Evaluating the hearing screening effectiveness of active noise cancellation technology among young adults: A pilot study

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Abstract

Background: The population of young adults who are hearing impaired increases yearly, and a device that enables convenient hearing screening could help monitor their hearing. However, background noise is a critical issue that limits the capabilities of such a device. Therefore, this study evaluated the effectiveness of commercial active noise cancellation (ANC) headphones for hearing screening applications in the presence of background noise. In particular, six confounders were used for a comprehensive evaluation.

Methods: We enrolled 12 young adults (a total of 23 ears with normal hearing) to participate in this study. A cross-sectional self-controlled study was conducted to explore the effectiveness of hearing screening in the presence of background noise, with a total of 240 test conditions (=3 ANC models × 2 ANC function statuses × 2 noise types × 5 noise levels × 4 frequencies) for each test ear. Subsequently, a linear regression model was used to prove the effectiveness of ANC headphones for hearing screening applications in the presence of background noise with six confounders.

Results: The experimental results showed that, on average, the ANC function of headphones can improve the effectiveness of hearing screening tasks in the presence of background noise. Specifically, the statistical analysis showed that the ANC function enabled a significant 10% improvement ($p < 0.001$) compared with no ANC function.

Conclusion: This study confirmed the effectiveness of ANC headphones for young adult hearing screening applications in the presence of background noise. Furthermore, the statistical results confirmed that as confounding variables, noise type, noise level, hearing screening frequency, ANC headphone model, and sex all affect the effectiveness of the ANC function. These findings suggest that ANC is a potential means of helping users obtain high-accuracy hearing screening results in the presence of background noise. Moreover, we present possible directions of development for ANC headphones in future studies.

Keywords: Active noise cancellation; Background noise Hearing screening

1. INTRODUCTION

Hearing is a critical function for human communication, and when hearing loss occurs, it directly affects the quality of life. A previous study showed that the global prevalence of hearing loss accounted for one in five people in 2019, and a 56.1% increase is expected by 2050 along with a corresponding increase in hearing-impairment-associated disability.[1–3] These numbers indicate that globally, the proportion of hearing-impaired people increases every year, and more research resources focused on this population are needed.

There are many factors (e.g., noise-induced hearing loss, ototoxicity, and idiopathic sudden sensorineural hearing loss) that cause hearing loss in patients;[4–6] meanwhile, a World Health Organization report has shown that over 1 billion young adults are at risk of permanent hearing loss due to unsafe listening practices. Therefore, a device that could allow hearing screening to be performed at any time would be valuable because of its ability to effectively support early treatment.[7–11] Classical hearing screening approaches, such as pure tone audiometry, are currently most often used to diagnose the hearing ability of

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patients. However, with such methods, it is often difficult to provide patients with a friendly personal hearing test environment because the available clinical staff and professional equipment may be insufficient. To alleviate this issue, a simple and low-threshold hearing screening device is one potential solution. For example, a portable hearing screening platform[12,13] (or popular mobile hearing test vans,[14] etc.) could be an alternative approach to accelerate service provision without delay.[13,15]

In the specifications for a suitable test environment established by the American National Standards Institute,[16] the ambient noise level is the major consideration for hearing screening tasks. Previous studies have shown that ambient noise affects the accuracy of hearing screening applications; in particular, a large discrepancy may arise in the low-frequency domain in the presence of background noise.[17] For example, Lankford et al.[14] investigated the ambient noise level from 13 audiometric test booths in 12 industrial mobile test vans. Although these mobile units met the maximum permissible ambient noise levels (MPANLs) specified by the Occupational Safety and Health Administration (1983), only five of the 13 booths complied with the MPANLs established by the American National Standard Institute (ANSI) for audiometric booths at all audiometric frequencies. These results highlight the difficulty of meeting ANSI MPANLs at low frequencies, which is a common problem faced by many mobile test vans and trailers. More recently, Jayawardena et al.[13] reviewed eight mobile audiometric platforms, none of which had ambient noise attenuation functions. The experimental results showed false-positive referrals under conditions of high background noise.[12] In addition, the current standard audiometry approaches require complicated processes and relatively time-consuming hearing screening tasks, which directly hinder the popularization of hearing screening. Therefore, in recent years, many methods based on mobile phone applications[11,12,17,18] have been extensively studied to alleviate the above problem.

With the advancement and increasing popularity of mobile phone devices, application-based systems have been developed for hearing surveys.[11,19,20] Recently, many researchers have studied the accuracy and reliability of mobile phone-based hearing screening tools. For example, Barczik and Serpanos[21] validated the accuracy of two smartphone-based hearing test applications compared with conventional audiometry across frequencies and earphones. Calibration errors of the transducers, participant ability, and background noise might all be factors influencing the validity of self-administered tests. The results of that study indicated that application-based hearing screening tools could exhibit high correlations with standard hearing screening procedures under quiet conditions. However, there were larger discrepancies in repeated tests in the low-frequency domain in the presence of background noise.[17] In other words, background noise will directly affect the accuracy of mobile phone-based hearing screening tools, thereby reducing their popularity. To overcome this issue, noise reduction technology is critical. Currently, many approaches can be used to overcome excessive background noise to provide a quiet hearing screening environment for users. For example, Berger[22] measured the attenuation performance of a dual protector (an earplug plus an earmuff) in hearing threshold tests conducted under noisy conditions. The experimental results showed that the dual protector provided at least 5 dB better attenuation than either the earplug or the earmuff alone. Overall, the noise reduction performance of the combined hearing protector varied from 0 to 15 dB, depending on the individual. However, although such passive noise reduction methods provide some benefit in helping obtain more accurate measurement results for patients under noisy conditions, there is still much room for improvement.[23]

In contrast to the passive approach, the active noise cancellation (ANC) algorithm is another well-known technology for mitigating the disturbance to users caused by background noise.[24–26] The ANC mechanism is based on the superposition of the primary noise signal with an 'anti-noise' signal of equal amplitude and opposite phase generated by the ANC algorithm, causing the two signals to cancel each other out.[24] This active method is superior to passive methods in terms of targeted design, allowing better control of the reduction of low-frequency noise that negatively affects device performance.[27] More specifically, every pair of ANC headphones contains certain key elements, including a reference microphone, a computer chip, a controller, a speaker, and an error-checking microphone. The principle of ANC relies on the estimation of the characteristics of the background noise as calculated by the algorithm. The controller generates opposite-phase sound waves to offset the incoming background noise to achieve noise reduction. Currently, ANC technology is widely used in various commercial headphones, such as Apple AirPods Pro, the Bose QuietComfort 35, and the Sony WF-1000XM3, and studies have investigated the capacity of such ANC headphones to alleviate the effects of background noise in hearing screening applications.[28–31] On average, the results show that the accuracy of hearing screening is improved when the ANC function of the headphones is activated under 30- to 40-dB background noise conditions compared with the case in which the ANC function is deactivated. However, to date, there has been no further investigation of various factors encountered in real application scenarios, such as different noise types (i.e., stationary and nonstationary), noise levels, and hardware settings of ANC headphones. Note that these factors may decrease the ability of ANC headphones to directly suppress background noise for hearing screening applications. For example, Bromwich et al.[28] addressed the utility of active noise reduction (ANR) headphones in audiometric tests in the presence of 30- and 40-dB narrowband noise. The ANR audiometry results confirmed lesser threshold shifts under 30- or 40-dB noise, indicating the advantage of ANC headphones in limiting the hearing threshold shift under background noise conditions. Therefore, detailed studies considering factors encountered in real application scenarios (e.g., various noise types and noise levels) are needed on this topic.

To address the above considerations, this study investigated the hearing screening accuracy achievable with commercial ANC headphones in the presence of confounding factors related to noise types, noise levels, hearing screening frequencies, ANC headphone models, sex, and age. Meanwhile, we further analyzed the differences in hearing screening accuracy with the ANC function turned on and off as affected by each confounder. Thus, we explored whether commercial ANC headphones, when used in combination with a self-administered app system, can effectively reduce environmental noise to achieve suitable performance in real hearing screening tasks.

2. METHODS

We followed the checklist of reporting guidelines for cross-sectional studies of the Strengthening the Reporting of Observational Studies in Epidemiology statement, as presented by the Enhancing the QUAlity and Transparency Of health Research network.[32]

2.1. Participants

For this study, we enrolled 12 young individuals (the mean age of these subjects was 23.3 ± 1.7 years [22–27]) to participate in a study evaluating the effectiveness of commercial ANC technology in a variety of noisy test conditions. The inclusion criteria were as follows: (1) audiometric hearing threshold lower than 25 dB hearing level (HL) across the frequency range 250 to 8 kHz; (2) no history of ear disease; and (3) subjects were capable of understanding instructions. Each participant completed a consent form. A total of 23 ears (11 right ears and 12 left ears) were included in the experiment. The 0.5-4 kHz pure tone average of all 23 ears, the 11 right ears, and the 12 left ears was 7.2 ± 3.4, 7.3 ± 3.1, and 7.2 ± 3.8 dB HL, respectively. The mean hearing level and standard deviation at 250 to 8 kHz from the 23 ears are displayed in Fig. 1. Note that the hearing thresholds of these subjects were evaluated in reference to the standard stages by an experienced audiologist using the GSI AudioStar Pro audiometer with the RadioEar DD45 audiometric headset to test the hearing threshold of each subject at Taipei Veterans General Hospital. The study protocol was approved by the Research Ethics Review Committee (2020-12-013CC) of Taipei Veterans General Hospital.

2.2. Experimental design

A cross-sectional self-controlled experimental design was used.[33] The main purpose of this study was to analyze the effectiveness of commercial ANC technology for hearing screening under several noisy test conditions. The subjects were first evaluated using standard hearing test procedures to confirm their hearing thresholds. Next, we developed a playback application using Android Studio software that could generate hearing screening pure tones intended to be played over commercial headphones. To study the capabilities of conventional ANC headset devices for hearing screening applications under several background noise conditions, three commercial headset devices were used in this study (AirPods Pro, Bose QC35, and EarPods). The setup method is shown in Fig. 2 AirPods Pro and Bose QC35 contain ANC technology. Among ANC headphones that are worn, we classified AirPods Pro and Bose QC35 as earbuds (in-ear) and circumaural ANC models, respectively. A combined ANC model, which consisted of EarPods covered by Bose QC35 ANC headphone, was tested to determine the effect of the combination on noise reduction. In our experiment flow, participants were first assigned one of the three possible ANC models (in-ear, circumaural, or combined). We then determined ANC function status, noise type, and hearing screening frequency in sequence. CLIO electrical and acoustical measurements software (Audiomatica Srl, Florence, Italy) was used to analyze the acoustics recorded in the KEMAR head and torso simulator (GRAS Sound & Vibration, Denmark) and to deliver the stimulus in the experiment. The output of the commercial headphones at hearing screening frequencies of 0.5, 1, 2, and 4 kHz at 25 dB HL was calibrated in accordance with the reference equivalent threshold sound pressure level specifications of ANSI S3.6 (2004).[34] To ensure the quality of the devices used in this study, we played 25 dB HL pure tone signals three times at each of the four frequencies, and the detailed results (mean and standard

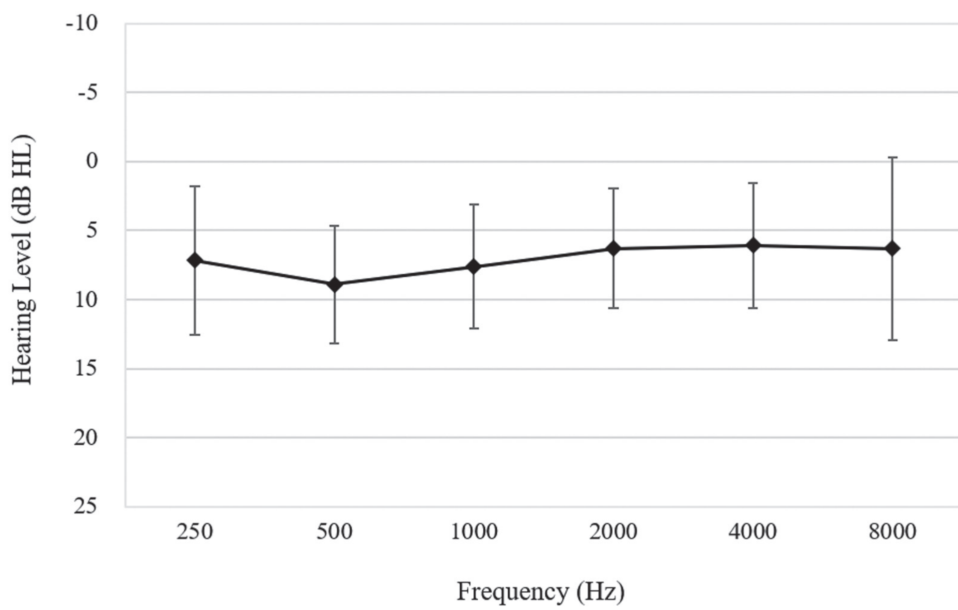

Fig. 1 The mean hearing level and standard deviation at 250 Hz to 8 kHz of 23 ears.

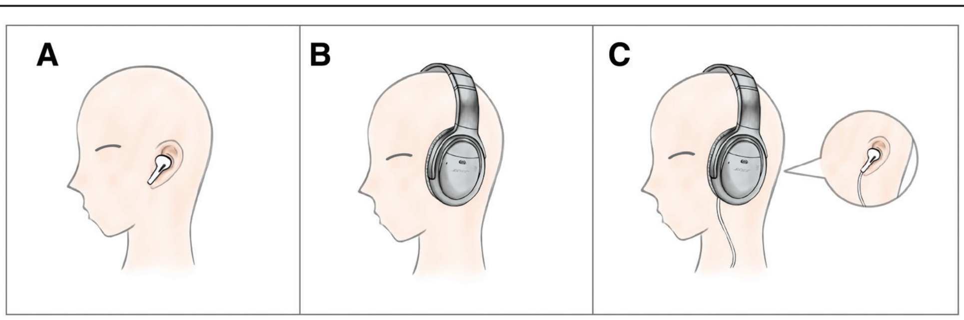

Fig. 2 The three configurations of the ANC headphones: (A) AirPods Pro alone, (B) Bose QC35 alone, and (C) combined model (EarPods plus Bose QC35).

deviation) can be seen in Table 1. Note that the low variance in the three individual electric–acoustic measurements indicates good device quality.

Next, two well-known types of background noise (i.e., pink noise and cafeteria babble noise) were used to evaluate the benefits of commercial ANC technology for hearing screening tasks. Note that pink noise and cafeteria babble noise represent stationary and nonstationary noise, respectively, and each type of noise was played at levels of 50, 60, 70, 80, and 90 decibels sound pressure level (dB SPL) to simulate different background noise levels, using the same four typical pure tone frequencies (0.5, 1, 2, and 4 kHz). The following experimental parameters were varied: (1) the ANC headphone model, (2) the status of the ANC function (switched on or off), (3) the background noise type and level, and (4) the hearing screening frequency, corresponding to ①, ②, ③, and ④ in Fig. 3. The participants sat in a sound booth, and the loudspeaker was located at a 45° azimuth. For each participant, we first used the standard hearing test approach to confirm the hearing threshold. Next, background noise was played by the speaker to stimulate a noisy hearing screening scenario. First, background noise was played at 50 dB SPL to test the benefits of using ANC headphone models first. Next, the background noise was increased in increments of 10 dB until the maximum background noise of 90 dB SPL was reached.

Table 1

The Calibrated Outputs of the Commerical Headphones at 25 dB HL for 0.5–4 kHz

	Calibrated Output			
	0.5 kHz	1 kHz	2 kHz	4 kHz
AirPods Pro	34.34 ± 0.23	30.43 ± 0.01	36.50 ± 0.09	40.21 ± 0.22
Bose QC 35	36.12 ± 0.03	30.28 ± 0.17	29.60 ± 0.20	34.53 ± 0.02
EarPods	34.60 ± 0.12	30.20 ± 0.12	36.44 ± 0.39	40.31 ± 0.14

Calibrated output: mean ± standard deviation in dB SPL.

A total of 240 test conditions (=3 ANC models × 2 ANC function statuses × 2 noise types × 5 noise levels × 4 frequencies) were applied for each ear. For each test condition, the pure tone signal was played three times with a 1- to 2-second duration and an irregular interstimulus interval. A minimum of two responses out of three trials defined a passing result. The pass rate (PR) was calculated as the proportion of the number of ears that passed a given test condition, as illustrated in formula (1).

$$PR = \frac{P}{T} \qquad (1)$$

where P denotes the number of ears that passed the hearing screening and T denotes the total number of ears with normal hearing in this study. The PR for each test condition was calculated and recorded in an Excel sheet (see ⑤ in Fig. 3). To evaluate the hearing screening accuracy with ANC technology, the number of measurements that passed each test condition with the ANC function switched on (ANC-ON) was compared with the audiometric results from the standard audiometric sound-treated booth. Note that the accuracy was defined as the ratio of the number of measurements that passed the test conditions to the total measurements performed under the same test conditions, as illustrated in formula (2).

$$\text{Accuracy}\ (\%) = \frac{PR_{ANC}}{T} \times 100\ \% \qquad (2)$$

where PR_{ANC} denotes the measurement results obtained with ANC headphones in the presence of background noise. Finally, the differences in accuracy among hearing screening performed with ANC technology in various scenarios were analyzed to explore the capacity of ANC technology (see ⑥ in Fig. 3).

For statistical analysis, the characteristics of the study subjects are displayed in Table 2. We removed missing data due to time issues to complete the experiment. A total of 5420 measurements for each variable, including the ANC function status,

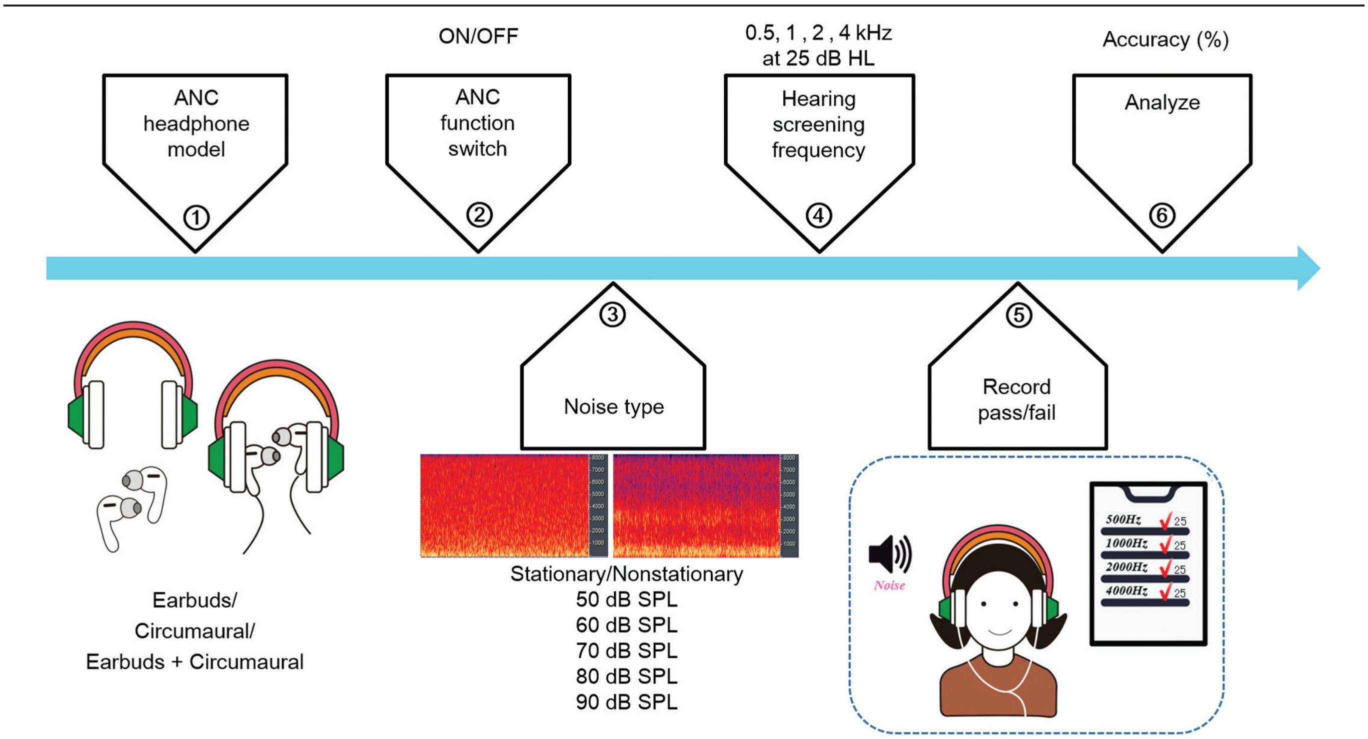

Fig. 3 The experimental flow diagram of this study.

Table 2

Characteristics of the Study Subjects

Variable	n (%)/mean ± SD (min, max)
Age[a], years (mean ± SD)	23.3 ± 1.7 (22, 27)
Sex[a]	
Male, n (%)	8 (67%)
Female, n (%)	4 (33%)
Ear sample[b]	
Right ear	11 (48%)
Left ear	12 (52%)
Measurement of five variables[c]	
ANC function status	
ANC-ON	2710 (50%)
ANC-OFF	2710 (50%)
Noise type	
Stationary	2710 (50%)
Nonstationary	2710 (50%)
Noise level	
50 dB SPL	1084 (20%)
60 dB SPL	1084 (20%)
70 dB SPL	1084 (20%)
80 dB SPL	1084 (20%)
90 dB SPL	1084 (20%)
Hearing screening frequency	
0.5 kHz	1360 (25.1%)
1 kHz	1360 (25.1%)
2 kHz	1340 (24.7%)[d]
4 kHz	1360 (25.1%)
ANC headphone model	
Earbuds	1840 (34%)
Circumaural	1740 (32%)[d]
Combined	1840 (34%)

ANC=active noise cancellation; ANC-OFF=ANC function switched off; ANC-ON=ANC function switched on; DB SPL=decibels sound pressure level; SD=standard deviation.
[a]Age and sex samples, n = 12.
[b]Ear samples, n = 23.
[c]For the five variables "ANC function status", "noise type", "noise level", "hearing screening frequency", and "ANC headphone model", the number of measurements, n = 5420.
[d]The number of measurements after the removal of missing data.

noise type, noise level, hearing screening frequency, and ANC headphone model, were entered into the data analysis. Linear regression analysis was performed using IBM SPSS Statistics version 25 (IBM Corp., Armonk, NY, USA). The linear regression model was used to analyze the significance of the differences in accuracy of hearing screenings conducted in the presence of noise with the ANC function turned on, considering six confounders: noise type, noise level, hearing screening frequency, ANC headphone model, sex, and age. A two-sided p value at $\alpha < 0.05$ was considered significant.

3. RESULTS

Three commercial headphone models were used in this study, and the results of electric–acoustic measurement showed that these devices provided high output quality. For the AirPods Pro ANC headphone, the electric–acoustic output levels were 34.34 ± 0.23, 30.43 ± 0.01, 36.50 ± 0.09, and 40.21 ± 0.22 dB SPL at frequencies of 0.5, 1, 2, and 4 kHz, respectively; for the Bose QC35 ANC headphone, the electric–acoustic output levels were 36.12 ± 0.03, 30.28 ± 0.17, 29.60 ± 0.20, and 34.53 ± 0.02 dB SPL, respectively; and for the EarPods headphone, the calibrated outputs were 34.60 ± 0.12, 30.20 ± 0.12, 36.44 ± 0.39, and 40.31 ± 0.14 dB SPL, respectively. These results indicate that the standard deviations of the calibrated outputs of these commercial headphones around the mean value of each device at each frequency were <1 dB; hence, the devices used met the ANSI S3.6-2004 specifications for audiometers.

Next, the accuracy was compared between the ANC-ON condition and the condition with the ANC function switched off (ANC-OFF) based on the PR under each test condition to explore the effectiveness of ANC technology. Six confounding variables were considered in this study: noise type, noise level, hearing screening frequency, ANC headphone model, sex, and age. In our experiment, the number of measurements was calculated using the number of ears × the number of test conditions at a dimension of the considered confounding factors. Table 2 shows that five variables (ANC function status, noise type, noise level, hearing screening frequency, and ANC headphone model) were included in the measurement. For example, if one hearing screening frequency and one ANC headphone model were considered, the test condition would be 20 (= 1 ANC model × 2 ANC function statuses × 2 noise types × 5 noise levels × 1 frequency). The number of measurements would be 460 (23 ears × 20 test conditions). The total number of measurements for one ANC headphone model would be 1840 (460 measurements × 4 frequencies). Missing data for the circumaural ANC model resulted in 22 ears at 0.5, 1, and 4 kHz and 21 ears at 2 kHz. Therefore, regarding each value of the confounding factor hearing screening frequency (0.5, 1, 2, and 4 kHz), the number of measurements for 0.5, 1, and 4 kHz was 1360 (23 ear samples × 20 test conditions + 22 ear samples × 20 test conditions + 23 ear samples × 20 test conditions for earbuds, circumaural, and combined ANC models), and the number of measurements for 2 kHz was 1340 (23 ear samples × 20 test conditions + 21 ear samples × 20 test conditions + 23 ear samples × 20 test conditions for earbuds, circumaural, and combined ANC models). The total number of measurements was calculated to be 5420 (=1360 + 1360 + 1340 + 1360 for 0.5 to 4 kHz). Table 3 shows the performance of the measurement of the five variables without

Table 3

Hearing Screening Passing Rates with ANC Headphones (ANC-ON vs. ANC-OFF) in the Background Noise Conditions, Without Controlling for Confounders

	The Number of Passing Measurements/Total Number of Measurements (%)	
Variable	ANC-ON	ANC-OFF
ANC function status	2083/2710 (76.9)	1813/2710 (66.9)
Noise type		
Stationary	1076/2710 (79.4)	938/2710 (69.2)
Nonstationary	1007/2710 (74.3)	875/2710 (64.6)
Noise level		
50 dB SPL	542/542 (100.0)	542/542 (100.0)
60 dB SPL	538/542 (99.3)	533/542 (98.3)
70 dB SPL	510/542 (94.1)	451/542 (83.2)
80 dB SPL	354/542 (65.3)	215/542 (39.7)
90 dB SPL	139/542 (25.6)	72/542 (13.3)
Hearing screening frequency		
0.5 kHz	534/680 (78.5)	376/680 (55.3)
1 kHz	460/680 (67.6)	391/680 (57.5)
2 kHz	499/670 (74.5)[a]	474/670 (70.7)[a]
4 kHz	590/680 (86.8)	572/680 (84.1)
ANC headphone model		
Earbuds	652/920 (70.9)	535/920 (58.2)
Circumaural	676/870 (77.7)[a]	598/870 (68.7)[a]
Combined	755/920 (82.1)	680/920 (73.9)

[a]The number of measurements after the removal of missing data.
ANC=active noise cancellation; ANC-OFF=ANC function switched off; ANC-ON=ANC function switched on; DB SPL=decibels sound pressure level.

considering the interaction between confounders. For a specific variable, such as ANC function status, the number of measurements for each condition of ANC function status would be one-half of 5420 because the ANC function status contains two dimensions (ANC-ON and ANC-OFF). The passing rate was calculated as the number of passing measurements to the total number of measurements at each dimension. In our study, the number of measurements that passed the hearing screening test in the presence of noise under the ANC-OFF status was 1813; therefore, the passing rate for ANC-OFF would be 1813/2710 (66.9%) without controlling for confounders. To avoid the interaction of the passing rate results with the measurements of the variables, the linear regression model calculated a more accurate outcome after controlling for confounding effects. After consideration of the six confounding variables, the results showed that 40% of the measurements passed the hearing screening in the presence of noise under the ANC-OFF status, and a significant increase in accuracy of 10% was observed with the activation of the ANC function ($p < 0.001$); for the detailed information, see Table 4. ANC technology effectively improved hearing screening accuracy when testing under noisy conditions. The results indicate that the ANC function successfully reduces the influence of background noise, bringing the hearing screening accuracy closer to that of audiometric results derived from a standard sound-treated booth.

From our statistical results, we find that the variables adopted in this study influence the hearing screening accuracy under the ANC-ON status. We find an obvious and significant 5% reduction in the hearing screening measurement in the presence of cafeteria babble noise compared with hearing screening in the presence of pink noise ($p < 0.001$), indicating that poorer hearing screening accuracy was obtained in the presence of nonstationary noise under ANC headphones. In addition, the ANC performance decreased as the background noise level increased. More specifically, compared with the pass results for hearing screening in the presence of 90 dB SPL noise, obviously higher accuracy was observed for hearing screening under noise levels of 50, 60, 70, and 80 dB SPL ($p < 0.001$ for each comparison). The louder the noise level of the test condition, the worse the hearing screening accuracy achieved under ANC-ON. Moreover, the statistical results indicate that the ANC headphone model also affected the hearing screening accuracy under ANC-ON.

Table 4

Considering Six Confounders, the Relationship Between the Activation of the ANC Function and the Accuracy of Hearing Screening Under Noisy Conditions

Variable	Coefficient	SE	t	*p*
ANC-OFF	0.40			
ANC (ON/OFF)	0.10	0.01	12.22	0.000
Noise type (stationary/nonstationary)	0.05	0.01	5.98	0.000
Noise level (50/90)	0.81	0.01	62.49	0.000
Noise level (60/90)	0.79	0.01	61.56	0.000
Noise level (70/90)	0.69	0.01	53.69	0.000
Noise level (80/90)	0.33	0.01	25.63	0.000
Hearing screening frequency (0.5/4)	−0.19	0.01	−16.10	0.000
Hearing screening frequency (1/4)	−0.23	0.01	−19.87	0.000
Hearing screening frequency (2/4)	−0.13	0.01	−11.11	0.000
ANC headphone model (earbuds/combined)	−0.13	0.01	−13.63	0.000
ANC headphone model (circumaural/combined)	−0.05	0.01	−4.65	0.000
Sex (female/male)	0.04	0.01	3.99	0.000
Age	0.00	0.00	0.81	0.417

Noise level (dB SPL); Hearing screening frequency (kHz).

ANC=active noise cancellation; ANC-OFF=ANC function switched off; ANC-ON=ANC function switched on; SE=standard error.

Regarding the confounder of the hearing screening frequency, the hearing screening accuracies under ANC-ON at 0.5, 1, and 2 kHz were significantly poorer than those at 4 kHz. Compared with the hearing screening performance at 4 kHz, the corresponding reductions in accuracy were 19%, 23%, and 13% at 0.5, 1, and 2 kHz ($p < 0.001$ for each comparison), with the maximum drop at 1 kHz. For this application, the primary purpose of an ANC system is to attenuate low-frequency noise. The poorer accuracy at 0.5 and 2 kHz indicates that commercial ANC headphones have limited ability to process noise in relevant scenarios, especially at approximately 1 kHz.

Furthermore, it is found that when the variables were not adjusted, 73.9% (680/920) of the measurements passed the hearing screening with the combined ANC headphone model (EarPods covered with the circumaural ANC headphone) with the ANC-OFF, which increased to 82.1% (755/920) when the ANC-ON. Table 4 shows that when confounding effects are considered, the decreases in accuracy with the earbuds and circumaural ANC models compared with the combined model are 5% and 13%, respectively, both of which are statistically significant ($p < 0.001$ for each comparison). These findings show that the combined ANC headphone model offers higher hearing screening accuracy than either earbuds or circumaural ANC headphones. This might imply that isolating the signal source from the ANC system enables better accuracy when performing hearing screening in noisy scenarios. Moreover, a difference in performance is found between female and male subjects, with the accuracy being 4% higher for female subjects than male subjects ($p < 0.001$). However, this sex effect may be due to the limited number of study participants.

4. DISCUSSION

The main purpose of this study was to investigate the effectiveness of commercial ANC headphones applied for hearing screening tasks in the presence of background noise. When the experimental results (Table 4) are controlled for six confounders, on average, the accuracy is improved by 10% under ANC-ON compared to ANC-OFF. This finding indicates that commercial ANC headphones offer a suitable ability to generate anti-noise waves to cancel incoming noise and provide benefits for hearing screening tasks in the presence of background noise. In hearing screening tasks, there is a consistent hearing threshold in both natural and clinical environments under supra-aural earphones within noise-reducing enclosures.[17,31] In our study, the observed significant 10% improvement proves the effectiveness of ANC technology when applied in a self-administered hearing test. Therefore, the results imply that commercial ANC headphones provide proper noise reduction for hearing screening tasks under noisy conditions; however, there is still room for improvement in future studies, such as proposing an advanced ANC algorithm to reduce the background noise and keep the intactness of signal waveforms and the sensory pleasantness of signals.

On the other hand, other variable factors, such as background noise type, background noise level, hearing screening frequency, ANC headphone model, and sex, were treated as confounders influencing the hearing screening accuracy under the activation of the ANC function. The detailed comparisons analyzing the capabilities of commercial ANC headphones can be found in Table 4. The background noise characteristics affect the efficacy of the ANC controller. Our findings indicate poorer pass results when hearing screening is performed with an unstable background noise type (e.g., cafeteria babble noise) compared with the results under stable background noise (e.g., pink noise); meanwhile, loud background noise conditions also lead to poorer pass results than quieter noise. These results show that commercial ANC headphone technology can provide suitable efficacy for users under stable and soft background noise conditions; however, when the background noise is unstable and loud, there is still room for improvement in what can be achieved with commercial ANC headphone technology in hearing screening application tasks. More specifically, the commercial ANC headphones used in this study can preserve the specificity of hearing screening at background noise levels of 50 and 60 dB SPL,[28,30,31] but an obvious decrease in accuracy outcome is seen as the noise level increases. One of the critical reasons is that a loud background noise level distorts the pure-tone signals, thereby directly affecting the quality of the test signals, and the anti-noise waves generated by ANC technology cannot provide correct estimated signals to sufficiently reduce the influence of noise in this case.[27,35] Therefore, advanced ANC technology, such as a deep-learning-based approach, could be needed to benefit users in future studies.

The hearing screening frequency also affects the results of the hearing screening task. In this study, the 4 kHz test frequency yielded higher accuracy than any other test frequency (0.5, 1, or 2 kHz). One of the reasons is that the ANC headphone case can act as a noise attenuator to cancel high-frequency noise. Thus, even when the ANC function is turned off in the commercial ANC headphones tested here, the headphone case works as a passive noise attenuator that is effective in canceling high-frequency noise but is less successful in reducing low-frequency acoustic noise. When the ANC function is turned on, the low-frequency component of the noise is also reduced, and there is less destructive interference from noise; thus, more of the low-frequency pure tone acoustic properties are preserved under noisy conditions. The magnitudes of the reductions in PR among the four pure tones show that the reduction is greatest at 1 kHz, followed by 0.5 kHz and then 4 kHz. The reason might be that artificial noise at approximately 1 kHz is generated by the ANC system.[30]

Our statistical results also show that the ANC headphone model affects the pass results of hearing screening tasks. The combined ANC headphone model resulted in higher accuracy than the earbuds and circumaural ANC models. We speculate that the isolation of the acoustic signal source from the ANC system might help reduce the interference between signal and noise and preserve more of the signal acoustics. More specifically, in the combined ANC headphone model, two types of headphones (earbuds and circumaural headphones) were used together to help test the user's hearing. The outer circumaural headphone was dedicated to alleviating the effect of background noise by means of ANC technology. Meanwhile, the inner earbuds headphone played the pure tone signals only, without also needing to produce anti-background noise signals. Therefore, this combined ANC headphone model could provide higher accuracy than the other two models.

A sex-related difference was observed in the accuracy of hearing screening in the presence of noise under the ANC-ON status. However, the number of participants might be a weak point of the study design. We attempted to compensate for this shortcoming by performing sufficient numbers of measurements to enhance the statistical power. Ultimately, our study proves that ANC technology improves the accuracy of hearing screening in the presence of noise. The features of the noise acoustics, the hearing screening signals, the ANC headphone model and sex are confounders that also significantly influence the accuracy of hearing screening under the activation of a commercial ANC function. The acoustic loads coupled with the headphone and acoustic effects constitute the main signal processing challenges of ANC algorithms.[36] Compromises may be necessary related to the size of the loudspeaker, the energy consumption, and the capacity of the ANC system. Advanced technology, such as a deep learning model for ANC, to expand the capacity of the ANC function to achieve real-time implementation of ANC headphones in audiometric tasks will be a focus of future work.

In conclusion, this study assessed the benefits of commercial ANC headphones in various noise scenarios. We found that commercial ANC headphones enable a 10% increase in accuracy for hearing screening applications in the presence of noise after controlling for six confounding variables (noise type, noise level, hearing screening frequency, ANC headphone model, sex, and age), which significantly influence the capacity of commercial ANC headphones. The findings indicate that headphones equipped with ANC technology can act as a quasi-sound-treated booth. Furthermore, the results suggest that ANC technology could also be beneficial for telemedicine applications in the future because it can help users alleviate the issue of background noise to provide more accurate hearing screening results under real application conditions.

The main limitations of this pilot study are the small number of participants and the narrow range of ages (22 to 27). Therefore, these findings apply to the young adult population only, and further research will be required to determine outcomes for broader age groups in future studies.

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