-ear attenuation at threshold (REAT) methods (ANSI/ASA S12.6 2020). As a useful device of audiometry, more detailed objective measurements that meet the current standards should be conducted.

Behavioural measurement

Method

Calibration

The absence of a universally accepted ear simulator for earbuds introduces challenges for calibration. To align the measured hearing thresholds with those obtained using manual audiometry with standard earphones, a practicable approach is to compensate the RETSPL of non-standard earphones with thresholds measured using standard audiometers (Ho et al. 2017).

Twenty-one otologically normal participants aged from 18 to 22 years (average age = 20) were recruited in the calibration phase. All of them had hearing thresholds below 20 dB HL at octave frequencies from 125 to 8000 Hz, and none of them had a history of ear diseases. Hearing thresholds were separately measured by a manual audiometer (Madsen Orbiter 922) with a pair of TDH-39 supra-aural earphones and an automated audiometer with ANC-off earbuds; twice for each participant. The manual PTA was conducted by assistants trained by licenced audiologists from hearing clinics using the modified Hughson-Westlake with a step of 5 dB. The automated PTA procedure was conducted through MATLAB software on a laptop, based on the modified Hughson-Westlake method. The procedure searches for six reversal points of the participant's response (heard or not) rather than only ascend serials. The average of the last four reversal points was regarded as the threshold. Afterwards, the RETSPLs associated with the earbuds were determined based on the difference between the average thresholds measured with manual PTA using TDH-39 earphones and those measured with automated PTA utilising the earbuds (see detailed procedures in Guo et al. 2021).

The experiment was carried out in a sound booth (background noise < 25 dBA, the results of octave analysis are shown in Table 1). The manual audiometer was calibrated prior to the experiment. The results of calibration and compensated RETSPL can be found in *Supplemental Material*. All participants signed informed consent statements and were paid for their participation. The study was approved by the Ethics Review Board of Guangdong Provincial People's Hospital (KY2023-655-01).

Evaluation under noise

After level calibration, the formal experiment assessing the accuracy of the automated audiometry system was conducted in both noisy and quiet environments. It was implemented in the same sound booth used for calibration (see previous section). 22 participants (not involved in the calibration experiment) were enlisted for this experiment. All of them exhibited hearing loss not exceeding 45 dB HL. This criterion was chosen because moderately and severely hearing-impaired individuals may be less affected by the background noise (Bromwich et al. 2008). The manual PTA was performed in the same manner as in the calibration process.

A pilot phase was first conducted with four normal hearing listeners not included in formal experiments. The thresholds were tested by automated PTA with ANC in both a quiet environment and noisy environments (three pink noise levels: 30 dBA, 40 dBA, and 50 dBA; two babble noise levels: 40 dBA and 50 dBA). It was found that participants might use spatial auditory cues (the spatial separation of the noise from the front and the pure tone from the sides, which induces the spatial release from masking) to detect pure tones in noise when there was only one loudspeaker playing noise. Besides, a similar phenomenon was also observed when the identical signal is originating from two loudspeakers located on both the left and right sides. To reduce the influence of spatial cues, an eighth-order maximum length sequence (MLS) decorrelation filter was applied to lower the correlation of binaurally received signals, but it also resulted in a flatter frequency spectrum (see Table 1). The two-channel de-correlated pink noise in the testing environment was then played by two loudspeakers positioned 1.85 metres from the participants, at ±45° relative to the participants (illustrated in the right panel of Figure 1). After that, the influence of the spatial cue was eliminated.

In addition to pink noise, babble noise was also presented because of its non-steady feature. The babble noise consisted of eight concurrent sentences, each loudspeaker emitting four distinct sentences. The sentences came from the Mandarin Hearing in Noise Test (MHINT) speech dataset, containing daily Mandarin speech produced by a male speaker (Wong et al. 2007).

The pink noise was presented at three levels: quiet (no noise), 40 dBA (refer to 40-pink in following contents), and 55 dBA (refer to 55-pink). The babble noise was only tested at 55 dBA (refer to 55-babble), because a pilot test showed no noticeable difference between pink and babble noise at 40 dBA. The sound levels of the noises were calibrated by a sound level metre (AWA 5636, class 2) at the position of the centre of the head when the head was removed. The octave-band analysis of the noise is shown in Table 1. The played pink noise did not have equal energy across octave bands due to the decorrelation filter. Levels higher than 55 dBA were not considered since the allowed maximum noise level for offices and residential buildings in China is 55 dBA (GB 3096, 2008).

In total, ten test conditions were involved: 3 PTA settings (manual PTA with TDH-39, automated PTA with ANC, and automated PTA without ANC) × 3 acoustic environments (quiet, 40-pink, and 55-pink), plus an additional setting (automated PTA with ANC under 55-babble). To alleviate the influence of learning effects, the test sequence was randomised by a Latin-square matrix. Two participants were tested in an alternating manner. Each participant was given 5 to 10 minutes of rest after completing each condition. We would only proceed with the experiment after the subjects felt sufficiently rested.

Results

Overall results of behavioural evaluation

The hearing thresholds of 22 participants were measured with both manual PTA and automated PTA in different noise conditions. Figure 3 presents the overall summary of the results of the final evaluation experiment. The measured hearing levels across all participants are presented for each frequency and test condition.

Generally, the results show that ANC can reduce the influence of pink noise on the accuracy of PTA at low frequencies (below 1000 Hz), while medium and high frequencies are susceptible to interference. The advantage of ANC diminishes for frequencies above 1000 Hz, for which there is no clear difference between ANC-on and ANC-off conditions (see the second and third boxes of each frequency in Figure 4(b,c)). These results are consistent with the objective measurement results depicted in Figure 2.

For subsequent statistical analysis, D'Agostino-Pearson normality tests were conducted on the datasets for each ear, frequency, and condition. Out of the 140 distinct data sets, 84 met the criteria for normality, and the remainder closely approached a normal distribution. Some thresholds > 20 dB HL might lead to slightly skewed distributions (Margolis et al. 2015).

A two-way (condition and frequency) repeated measures analysis of variance (rmANOVA, with the Greenhouse-Geisser correction in case of violation of sphericity) was conducted on the thresholds (IBM SPSS Statistics). Eight conditions were involved:

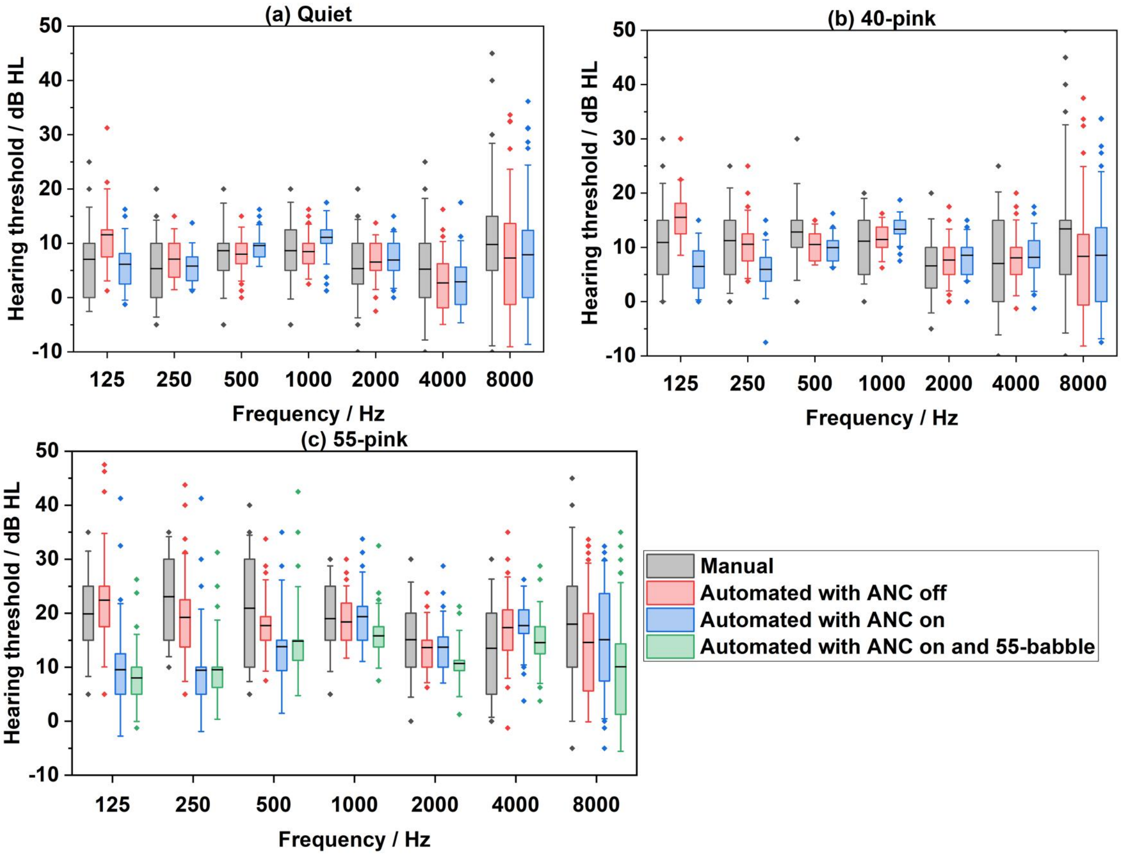

Figure 3. Box plots of the thresholds for all conditions. Each box corresponds to a specific frequency and test condition for both ears, organised into three panels by different pink noise levels. Titles of each panel specify the background noise conditions. The middle lines in each box show the average. The whiskers attached to the boxes represent standard deviations, and the upper or lower points indicate outliers.

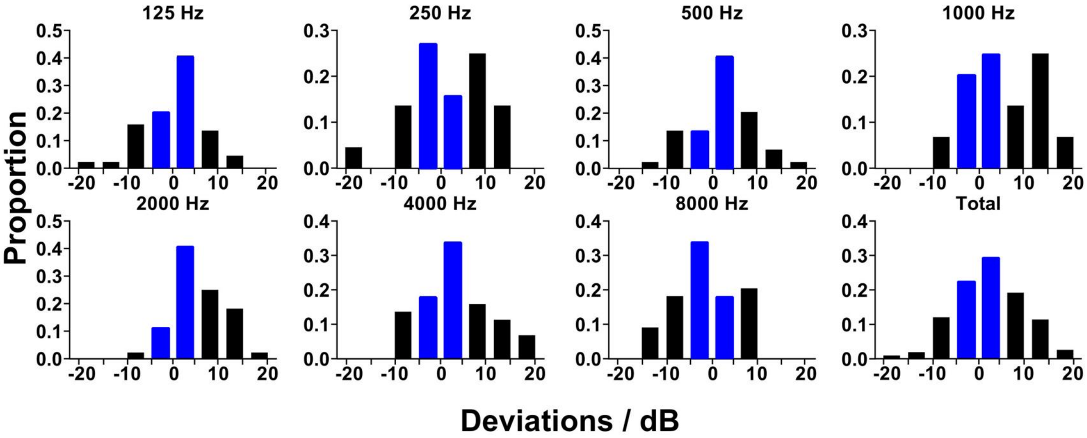

Figure 4. Distribution of the deviations between thresholds of the baseline and automated PTA with ANC and 40-pink collapsed across ears. The blue bars highlight the ideal interval of the deviations (within 5 dB). The first seven panels show the deviations for each frequency. The last panel shows deviations summed across all frequencies.

automated PTA with ANC-off/on in quiet, ANC-off/on in 40-pink, ANC-off/on in 55-pink, ANC-on in 55-babble, and manual PTA in quiet. The results showed significant effects of condition ($F[7,301] = 61.27$, $p < 0.001$) and frequency ($F[6,258] = 22.08$, $p < 0.001$). Significant interaction effect of condition × frequency ($F[42,1806] = 23.368$, $p < 0.001$) was observed. The interaction effects might be caused by the fact that ANC was more effective at low frequencies. The simple effect and post-hoc pairwise comparisons with the Bonferroni corrections are shown in the following sections.

Accuracy of automated PTA using ANC compared with the baseline

This section further evaluates the accuracy of automated PTA with ANC in noisy environments (automated PTA with ANC-on in quiet, ANC-on in 40-pink, ANC-on in 55-pink, ANC-on in 55-babble). The outcomes of manual PTA with TDH-39 earphones conducted in quiet conditions serve as the baseline values in this section.

The difference among the conditions of PTA is of interest. Post-hoc pairwise comparisons with the Bonferroni corrections were then conducted to further explore the specific group differences between the conditions. For simple effect, there were no significant differences between the baseline and ANC-off in quiet (difference, diff. = 0.23 dB, $p > 0.999$) and ANC-on with 40-pink (diff. = 1.58 dB, $p = 0.62$). There were significant differences between the baseline and ANC-on with 55-pink (diff. = 6.95 dB, $p < 0.001$) and ANC-on with 55-babble (diff. = 4.79 dB, $p < 0.001$).

Furthermore, the detailed post-hoc pair-wise comparisons of different conditions (threshold differences between automated PTA in noise and manual PTA in quiet) are reported in Table 2. The positive values of the differences represent that automated PTA obtained higher thresholds. In summary, absolute differences between the thresholds of baseline and the conditions of ANC-off quiet and ANC-on with 40-pink, 55-pink, and 55-babble across all frequencies and both ears were 5.2, 5.4, 7.3, and 9.3 dB, respectively.

Table 2. Average signed (Signed) and absolute differences of hearing thresholds between the baseline and four noise conditions using ANC automated PTA, along with standard deviation (Std.) of the signed difference.

		Frequency/Hz						
Condition		125	250	500	1000	2000	4000	8000
ANC-off quiet	Signed	4.5*	1.7	−0.6	−0.2	1.2	−2.5	−2.5
	Std.	6.6	6.5	5.2	6.4	4.8	6.1	6.8
	Absolute	6.4	5.7	4.0	5.3	3.7	5.5	6.0
ANC-on 40-pink	Signed	−0.6	0.6	1.3	4.7*	3.2*	3.0	−1.2
	Std.	5.8	6.7	6.0	6.8	5.0	7.1	6.2
	Absolute	4.4	5.7	4.8	6.8	4.5	6.2	5.3
ANC-on 55-pink	Signed	2.5	4.1	5.2*	10.7*	8.4*	12.5*	5.3*
	Std.	8.9	8.8	9.5	8.8	7.1	9.1	9.5
	Absolute	6.2	7.6	7.7	11.8	9.2	13.6	8.9
ANC-on 55-babble	Signed	1.0	4.2*	6.2*	7.2*	5.3*	9.3*	0.3
	Std.	6.4	8.1	8.6	7.3	5.1	7.2	7.0
	Absolute	5.2	7.6	8.0	8.6	6.0	10.0	5.7

The positive values represent higher thresholds. “Absolute” means the average absolute difference. “*” indicates statistical significance ($p < = 0.05$).

For 40-pink (the second part of Table 2), pair-wise comparisons showed significant differences for 1000 and 2000 Hz. Compared with the first part of Table 2 (without ANC in quiet), the absolute difference increased by about 1 dB, but the signed difference increased (higher thresholds than the baseline) at 1000 to 4000 Hz and decreased at 125 Hz obviously, which showed that both ANC and noise have an apparent effect at these three frequencies.

For 55-pink (third part of Table 2), the largest deviations were at 1000 and 4000 Hz, being more than 10 dB. 55-pink showed a bigger standard deviation than 40-pink, which suggests greater individual variations. The results of 55-babble (the fourth part of Table 2) were generally greater than those of 40-pink but smaller than those of 55-pink.

Figure 4 shows histograms of deviations between the baseline and ANC automated PTA with 40-pink. According to the aforementioned findings, automated PTA measurement could obtain relatively reliable hearing levels with the help of ANC in a 40-pink condition. In general, the thresholds measured by ANC-on automated PTA under 40-pink were slightly higher than the baseline. For all frequencies, the percentage of absolute deviations below 5 and 10 dB was 51.6% and 82.8%, respectively. The deviations primarily cluster within 0 to 5 dB, except for results at 250 and 1000 Hz.

Comparisons among automated PTAs

In the following sections, the differences between the seven groups of automated PTA (ANC-on/off × quiet/40-pink/55-pink and ANC-on with 55-babble) were examined.

Table 3. The differences between automated PTA with ANC on and off for each ambient noise collapsed across both ears.

		Frequency/Hz			
Condition		125	250	500	1000
Quiet	Sign	−5.4*	−1.3*	1.6*	2.6*
	Std.	4.3	2.3	2.8	3.7
	Absolute	5.5	1.8	2.2	3.7
40-pink	Sign	−9.0*	−4.6*	−0.6	1.9*
	Std.	4.3	3.3	2.0	2.7
	Absolute	9.1	4.6	1.3	2.5
55-pink	Sign	−12.9*	−9.8*	−3.9*	1.0
	Std.	9.9	8.2	7.5	4.5
	Absolute	14.5	11.4	6.9	3.4

The negative values represent lower thresholds for ANC-on conditions than those for ANC-off. "*" indicates statistical significance ($p < = 0.05$).

Table 4. The differences between automated PTA with ANC-on under different noise conditions and automated PTA with ANC-on in a quiet environment.

		Frequency/Hz						
Condition		125	250	500	1000	2000	4000	8000
40-pink	Signed Std.	0.3	0.2	0.4	2.2*	1.6*	5.3*	0.7
		3.1	2.5	2.2	3.2	2.8	3.8	3.1
	Absolute	2.4	1.5	1.5	2.6	2.3	5.3	2.5
55-pink	Signed	3.4*	3.6*	4.2*	8.2*	6.8*	14.8*	7.2*
	Std.	6.6	7.2	7.5	5.7	5.2	6.2	5.6
	Absolute	4.3	4.5	4.7	8.2	6.9	15.1	7.6
55-babble	Signed	1.9	3.8*	5.3*	4.7*	3.8*	11.7*	2.2*
	Std.	4.1	5.3	6.0	3.6	3.0	4.2	2.4
	Absolute	3.1	4.0	5.3	4.7	4.0	11.6	2.5

The positive values represent higher thresholds than those measured using automated PTA with ANC in a quiet environment. "*" indicates statistical significance ($p < = 0.05$).

The following two sections further analyse the effect of ANC by excluding different biases: the first section compared thresholds of ANC on and off to investigate the effect of ANC on measurement; and the second section set automated PTA with ANC-on in a quiet environment as a baseline to exclude the influence of output level change imported by ANC. Additionally, the measurement which excludes the bias between manual and automated PTA was analysed in *Supplemental Material.*

Effect of ANC on automated PTA measurement

The pairwise comparison of results first focused on the differences between thresholds measured by automated PTA with ANC-on and ANC-off for various noise levels. For simple effect, there was no significant difference between ANC-on and off in quiet (signed diff. = 0.18, $p > 0.999$). There were significant differences for 40-pink (signed diff. = 1.59, $p < 0.001$) and 55-pink (signed diff. = 3.52, $p < 0.001$).

Table 3 shows the detailed results of post-hoc pair-wise comparisons. Since ANC predominantly reduces noise at frequencies below 1000 Hz, higher frequencies were excluded from Table 3 (all p-values for these frequencies were ≥ 0.98 in multiple comparison tests, and deviations were less than 1 dB).

Thresholds at 125 and 250 Hz decreased across all noise conditions with ANC-on, as shown in Table 3(negative sign values). These differences between ANC on and off can be attributed to a combination of two factors: the attenuation of background noise and the amplification of output levels resulting from the ANC function. ANC decreased output levels slightly at frequencies at 500 and 1000 Hz (see the Quiet condition in Table 3). When increasing the noise level, the differences between ANC on and off became larger, indicating a slight attenuation effect.

Effects of noise on accuracy of automated PTA

The analysis in this section excludes the effects of output level changes and evaluates the impact of noise on automated PTA accuracy. This was accomplished by comparing the thresholds of ANC-on in a quiet environment with those of ANC-on under various noise conditions (40-pink, 55-pink, and 55-babble).

For all frequencies, the percentage of absolute difference between automated PTA with 40-pink (ANC-on) and in a quiet environment (ANC-on) below 5 and 10 dB was 79.9% and 98.1%, respectively.

A detailed post-hoc comparison of conditions is shown in Table 4. The results show that the noise led to higher thresholds than those measured in a quiet environment, even for 40-pink, though the differences were small.

The results for 40-pink (the first part of Table 4) were small for both the average signed differences and standard deviations, which implies reasonably accurate hearing threshold measurement with the 40-pink condition. The post-hoc comparison illustrates significant differences at 1000, 2000, and 4000 Hz. The results for 4000 Hz were affected most by the noise among all the frequencies for all the noise conditions.

The values in the second part of Table 4 were generally larger than those in the first part. The difference between quiet and 55-pink was only 3.4 dB at 125 Hz. However, for frequencies at or above 1000 Hz, the difference exceeded 5 dB. The earbuds are less effective in mitigating the impact of high-frequency noise at elevated noise levels.

In summary, the noise interference on the accuracy of automated PTA with the earbuds at different frequencies can be ranked from highest to lowest as follows: 4000, 1000, 8000, 2000, 500, 250, and 125 Hz. ANC can enhance the precision of PTA measurements in noise conditions at low frequencies.

Additionally, the third part of Table 4 shows the results of 55-babble. The babble noise had a smaller impact (and less significant difference) on accuracy than pink noise for frequencies higher than or equal to 1000 Hz.

Discussion

Accuracy of the system

When comparing hearing thresholds using automated PTA with ANC under 40 dB pink noise to manual PTA in quiet, average deviations were 1.6 (signed) and 5.4 dB (absolute), with 52% of deviations $\leq$ 5 dB and 83% $\leq$ 10 dB. Earlier research using automated PTA in a quiet booth (Guo et al. 2021) showed similar accuracy, with average deviations of 3.1 (signed) and 6.7 dB (absolute), and 53% and 78% of deviations within 5 and 10 dB, respectively. Despite different testing environments (noisy vs. quiet), both studies showed comparable accuracy.

Most previous studies evaluating the accuracy of PTA with ANC utilised standard audiometric earphones rather than earbuds, and some of them obtained better results than this study. Bromwich et al. (2008) found that ANC audiometry at 30 dB noise level matched thresholds obtained in double-walled booths, with deviations increasing to about 10 dB at 40 dB noise. Saliba et al. (2017) assessed mobile audiometry applications in 50 dB white noise with circumaural ANC headphones and insert earphones for playback, finding deviations from baseline of $\leq$ 5 dB in 77% and 80% and $\leq$ 10 dB in 87% and 91% of cases for two applications, respectively. This superior accuracy can be attributed to the higher noise attenuation capabilities of their devices and the use of standard insert audiometric headphones. Sun et al. (2019) reported that average shifts in thresholds for noise levels below 45 dB were less than 5 dB, with 83% of the shifts being $\leq$ 5 dB. The shifts were largest at 1000 Hz, whereas in our study, the frequency most affected by noise was 4000 Hz, followed by 1000 Hz. These differences may be attributed to variations in the passive attenuation of different earphones and different spectrum features of noise. For this study with 40 dBA of pink noise, the above high accuracy was only possible when the baseline was changed to automated PTA with ANC-off in a quiet environment (64% and 94% of differences were $\leq$ 5 and 10 dB, respectively) or automated PTA with ANC-on in a quiet environment (80% and 98% of differences were $\leq$ 5 and 10 dB, respectively).

There are also some studies that used non-standard ANC earphones. For example, Lo and McPherson (2013) used Sennheiser PXC450, and Wu et al. (2014) used Bose QuietComfort 15. However, their results cannot be directly compared with ours because they only report the referral rate instead of the detailed accuracy of the ANC audiometer.

The measurement errors in the present study primarily arose from three factors: the limitation of ANC in reducing noise, the bias between automated and manual PTA, and the output level change produced by ANC. The average absolute deviations between automated PTA with ANC and manual PTA were 5.4 and 9.3 dB for 40-pink and 55-pink, respectively. Excluding biases between automated and manual PTA (automated PTA without ANC in a quiet environment as the baseline), absolute deviations were reduced to 3.6 dB for 40-pink and 8.3 dB for 55-pink noise. Further excluding the impact of output level changes, deviations decreased to 2.6 and 7.3 dB for 40-pink and 55-pink, respectively. Deviations at 40 dB pink noise generally remained within ± 5 dB, though higher deviations were noted at 1000 and 4000 Hz, possibly due to low ANC performance and the high-energy distribution of spatially de-correlated pink noise at these frequencies.

Applicable scenarios

Although the results show that the current system could obtain reasonably accurate hearing thresholds in the 40-pink noise condition, this may not be sufficient for a real-world in-home PTA scenario, as suggested by Saliba et al. (2017). Higher levels of noise led to non-negligible deterioration in the accuracy of the PTA when using TWS earbuds with ANC. Therefore, the present system still requires a relatively quiet environment, especially for mid- and high-frequency noise. Future studies aiming to enhance ANC audiometry may need to explore the use of commercial ANC earphones with sufficient attenuation at both low and high frequencies (ANSI/ASA S3.1 2018). This will gradually be met with the iteration update of the earphone's shape and materials, as well as the optimisation of noise reduction algorithms. The electroacoustic performance of the earphone also changes during the update, consequently necessitating a new calibration and verification experiment. Further standard verification routines specifically designed for commercial earphones will also help advance the field.

Limitations and further work

The present study had several limitations. Noise levels between 40 and 55 dBA were not evaluated, leaving the exact upper noise limit for conducting PTA undefined. The tests were conducted in a sound booth with steady noise to control the environment, which does not fully represent real-world environments. In addition, the number of participants was relatively small. The changed output levels caused by ANC were considered an error introduced by ANC in the present study. The calibration process did not follow the standard due to the mismatch of the acoustic coupler.

Therefore, future research should focus on conducting more comprehensive and detailed experiments within controlled sound booth environments to define tolerable noise levels. Larger-scale studies conducted in real-life daily environments, adhering to the tolerable noise levels, and potentially involving collaboration with healthcare facilities, could provide further insights into the practical applicability of ANC-based PTA systems.

As TWS earbuds continue to evolve rapidly, future extensions of this research may involve the incorporation of an acoustic coupler or standard ear simulator designed for earbuds. This would facilitate the calibration of earbuds, as demonstrated in previous studies (Sun et al. 2019; Wu et al. 2014). What's more, the fitting between the earbuds and the ear canal entrance also affects the pure tone threshold due to sound leakage, especially at low frequencies. The reliability of acoustic and subjective hearing measurement, hence, will be degraded. Therefore, the effect of fitting needs to be further quantitatively evaluated in future studies to quantify its effect size.

Conclusions

This study explored the possibility and accuracy of automated PTA using commercial ANC TWS earbuds in various noisy environments. Results of both objective and behavioural experiments suggest that this technology has the potential to be employed for self-hearing screening or monitoring when the levels of pink noise are around or below 40 dBA. In the presence of 40 dBA pink noise conditions, the average signed and absolute differences between manual and automated PTA measurements were 1.6 and 5.4 dB, respectively. However, the error of threshold measurement at 1000 and 4000 Hz was unacceptable (larger than 10 dB) when the ambient noise level was increased to 55 dBA (average signed and absolute difference were 7.0 and 9.3 dB, respectively). Additionally, the ANC function mainly reduced ambient noise at 125 and 250 Hz. It is important to emphasise the significance of addressing medium and high frequency (1000 Hz and higher) noise when considering TWS earbuds. Additionally, it should be noted that the output levels can be affected by the ANC function when signals are played directly through earphones equipped with ANC.

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