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Variability in Hearing Threshold When Earphones are Self-Fit

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UNIVERSITY OF NORTHERN COLORADO

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The Graduate School

VARIABILITY IN HEARING THRESHOLD WHEN EARPHONES ARE SELF-FIT

A Scholarly Project Submitted in Partial Fulfillment
of the Requirements for the Degree of
Doctor of Audiology

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College of Natural and Health Sciences
Audiology and Speech-Language Sciences

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This Scholarly Project by: Ashley Katalin Potter

Entitled: *Variability in Hearing Threshold When Earphones are Self-Fit*

has been approved as meeting the requirements for the Degree of Doctor of Audiology in the College of Natural and Health Sciences, in the Department of Audiology and Speech-Language Sciences

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ABSTRACT

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Pure tone audiometry is the gold standard for diagnostic audiology assessments and is used to determine degree and type of hearing loss via air and bone conducted pure tones. The clinically accepted test–retest variability for pure tone audiometry is ±10 decibels (dB) (Carhart & Jerger, 1959; Landry & Green, 1999). The current study evaluated the variability in hearing thresholds for three earphones: TDH-50 supra-aural, Sennheiser HDA 200 circumaural, and Etymotic ER-2 insert phones when earphones were self-fit and when fit by an audiologist. Twenty young adult participants completed six air conducted pure tone audiometric exams for one ear using the three earphones. Testing included conventional and extended high frequency (EHF) audiometry. For each earphone, the participant fit and removed the earphone in the first trial, and the second trial was completed with the audiologist fitting and removing the earphones. A repeated measure two-way analysis of variance (ANOVA) was completed for conventional and EHF audiometry comparing hearing threshold variability, earphone, and fitter. The fitter condition did not have a statistically significant effect on hearing threshold for conventional or EHF audiometry. The type of transducer did have a statistically significant effect on hearing threshold ($\alpha = 0.05$, $p = 0.001$); however, this effect was not considered clinically significant as the hearing threshold differences were less than 5 dB and within 10 dB of test–retest variability.

This suggests that when properly instructed, patients with adequate cognitive ability and hand dexterity should be able to self-fit insert, supra-aural, and circumaural earphones.

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LIST OF ABBREVIATIONS

ASA	Acoustical Society of America
ANOVA	Analysis of variance
ANSI	American National Standards Institute
ASHA	American Speech-Language-Hearing Association
dB	Decibel
EHF	Extended high frequency
HL	Hearing level
Hz	Hertz
Kg	Kilogram
kHz	Kilohertz
kPa	Kilopascal
MPANL	Maximum permissible ambient noise level
RETSPL	Reference equivalent threshold sound pressure level
SPL	Standard pressure level

CHAPTER I

STATEMENT OF THE PROBLEM

Audiometry

Pure tone audiometry is used in conjunction with other audiologic assessments to establish degree and type of hearing loss by utilizing air and bone conducted pure tone signals. Clinically, pure tone audiometry is the gold standard for hearing sensitivity assessment. Audiometry is conducted using a calibrated audiometer (American National Standard Institute [ANSI], 2018; Carhart & Jerger, 1959). The ANSI and the American Speech-Language-Hearing Association (ASHA) have published standards and guidelines, respectively, that indicate which frequencies should be tested. For conventional air conduction testing, 0.25, 0.5, 1, 2, 3, 4, 6, and 8 kilohertz (kHz) are tested (ANSI, 2004; ASHA, 2005). Extended high frequency (EHF) audiometry is a supplement to conventional pure tone audiometry, which extends the frequency range when measuring hearing sensitivity to include 9, 10, 11.2, 12.5, 14, and 16 kHz (Al-Malky et al., 2015; de la Vega et al., 2016; Roeser & Clark, 2007). The EHF audiometry has a few clinical applications, such as ototoxic monitoring, early detection of noise-induced hearing loss, tinnitus management, and frequency transposition in amplification (Al-Malky et al., 2015; Roeser & Clark, 2007; Vielsmeier et al., 2015). The audiogram is the form used to record hearing thresholds obtained either in tabular or graphical form. It denotes the reference threshold that the audiometer is calibrated to. The symbols marked on the graphical audiogram indicate the location on the head that the transducer is placed (ANSI, 2004; ASHA, 2005).

Transducers

The audiometer is coupled to the listener’s ear with a transducer that converts the electrical signal of the audiometer into an acoustic signal. There are five styles of transducers that may be coupled to the audiometer: circumaural earphones, insert earphones, supra-aural earphones, sound field speakers, and bone oscillator. Supra-aural earphones, circumaural earphones, and insert earphones are utilized for air conduction testing. Supra-aural earphones are comprised of a diaphragm with molded rubber cushions that rest on the pinna. Supra-aural earphones are utilized in conventional pure tone audiometry due to their flat frequency response up to 8 kHz. Circumaural earphones are comprised of a diaphragm, a plastic dome, and cushions that encircle the entire pinna. Circumaural earphones are used in EHF audiometry due to their flat frequency response above 8 kHz. Insert earphones are made up of transducers coupled to sized foam eartips. The transducers may be ear level or shoulder mounted. The foam tip is rolled down and inserted into the ear canal (Roeser & Clark, 2007). Some insert earphones may be utilized for both conventional and EHF audiometry due to the flat frequency response from 0.2 to 20 kHz (Killion, 1984). The transducers should be fit on the listener by the audiologist (ASHA, 2005).

Hearing Threshold Measurement

The Hughson–Westlake method is the preferred method of pure tone audiometric hearing threshold determination (ANSI, 2004; ASHA, 2005). Hearing threshold search is done by descending in 10 decibel (dB) steps until the listener no longer responds to the stimulus. The stimulus is then raised in 5 dB steps until a response is elicited. The threshold is determined as the lowest level that responses are obtained in more than half of ascents (ASHA, 2005; Carhart & Jerger, 1959; Hughson & Westlake, 1944). The two common stimuli used in pure tone audiometry are pulsed and continuous tones. These stimuli are differentiated by their perceptual quality and their rise/fall time (Mineau & Schlauch, 1997). The ANSI and ASHA guidelines for manual pure-tone threshold audiometry state that threshold should be obtained in steps no larger than 5 dB when ascending (ANSI, 2004; ASHA, 2005).

Earphone Placement Variability

The ASHA (2005) guidelines stated that transducers should be fit by the testing audiologist. Currently, there have only been a limited number of studies specifically investigating how the placement of earphones affects hearing thresholds. In a cross-sectional study, Almeida et al. (2015) evaluated two occupational audiology facilities in Brazil. Auditory thresholds were obtained utilizing the Hughson-Westlake method in 5 dB steps using TDH-50 supra-aural earphones. A statistically significant difference in thresholds was found between self-fit and clinician-fit at higher conventional frequencies. It was concluded that improved hearing thresholds were obtained at higher frequencies when the earphones were self-fit by the patient. Paquier et al. (2016) completed a similar study with 20 normal hearing subjects who were inexperienced with hearing testing. It was found that generally, retest reliability was better for the HD600 earphones than the TDH-39. It was concluded that depending on the model of earphone being utilized, the positioning may have a significant effect on threshold measurement at middle and high frequencies.

Research Rationale

Currently, there are no published studies, which specifically evaluate the relationship between self-fitting the three types of ear-level air conduction transducers and the audiometric thresholds, obtained. Because of this and the fact that it is clinically relevant to many practicing audiologists, this area requires attention.

Purpose

The goal of this capstone was to evaluate hearing threshold variability between self-fit and audiologist-fit supra-aural earphones, circumaural earphones, and insert earphones for conventional and EHF audiometry.

Research Questions

Q1 Is there a significant difference in hearing thresholds for the conventional test frequencies between self-fit and audiologist-fit for three types of earphones (supra-aural, insert, and circumaural)?

Q2 Is there a significant difference in extended high frequency hearing thresholds between self-fit and audiologist-fit when tested with circumaural and insert earphones?

Hypotheses

H01 Conventional hearing thresholds will not vary depending on whether the audiologist or the participant fits the earphones.

H02 Extended high frequency hearing thresholds will not vary depending on whether the audiologist or the participant fits the earphones.

CHAPTER II

REVIEW OF THE LITERATURE

Audiometry

Pure tone air and bone conduction audiometry are used in conjunction with other audiometric tests to establish degree and type of hearing loss. Among audiologists, pure tone audiometry is the gold-standard for clinical hearing sensitivity assessment (Carhart & Jerger, 1959). Pure tone audiometry utilizes a transducer and an audiometer that is calibrated annually to specifications set forth by the American National Standard Institute (ANSI, 2018) in S3.6-2018. To be considered calibrated, the audiometer must (a) produce the signal at the intensity level and frequency that it indicates; (b) deliver the signal to the intended transducer only; and (c) emit a signal that does not contain contamination from outside sources, such as static or electromagnetic interference or by-products from the signal itself, for example, combination tones and harmonics (Harford, 1967).

Conventional Pure Tone Audiometry

The ANSI (2004) adopted S3.21-2004 (R2009) *Methods for Manual Pure Tone Threshold Audiometry* to standardize test procedures used by all audiologists. The American Speech-Language-Hearing Association (ASHA, 2005) has also published *Guidelines for Manual Pure-Tone Threshold Audiometry*. These actions have been taken to promote consistency among testers and minimize variance due to test method. The standard air conduction diagnostic technique tests the frequencies 1, 2, 3, 4, 6, 8, 1, 0.5, and 0.25 kilohertz (kHz). Extended high frequency (EHF) testing from 9 to 16 kHz may also be used in special circumstances (ANSI, 2004; ASHA, 2005).

Pure tone audiometry requires a clear response to a perceived auditory stimulus. Common responses are raising one's hand and pressing a response button. The tester must then determine if the response was a true indication of perception of a stimulus. The latency of the response may be delayed close to the patient's hearing threshold (ANSI, 2004). Manual audiometry requires the clinician to find each threshold by hand.

Automatic audiometry is a procedure in which an audiometer and computer are integrated, and a series of algorithms evaluate pure tone hearing thresholds for air and bone conduction. A clinician does not have to physically obtain hearing thresholds unless a patient cannot be tested with this approach due to inconsistent responses. The presence of tinnitus and other conditions may cause the patient to give inconsistent responses, causing the audiometer to malfunction (Ho et al., 2009; Mahomed-Asmail et al., 2016; Sakabe et al., 1978). Hearing thresholds obtained by both conventional and automated audiometry are plotted on an audiogram.

The audiogram form must have spaces to denote patient name, patient age, patient gender, test site, number of test subject, time and date of test, audiometer manufacturer's name, audiometer type and serial number, and tester's name. It is also advisable to include the equipment and sound booth calibration date as required by the Occupational Safety & Health and other regulatory agencies (Occupational Safety & Health Administration, 1981). The results of hearing threshold measurement may be recorded in a graphical audiogram or in a numerical table. The audiometric test record must explicitly denote the reference threshold the audiometer is calibrated to, since these reference thresholds have changed historically. For example, the most used reference threshold is 0 decibel (dB) hearing level (HL). This is based on the average threshold for normal hearing in young adults.

The graphical audiogram is a grid used to plot the results of pure tone audiometry. Frequency is represented on the abscissa in hertz (Hz) on a logarithmic scale for manual and sweep frequency automatic audiograms. In automatic fixed frequency audiograms, the scale should be in equal intervals. The HL in decibels is represented on the ordinate linearly. The HL scale includes intensity levels from −10 dB to at least the limits of the audiometer in no more than 10 dB increments (ANSI, 2004).

An octave on the frequency scale is equivalent to 20 dB on the HL scale for manual audiometry. All the gridlines are equal in darkness and thickness except for 0 dB HL. It is denoted prominently to stand out from other grid lines. Gridlines for inter-octave frequencies are dashes or finer in width to differentiate them from octave frequencies. The frequency scale must include frequencies from 0.125 to 8 kHz but may contain higher frequencies on the logarithmic scale. Like the frequency scale, a wider range of intensity levels may be included. Optionally, effective masking levels can be recorded in a table below the audiogram (ANSI, 2004; ASHA, 2005).

Symbols marked on the audiogram represent where the transducer is placed on the head. The midpoint of air conduction symbols is drawn at the intersection of the correct vertical and horizontal axes on the audiogram. The unmasked left ear is represented by an “X” and the right ear is represented by an “O.” The masked symbol for the left ear is a square, and the masked symbol for the right ear is a triangle. Air conduction thresholds are connected by solid lines between each symbol for the same ear (ASHA, 2005). Figure 1 illustrates an example of an audiogram that meets ANSI standards (ANSI, 2004).

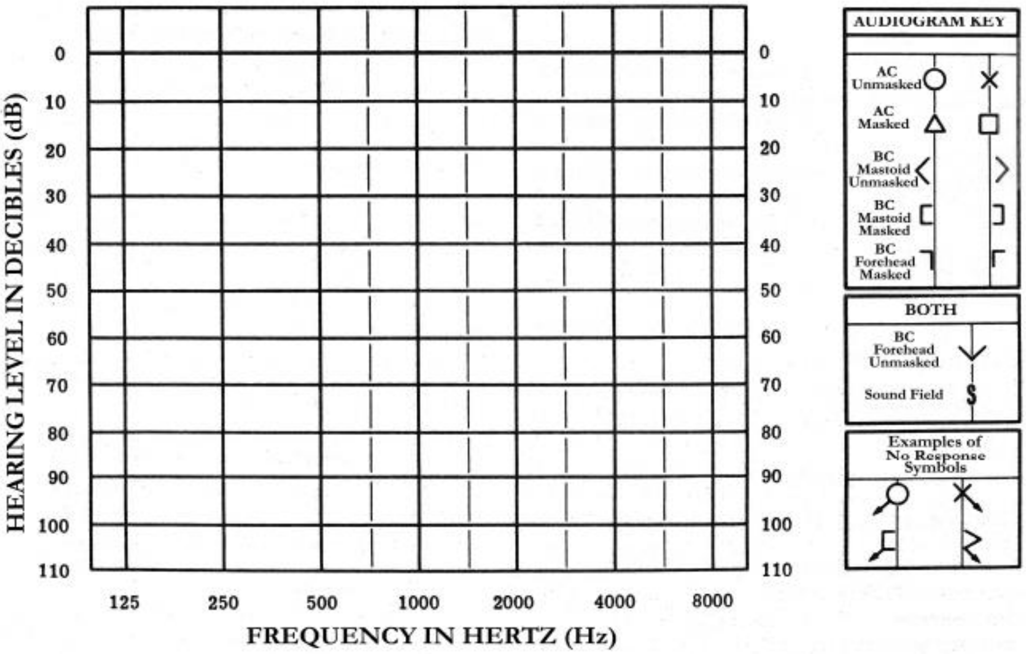

Figure 1

Recommended Form of Audiogram.

Note. Adapted from *Methods for Manual Pure-Tone Audiometry*, by the American National Standard Institute, 2004. Copyright 2004 by the American National Standard Institute. Reprinted with permission.

Extended High Frequency Audiometry

Although conventional pure tone audiometry measures thresholds between 0.125 and 8 kHz, the human auditory system is sensitive to sounds as a high as 20 kHz (Northern et al., 1971; Rodríguez Valiente, Trinidad, et al., 2014). The EHF audiometry is a supplement to conventional pure tone audiometry, measuring hearing sensitivity at 9, 10, 11.2, 12.5, 14, 16, 18, and 20 kHz. The EHF audiometry requires the use of a transducer and an audiometer with the capability to produce tones between 9 and 20 kHz. There are standalone EHF audiometers; however, some conventional pure tone audiometers have high frequency audiometry included in the software

(Al-Malky et al., 2015; de la Vega et al., 2016; Roeser & Clark, 2007). One consideration for EHF audiometry is the presence of standing waves. A standing wave is a result of sound that is reflected from the tympanic membrane, and incident waves are reduced or enhanced due to the interaction. High frequency tones have relatively shorter wavelengths and consequent susceptibility to standing waves (Schmuziger et al., 2004).

Clinical Applications

The EHF audiometry has a few clinical applications, including ototoxic medication monitoring. Ototoxic medications can cause a decline in hearing sensitivity typically beginning in the highest frequencies (Al-Malky et al., 2015). The EHF audiometry may also be used to monitor noise induced hearing loss and aid in early detection. The goal of monitoring this irreversible loss is to detect it early to prevent the hearing loss from extending to the frequencies important for speech understanding. Tinnitus is the perception of sound with no external source. Hearing loss is a risk factor for tinnitus, and most tinnitus patients exhibit poorer thresholds in the high frequency range. Consequently, their tinnitus perception corresponds to the frequency range of their hearing loss. This suggests that conventional pure tone audiometry may not be sufficient for the diagnosis of hearing loss in patients with tinnitus, and EHF audiometry should be a standard procedure in the assessment of these patients (Vielsmeier et al., 2015). For patients who have hearing loss in low and middle frequencies and better thresholds in high frequencies, EHF audiometry may reveal more usable regions of the cochlea. This is the final application of high frequency audiometry: frequency transposition for amplification (Roeser & Clark, 2007).

The Audiogram

The EHF audiogram form must have the same spaces to denote name, age, gender, test site, number of test subject, time and date of test, audiometer manufacturer's name, type and serial number of audiometer, and tester's name. Again, the results of hearing threshold measurement may be recorded on a graphical audiogram or in a numerical table and must explicitly denote the reference threshold to which the audiometer is calibrated to. It is possible to include both conventional and EHF audiometry on the same audiogram form in the same format if transducer calibration references are specified for each.

Audiometric Equipment

Audiometers

The pure tone audiometer is used to elicit pure tones as the stimulus. The simplest conventional pure tone audiometer has a pure tone generator, presentation switch, amplifier, attenuator, output selector switch, and transducer coupler. The generator produces specific pure tones that are selected with a frequency control on the audiometer. The presentation switch controls whether the tone is on or off. The amplifier amplifies all stimuli. The attenuator changes the intensity of the signal after it has passed through the amplifier and is controlled by the intensity control. The output selector switch determines which transducer is used (supra-aural, circumaural, or insert earphone) and where in the transducer the signal goes: left ear, right ear, or both earphones (Dondelinger, 2010; Frank & Rosen, 2007).

Audiometers are named based on six categories: (a) type of signal produced—pure tone or speech; (b) frequency range—limited, conventional, or EHF; (c) measurement method—manual, automatic, or computer based; (d) purpose—clinical, diagnostic, screening, or industrial; (e) number of independent audiometers, or channels, contained in the unit—one channel, two channels, or channel and a half; and (f) portability. The ANSI S3.6-2018 classifies audiometers based on the signal they produce, operation mode, and testable auditory functions due to required features, frequencies, and maximum hearing levels (Frank & Rosen, 2007).

Screening Audiometer

Screening audiometers are semi-automated devices used to quickly determine if hearing loss is present. Some screeners can test multiple patients concurrently. This is convenient for mass screening in schools and industrial operations. While screening audiometers can assess the degree of hearing loss, they cannot be used to determine the type of hearing loss. This requires the use of a clinical diagnostic audiometer that allows for testing with both air and bone conduction stimuli as well as speech stimuli and masking stimuli (Dondelinger, 2010).

Diagnostic Audiometer

Typically, speech and pure tone audiometers are merged and called a diagnostic or clinical audiometer (Dondelinger, 2010; Frank & Rosen, 2007). Speech audiometers have similar components to pure tone audiometers. The primary difference is that the pure tone generator is replaced with a microphone and external inputs. There is also a volume monitor/meter between the amplifier and the talk-over intensity control. The microphone is used for live speech testing, and the external inputs introduce playback for recorded speech testing.

Transducers

To determine the listener’s hearing threshold, the output from the audiometer must be coupled to the listener’s ear. A transducer is utilized to convert the electrical energy of the audiometer to acoustic energy (Roeser & Clark, 2007). There are five types of transducers that can be connected to the audiometer: supra-aural earphones, circumaural earphones, insert earphones, sound field loudspeakers, and a bone oscillator. The first four are utilized in air conduction testing, while the last is used for bone conduction testing. The three earphones provide ear-specific threshold information.

The most common supra-aural earphones are the Telephonics TDH models 39, 49, and 50. These earphones have a diaphragm that rests over the ear canal opening with molded rubber MX41/AR cushions that rest on the periphery of the pinna. The earphones are mounted on an adjustable headband by a Y-shaped yoke that the earphones snap into. This allows the earphones to swivel and make vertical adjustments to fit the listener’s head. The yoke extends through a spring-loaded clip that adjusts the horizontal aspect of the configuration. The headband produces a standard of 4.0 to 5.0 Newtons of force (Roeser & Clark, 2007). The TDH supra-aural earphones have a relatively flat frequency response between 0.125 and 8 kHz, meaning the input is essentially equal to the output. The reference equivalent threshold sound pressure levels (RETSPLs) are the mean threshold sound pressure levels measured in decibels (dB) at specific frequencies for a specific transducer. These levels have been measured in an acoustic coupler or ear simulator and are based on hearing threshold data from otologically normal males and females between 18 and 25 years. The RETSPL values for supra-aural earphones may be found in Table 1.

Table 1

Supra-Aural Earphone Reference Equivalent Threshold Sound Pressure Levels (RETSPLs)

	RETSPL (dB)	
Frequency (kHz)	Telephonics TDH-39	Telephonics TDH-49, TDH-50
0.125	45	47.5
0.25	25.5	26.5
0.5	11.5	13.5
0.75	8	8.5
1	7	7.5
1.5	6.5	7.5
2	9	11
3	10	9.5
4	9.5	10.5
6	15.5	13.5
8	13	13

Note. dB = decibel; kHz = kilohertz. Adapted from *Specification for Audiometers* (Standard No. ANSI/Acoustical Society of America [ASA] S3.6-2018) by the American National Standard Institute, 2018. Copyright 2018 by the American National Standard Institute.

Supra-aural earphones have some characteristics that make them ineffective for EHF testing. They have a limited output above 8 kHz and can only reliably test between 0.125 and 8 kHz. A different transducer must be used for EHF (Roeser & Clark, 2007). Another downfall of the supra-aural earphones is they may produce a vibrotactile response in patients with severe or profound sensorineural hearing loss in which the patient feels the vibration of the sound rather than hearing the sound. This is common in those with “left corner” audiograms (Killion & Villchur, 1989; Marangoni & Gil, 2009). Zwislocki et al. (1988) reported poor reliability at low frequencies due to the instability and variability of the coupling between the earphone and the ear. Supra-aural earphones are susceptible to standing wave effects at frequencies above 2 kHz due to the closed cavity that is created when the earphone is placed over the ear canal. Due to the shorter wavelength of high frequency sounds, the tone bounces off the tympanic membrane and may reduce the intensity of subsequent waves. Some patients may exhibit false high frequency hearing loss due to the ear canal collapsing when the supra-aural earphones are placed over the pinnae (Killion & Villchur, 1989). The main strength of the TDH supra-aural earphones is their widespread availability and standardized calibration method (Zwislocki et al., 1988).

The most popular circumaural earphones have been the Sennheiser Electronic Corporation HDA 200. Since the HDA 200 earphones are now out of production, the RadioEar DD450 model was designed to replicate the characteristics of the Sennheiser earphones. These earphones have a flat frequency response from 0.020 to 20 kHz (Frank, 2001; Han & Poulsen, 2009; Smull et al., 2018). Since the HDA 200 circumaural earphones have been discontinued, Sennheiser has produced the HDA 300 circumaural earphones. These earphones also have a frequency response of 0.020 to 20 kHz, the same as the HDA 200 earphones. Circumaural earphones are attached to a plastic dome and have cushions that encircle the entire pinna. They use the same attachment and procedure as the TDH supra-aural earphones mentioned previously and are mounted to a headband that produces a static force between 9 and 10 newtons. The earphones are fit similar to earmuff-style hearing protection. They are most often used for EHF audiometry above 8 kHz (Roeser & Clark, 2007). The RETSPL values for circumaural earphones may be found in Table 2.

Table 2

Circumaural Earphones Reference Equivalent Threshold Sound Pressure Levels (RETSPLs)

Frequency(kHz)	RETSPL (dB)		
	Sennheiser HDA 200[a]	Sennheiser HDA 300[b]	RadioEar DD 450[c]
0.125	30.5	26.2	30.5
0.25	18	20.1	18
0.5	11	8.6	11
0.75	6	5.1	6
1	5.5	2.7	5.5
1.5	5.5	3.2	5.5
2	4.5	0.5	4.5
3	2.5	−1.6	2.5
4	9.5	0.1	9.5
6	17	11.3	17
8	17.5	20.9	17.5
9	19	23.1	19
10	22	18.5	22
11.2	23	22.9	23
12.5	27.5	27	27.5
14	35	32.8	35
16	56	47.7	56

Note. dB = decibel; kHz = kilohertz.

[a] Adapted from *Specification for Audiometers*, by American National Standard Institute, 2018, when testing to 0 dB HL from 125 to 16,000 Hz.

[b] Adapted from *HDA 300 Audiometric Headphone*, by Sennheiser, n.d.

[c] Adapted from *DD450 Technical Specifications*, by RadioEar, n.d.

Circumaural earphones have some disadvantages. Like supra-aural earphones, circumaural earphones are subject to standing wave effects. These earphones provide the least interaural attenuation of the three transducers described. This requires more contralateral masking to be used when the ears have unequal auditory sensitivity (Zwislocki et al., 1988). However, circumaural earphones have greater ambient noise attenuation, making them beneficial for testing in less-than-ideal environments, like schools and community centers where ambient noise is higher. It is improbable circumaural earphones would cause collapsed ear canals, unlike supra-aural earphones (Smull et al., 2018).

Insert Earphones

Although now out of production, the Etymotic ER-3A and ER-5A are widely used insert earphones for conventional audiometry. These earphones were designed to reproduce the electro-acoustic characteristics of the TDH-39 earphones, so that the transducers could be used interchangeably (Killion & Villchur, 1989; Marangoni & Gil, 2009). The insert earphones utilize foam tips in three sizes: large, normal, and small to accommodate varying ear canals sizes. The ER-3A consists of shoulder mounted transducers that are coupled to a sound tube. The sound tube is attached to a coupler that runs a tube through a foam eartip that is inserted into the ear canal (Roeser & Clark, 2007). The ER-5A has a small ear-level transducer that the foam eartip attaches to directly. Both models have a relatively flat frequency response from 0.1 to 4 kHz that then decreases as it approaches 8 kHz. These earphones also have a greater dynamic range compared to TDH earphones at low frequencies (Killion & Villchur, 1989). Although they may be used for testing up to 8 kHz, the maximum output above 6 kHz is reduced compared to lower frequencies. The Etymotic ER-2 insert earphones have a similar configuration to the ER-3A insert earphones as they are comprised of a shoulder-mounted transducer coupled to a sound tube that is coupled to the ear via foam tips. These earphones were designed to be used primarily for research. The ER-2 earphones have a relatively flat frequency response from 0.2 to 20 kHz with a maximum output of 95 dB HL. This frequency response allows for insert earphones to be utilized in EHF audiometry (Killion, 1984). Since the discontinuation of the ER-3A and 5A, the E-A-RTONE 3A is now commonly used. These earphones were also designed to reproduce the characteristics of the TDH-39 earphones. The E-A-RTONE 3A earphones have a similar configuration to the Etymotic ER-3A, as the eartip that goes in the ear is connected to a sound tube that then connects to shoulder-mounted transducers (3M, n.d.). Insert earphone RETSPL values may be found in Table 3.

Zwislocki et al. (1988) reported that insert earphones are vulnerable to variability due to the possible differences between subjects' ear canal shapes and tympanic membrane compliance and the lack of control of the exact insertion depth. There may be some concerns with the insert earphones being placed in the canal, such as cerumen impaction. Insert earphones have a number of benefits that make them a desirable choice for audiometric testing. They reduce the area of skin that makes contact with the transducer, reducing vibrotactile sensation and potentially inaccurate responses (Killion & Villchur, 1989; Marangoni & Gil, 2009). With average insertion depth, insert earphones minimize ambient and physiologic noise. With deep insertion this benefit increases (Zwislocki et al., 1988). Insert earphones may be more hygienic compared to other earphones as it is recommended that the eartips be used for one patient only and disposed of after one use (Killion & Villchur, 1989). The insert earphones also have an increased interaural attenuation resolving the necessity for high levels of contralateral masking for unequal hearing sensitivities between ears. Insert earphones also hold the ear canal open, eliminating the risk of collapsing canals that may result in a false high frequency hearing loss (Killion & Villchur, 1989; Marangoni & Gil, 2009).

Table 3

Insert Earphones Reference Equivalent Threshold Sound Pressure Levels

Frequency (kHz)	Insert earphone		
	ER-2	ER-3A	E-A-RTONE 3A
0.125	28	28	28
0.25	17.5	17.5	17.5
0.5	9.5	9.5	9.5
0.75	6.0	6.0	6.0
1	5.5	5.5	5.5
1.5	9.5	9.5	9.5
2	11.5	11.5	11.5
3	13	13	13
4	15	15	15
6	16	16	16
8	15.5	15.5	15.5
9	16	-	-
10	20	-	-
11.2	30.5	-	-
12.5	37	-	-
14	43.5	-	-
16	53	-	-

Note. kHz = kilohertz. Adapted from *Specification for Audiometers*, by American National Standard Institute, 2018, for testing to 0 decibels (dB) hearing level (HL) between 125 and 16,000 Hz.

Audiometer Specifications

The ANSI (2004) set forth a standard outlining the specifications for audiometers. This standard was created to ensure consistency in hearing threshold tests across various audiometers and ensure that differing test results are a result of actual threshold differences and not equipment variability.

Manual audiometers must have a tone switch to present the test tone. This switch must only present the test tone and not introduce extraneous mechanical noise. The audiometer must have a subject response system to inform the tester that a stimulus has been perceived. Typically, this system takes the form of a handheld button that activates an indicator on the audiometer. The button must be operational with one hand and not generate any mechanical or electrical noise that could affect hearing threshold measurement.

If a monitoring system is provided, it must have an electroacoustic system that allows the tester to hear the signals presented via earphone or loudspeaker. If a talk-back system is included, it must have an electroacoustic system that allows the tester to hear the patient’s verbal responses.

For diagnostic audiometers, the accuracy for frequency presented must be within 1% of the frequency indicated on the audiogram for standard test frequencies. The hearing level should only have one scale. The audiometer should be calibrated in 5 dB or less increments. At each frequency 0 dB must correspond to the reference equivalent threshold level.

Exhaustive calibration must be performed once per 12-month period by a trained technician (ANSI, 2004). Calibration is performed specific to each audiometer and the transducers coupled to it. Transducers cannot be interchanged between audiometers without being recalibrated. All calibration records should be kept on file. Supra-aural earphone calibration should be performed using an IEC 60318-3 ear simulator with a static weight of 0.5 kilogram (kg) being applied. Circumaural earphones are to be calibrated utilizing IEC 60318-2 with a flat plate having a static weight if 0.9 to 1 kg being applied. Insert earphones are calibrated utilizing the HA-1 or HA-2 coupler. These couplers mimic the characteristics of an occluded ear (Roeser & Clark, 2007). Earphones used for EHF testing must only occur when atmospheric pressure is between 90 and 104 kilopascals, temperature is between 18 and 26℃, and the humidity is between 30 and 80% relative humidity (ANSI, 2004). Recalibration is required after any of the following conditions: (a) 12 months has elapsed, (b) set operating hours has been surpassed, (c) audiometer or transducer has experienced an event or replacement that may have put the audiometer out of calibration, and (d) when thresholds appear to be the result of questionable audiometer function.

The calibration technician is required to perform a number of functional checks. The power cord and accessory cord integrity, headband tension, and earphone cushion condition must be assessed. Actual measurements of all frequencies must be recorded. Any distortion is recorded as a percentage of total harmonic distortion at all frequencies. Output levels and linearity of all channels is recorded as a deviation from standard for all transducers. Actual measurement of stimulus rise time and fall time and overshoot are recorded. On/off ratio and crosstalk are measured and recorded in decibels. On/off ratio ensures that the stimulus cannot be heard when it is turned off. Crosstalk is the undesirable signal transfer between channels (Frank & Rosen, 2007). The duration of pulsed tones is measured and recorded as a pass or fail. Unwanted noise check for interrupter switch, switch sounds, and mechanical sounds is recorded as pass or fail. Test equipment used for calibration must be calibrated annually in a laboratory that can be traced to the ANSI (2004).

Daily visual inspection, performance checks, and bioacoustics checks are required in order to verify performance of equipment and that the equipment calibration has not significantly changed.

Test Environment

Along with audiometers, the test environment is also calibrated annually to ANSI (1999) specifications in ANSI/ASA S3.1-1999 (R2018). To increase the reliability of the test environment, sound isolated booths are utilized (ANSI, 1999, 2018; ASHA, 2005).

In an audiometric test room, pure tone and speech audiometry are performed. If the ambient noise in the room is too high, a false elevation in hearing threshold may be observed due to ambient noise masking the stimulus. Masking is the psychoacoustic phenomenon in which high ambient noise levels cause hearing threshold levels to become elevated. It would not be realistic or practical to attempt to remove all ambient noise from an audiometric test room due to the structural and expenditure considerations. The *Maximum Permissible Ambient Noise Level* (MPANL) *for Audiometric Test Rooms* (ANSI, 1999) was put in place to ensure that ambient noise does not impact the hearing test results and to ensure consistency across test sites.

Ambient noise must be measured at octave or one-third band intervals from 0.125 to 8 kHz in dB referencing micropascals. If measurement of ambient noise levels is equal to the values listed in Table 4, a maximum of 2 dB threshold shift may occur (ANSI, 1999). The ambient noise levels should be measured with a Type 1 sound level meter with octave or one-third octave band filter. It is recommended to utilized one-third octave band measurements when possible. The ambient noise measurement should occur when all noise sources are represented. Possible noise sources include exhaust fans, ventilation systems, lights, audiometer, amplifiers, and other instrumentation. These measurements should be obtained annually and/or when a new noise source is placed in the test room or vicinity. The sound level meter should be placed with the microphone pointing at the location(s) in which the listeners head could be placed. The person taking the measurement should be positioned in such a way that their body will not affect the level of ambient noise being recorded. If the ambient noise levels recorded are greater than the values listed in the tables, it becomes necessary to find a quieter environment for testing.

The most important requirement is that the ambient noise does not surpass the values in Table 4. Individual audiometric test rooms should be in separate rooms or large sections of a room. The rooms should be visually and acoustically separated from each other and the floor of each room be carpeted. To provide an appropriate test atmosphere and ensure maximum attenuation of sound within the room, an absorbent material should be used to treat the walls and ceiling. Suitable ventilation must be afforded and furniture in the room should be comfortable.

Table 4

One-Third Octave Band Maximum Permissible Ambient Noise Levels for Covered Ears

1/3 octave band intervals	Supra-aural earphone			Insert earphone		
	0.125 to 8 kHz	0.25 to 8 kHz	0.5 to 8 kHz	0.125 to 8 kHz	0.25 to 8 kHz	0.5 to 8 kHz
0.125	30.0	34.0	44.0	54.0	62.0	73.0
0.25	20.0	20.0	30.0	48.0	48.0	59.0
0.5	16.0	16.0	16.0	45.0	45.0	45.0
0.8	19.0	19.0	19.0	44.0	44.0	44.0
1	21.0	21.0	21.0	42.0	42.0	42.0
1.6	25.0	25.0	25.0	43.0	43.0	43.0
2	29.0	29.0	29.0	44.0	44.0	44.0
3.15	33.0	33.0	33.0	46.0	46.0	46.0
4	32.0	32.0	32.0	45.0	45.0	45.0
6.3	32.0	32.0	32.0	48.0	48.0	48.0
8	32.0	32.0	32.0	51.0	51.0	51.0

Note: kHz = kilohertz. Adapted from *Maximum Permissible Ambient Noise Levels for Audiometric Test Rooms,* by American National Standard Institute, 1999.

Hearing Threshold Measurement

Pure Tone Stimuli

The two stimulus types typically used for adult pure tone audiometry are pulsed tone and continuous tone. The two stimuli are differentiated by their rise and fall times and the perceptual quality of the tone. Rise time is the time it takes the signal to reach 90% of its full amplitude, and fall time is defined as the time it takes to return to baseline when the signal is turned off.

The continuous tone elicits a steady tone for 1 to 2 seconds in manual audiometry and is precisely controlled in automatic audiometry (Mineau & Schlauch, 1997). Rise time should not exceed 200 milliseconds with sound pressure level increasing consistently, and fall time should not exceed 200 milliseconds with sound pressure level decreasing consistently. The overall sound pressure level produced must not exceed +1 dB compared to the steady state level in either condition per ANSI/Acoustical Society of America (ASA) 3.6-2010 (ANSI, 2018).

The pulsed tone elicits the pure tone in a 200 millisecond on and 200 millisecond off pattern. The rise time should be between 20 and 50 milliseconds with sound pressure increasing at a steady rate. The fall time should be between 20 and 50 milliseconds with sound pressure decreasing at a steady rate. The plateau of the signal must be at least 150 milliseconds (ANSI, 2018).

The ASHA (2005) *Guidelines for Manual Pure-Tone Threshold Audiometry* recommended using a continuous tone; however, the use of pulsed tones is also acceptable. There is not a significant difference in threshold between the stimulus types when using five measurement intervals with patients with sensorineural hearing loss (Dancer et al., 1976). Pulsed tones have also shown a decrease in false positive responses when the patient responds when the stimulus is not presented for patients of all hearing and tinnitus statuses. Patients have more awareness to pulsed tones and this signal choice may be more effective at determining the lowest threshold (Burk & Wiley, 2004).

Signal Detection Methods

Hughson-Westlake Method

The most utilized pure tone audiometry method is the modified Hughson-Westlake method. The first step in the test procedure is familiarizing the listener with the task they will be expected to perform in the patient's better ear. A pure tone is presented for 1 to 2 seconds at a level that the listener can hear and will evoke a clear response (ASHA, 2005). The tone may be continuous or pulsed. Pulsed tones have improved the listener's awareness of the presence of stimuli (Burk & Wiley, 2004). The response to the stimulus can range from a hand or finger raise to a press of a response button depending on the patient's physical and cognitive abilities. When it is clear that the listener understands the task, the threshold search begins, and the intensity level is lowered in 10 dB increments until the listener no longer responds. The interval between tone presentations should be varied and at least as long as one tone presentation in duration. This reduces the likelihood the tester will get into a rhythmic pattern of presentation the patient may be able to anticipate (ASHA, 2005). When the listener no longer responds, the signal increases in 5 dB steps until a response is obtained. When the response is elicited, the intensity level is lowered by 10 dB. Threshold is defined as "the minimum level at which perception is achieved in more than half of the ascents" (Carhart & Jerger, 1959, para. 4) and is typically established in three to four ascents (ASHA, 2005; Hughson & Westlake, 1944).

Békésy Audiometry

Georg von Békésy (1947) developed a self-recording audiometer and measurement technique which became known as Békésy audiometry. With this technique, the patient controls the intensity level by pressing and releasing a response button. The patient releases the button when they do not hear the tone, causing the audiometer to increase the intensity level steadily. When the patient presses the button, they are indicating that the tone is audible to them. Due to the response, the tone is then decreased until the patient no longer hears it. This restarts the pattern, and the patient will move between audibility and inaudibility while the audiometer traces the responses on an audiogram (Békésy, 1947; Roeser & Clark, 2007; Watson & Tolan, 1949). There are a variety of stimuli that can be used in Békésy audiometry, including a sweep of frequencies, fixed frequencies, steady tones, and pulsed tones (Békésy, 1947). However, studies have shown less than 15% of clinical audiologists clinically use Békésy audiometry (Roeser & Clark, 2007). Békésy audiometry and Hughson-Westlake audiometry yield similar results, and Békésy audiometry is an acceptable alternative to conventional pure tone audiometry (Burns & Hinchcliffe, 1985).

Step Size

Jervall and Arlinger (1986) specifically compared the test–retest reliability with regard to the influence of intensity step size (2 and 5 dB). The subjects comprised two groups, 10 normal hearing adults and 10 subjects with moderate cochlear hearing loss. The subjects were tested on two different occasions in which unmasked air conduction thresholds were obtained. During each test sessions, both step sizes were used. In this counterbalanced design, half of the participants in the test groups tested with 2 dB steps, and the other half of the participants started with 5 dB steps. In the following trial, the subjects were tested using the step size they had not been exposed to in the first trial. Conventional audiometry frequencies 0.25, 0.5, 1, 2, 3, 4, 6, and 8 kHz were tested using the modified Hughson-Westlake method performed by the same tester. There was no significant difference in threshold in the normal hearing group. In the cochlear hearing loss group, significantly smaller threshold standard deviations were obtained with the smaller step size, but overall, there was no statistically significant difference in hearing thresholds obtained with either step size. However, the smaller step size required 64% more threshold crossings for the normal hearing group and 47% more threshold crossings for the hearing loss group when compared to the larger step size. At each individual frequency, the difference in threshold crossings was statistically significant (t-test, $p < 0.001$) in both groups. There was a significant correlation ($r = 0.69$) between the mean number of threshold crossings with 2 dB and 5 dB step sizes. There was a good correlation between the thresholds obtained with both step sizes, but the thresholds found with the 2 dB step size were slightly lower than the 5 dB threshold for the subjects with cochlear hearing loss. Reducing the step size in pure tone audiometry did not produce an overall improvement in test–retest reliability and using a smaller step size increased the test time due to the increase in the number of threshold crosses needed at the lower level.

The *Guidelines for Manual Pure-Tone Threshold Audiometry* set forth by ASHA (2005) and *Methods of Manual Pure Tone Threshold Audiometry* (ANSI, 2004) stated that threshold should be determined in steps no larger than 5 dB when ascending.

Listener Considerations

Otoscopy

The pinna and ear canal are visually inspected to identify abnormalities, collapsing canals, and excessive cerumen that may affect pure tone testing. The size, shape, and position of the pinna are evaluated. If collapsing ear canals are present, insert earphones may be used to keep the canals open for testing. To assess the medial portion of the ear canal, the pinna is pulled back and upward. An otoscope is used to better visualize the external auditory canal (Castillo & Roland, 2007).

Instructions

After otoscopy, the tester gives instructions for the test in a manner that is appropriate for the listener. Additional direction may be given to clarify the meaning of the instructions if the patient is confused. These may be written instructions, gestures, or demonstrations (ASHA, 2005). The participant is seated in a manner that allows the tester to easily observe them and enables appropriate monitoring and reinforcement of responses while avoiding giving visual cues.

Test–Retest Reliability

Test–retest reliability is the repeatability of pure tone threshold results. This reliability is defined as consistent over time regardless of the examiner. If a test does not have good test–retest reliability, the test will not be accurate, and the results are not dependable. Poor reliability may be combatted with standardized testing protocols, equipment calibration, and the control of patient variables (Roeser & Clark, 2007). The ANSI S3.6-2018 states that standard deviation of ±10 dB is an acceptable amount of test–retest variation. Time between test and retest can affect the outcomes as there may be fluctuations in hearing threshold over time (ANSI, 2018).

Landry and Green (1999) conducted a study examining the test–retest variability between three groups of adults: young adults ages 22 to 34 years, old adults ages 50 to 63 years, and oldest adults ages 65 to 81 years. Participants were tested in a sound-treated booth at 0.25, 0.5, 1, 2, 4, and 8 kHz with a clinical audiometer utilizing the modified Hughson-Westlake method. Each participant was tested with TDH-50P supra-aural earphones and Etymotic Research ER-3A insert earphones. The test ear, frequencies, transducers, and order of testers were counterbalanced. A short break was given for participants who were retested the same day, and the other participants were retested within four months of the initial test. A mixed two-factor analysis of variance (ANOVA) was used individually for each test frequency to examine test–retest variability in relation to the groups and transducers. There was a significant main effect found at 2 and 8 kHz ($p < 0.05$), indicating that there was a statistically significant difference between test and retest thresholds. They also found transducer variability at 2 kHz with insert earphones ($p < 0.05$), where a greater test–retest difference was observed. When compared to the young and older adult groups, test–retest variability was significantly larger at frequencies greater than 1 kHz for listeners in the oldest group, those above 65 years of age. There were several factors that contributed to transducer variability. The first factor was the method of coupling the transducer to the ear. Physiological differences between older and younger participants, such as changes in tissue, may have also contributed to the variability between the groups. A third factor may have been the consideration that older adults may be more difficult to test. Threshold variability was larger for older adults at the higher conventional frequencies when compared to younger adults.

Schmuziger et al. (2004) evaluated the test–retest reliability of pure tone thresholds using the Sennheiser HDA 200 circumaural earphones and Etymotic Research ER-2 insert earphones. Pure tone hearing thresholds from 0.5 to 4 kHz and 8 to 16 kHz were obtained in one ear of 138 otologically healthy participants (77 women, 61 men; mean age: 24.4 years, range 12–51 years). For each subject, thresholds were obtained two times for both transducers during the same test session. Threshold variability for the HDA 200 and ER-2 could be determined in 138 ears for each transducer from 0.5 to 12.5 kHz. Four subjects failed to respond at 14 kHz and 24 subjects failed to respond at 16 kHz. Variability for HDA 200 was within ±5 dB for 90 to 99% of ears in the frequency range 0.5 to 12.5 kHz. Variability was reduced to 87% at 14 kHz and 83% at 16 kHz. Variability was within ±10 dB for the HDA 200 for 98 to 100% of ears from 0.5 to 14 kHz and decreased to 94% at 16 kHz. A higher incidence of variability was demonstrated from 9 to 16 kHz when compared to the 0.5 to 8 kHz range. Variability for ER-2 was within ±5 dB for 89 to 99% of ears from 0.5 to 14 kHz and decreased to 85% at 16 kHz. Variability was within ±10 dB for 90 to 100% of ears from 0.5 to 16 kHz. Wilcoxon signed rank test of average threshold variability demonstrated small but significantly increasing intrasession threshold variability in EHFs for both transducers ($p < 0.0002$). A comparison of variability for both transducers demonstrated no difference in variability ($p > 0.2$). Intrasession test–retest repeatability for both transducers was excellent for each frequency between 0.5 and 12.5 kHz. Repeatability was slightly, but significantly poorer from 14 to 16 kHz when compared to lower frequencies. It was concluded that the HDA 200 and ER-2 have similar test–retest reliability, and, therefore, both may be used reliably for EHF audiometry.

Flamme et al. (2014) investigated the short-term variability in pure tone thresholds obtained using audiometric equipment used for occupational testing. The participants were 527 adults (275 male, 252 female) between the ages of 20 and 69 years from the general population around Kalamazoo, Michigan. The participants were required to have thresholds better than 80 dB HL at all frequencies between 0.5 and 8 kHz and no more than 40 dB of asymmetry between ears. Participants were also required to have tympanic membrane visibility with the use of conventional otoscopy, no middle ear pathology determined by tympanometry and otoscopy, and the capacity to comprehend written and spoken instructions. Participants were tested using TDH-39P earphones at 0.5, 1, 2, 3, 4, 6, and 8 kHz. The test–retest reliability at 4 and 8 kHz was poorer than at other frequencies, with 8 kHz being the most variable. The test–retest reliability at

4 kHz had a mean −0.5 dB with a standard deviation of ±6.4 dB. The test–retest reliability at 8 kHz had a mean of −0.2 dB with a standard deviation of ±7.0 dB. However, the authors concluded that this difference did not impact the 50 or 90% critical difference. Moreover, the variability can be expected to rarely result in a spurious 4 kHz notch of 10 dB or greater.

Instructions

Conventional instructions were proposed by Carhart and Jerger (1959). These instructions contained these four points: (a) how the patient should respond, (b) the patient should respond to the faintest tone they hear, (c) the patient should respond as soon as the stimulus is heard, and (d) each ear should be tested separately. Instructions may be altered if the false-alarm rate is too high or if the hearing thresholds obtained are poorer than expected. A false alarm is defined as a response from the patient when there is no stimulus presented. Strict instructions may be used to discourage the patient from guessing when the false alarm rate is too high. Strict instructions direct the patient to only respond when the patient knows they heard a stimulus. Lax instructions direct the patient to respond even if they only think they heard a stimulus and may be given encourage guessing when if the threshold obtained is poorer than expected (Dancer et al., 1976).

Dancer et al. (1976) conducted a study investigating the effect the type of instructions has on auditory threshold. The sample was comprised of 20 male subjects ranging in age from 21 to 64 with at least a mild sensorineural loss at 4 kHz. The testing was conducted in an audiometric testing booth using TDH-39 earphones. Prior to the earphones being placed, the conventional instructions outlined by Carhart and Jerger (1959) were given. The pure tone thresholds were determined using pulsed and continuous tones. Conventional pure tone audiometry was conducted in all three instruction conditions: conventional, strict, and lax. The experimental conditions were counterbalanced for practice effects. There was a similar number of false alarms in the conventional and lax conditions: 36 false alarms when conventional instructions were used and 43 false alarms using lax instructions. Conventional instructions are not effective at reducing false alarms. The least number of false alarms were recorded using strict instructions; the number of false alarms in this condition was 18. They suggest using strict instructions in which they instruct the subject to respond to the faintest tone they hear, but not guess. Due to the skewed distribution of data, inferential statistics were not utilized.

Stimulus

Burk and Wiley (2004), Hochberg and Waltzman (1972), and Mineau and Schlauch (1997) found that pulsed tones facilitate a higher incidence of patient awareness and found less presentations were required with pulsed tones to elicit a response at threshold. Pulsed tones may be preferable when testing patients with tinnitus, as patients are better able to determine if the sound perceived is an actual test stimulus or internal noise like tinnitus. Burk and Wiley also found that most patients, regardless of hearing or tinnitus status, have a significant preference for pulsed tones, further supporting the hypothesis that pulsed tones may be the more desirable stimulus.

Patient Factors

Initial conversation and case history can give additional information regarding the patient’s communicative abilities. Case history may indicate the patient’s perceived communication impairments, tinnitus, and sounds that are difficult to hear. Thresholds may be elevated due to the patient’s lack of motivation, for example, if the patient appears fatigued or irritated (Roeser & Clark, 2007).

Earphone Placement Variability

There are a small number of studies that primarily focus on the placement of earphones and the effects of auditory thresholds. Almeida et al. (2015) were the first to publish their findings on the topic. The cross-sectional study was conducted at two facilities for occupational audiology in Recife, Brazil. The sample was made up of 324 workers, including both sexes, with a wide range of occupations. Auditory thresholds were measured using the modified Hughson-Westlake method in 5 dB steps. The frequencies tested were the standard frequencies utilized in the monitoring technique, 0.25 to 8 kHz at octaves and inter-octaves, with a GSI 64 audiometer and TDH-50 earphones. The earphones were alternately placed by the audiologist and the worker. The order was switched for every other participant. The thresholds for 4, 6, and 8 kHz were analyzed due to their relatively shorter wavelengths and consequent susceptibility to standing waves. The student's *t*-test for individual samples was applied to the results obtained for both ears and demonstrated no significant difference in auditory thresholds between the experimental and control group ($p > 0.2$), indicating that the same results were obtained for the frequency regardless of the ear that was tested. The student's *t*-test for paired samples was applied to the results obtained from the earphones placed by the tester and the results obtained from the earphones placed by the subject and revealed a statistical difference between the groups for 4, 6, and 8 kHz ($p < 0.001$). An ANOVA revealed statistically significant differences in thresholds depending on who fit the earphones ($p < 0.001$). Improved auditory thresholds were obtained when the subjects fit the earphones at 4, 6, and 8 kHz when compared to thresholds obtained when the earphones were fit by the examiner.

Paquier et al. (2016) constructed a similar study using 20 normal hearing subjects who were inexperienced in hearing testing. Threshold measurements were made in the left ear only, and the earphones (Sennheiser HD600 or Telephonics TDH-39) were positioned by the participant to their preference. Sennheiser HD600s are circumaural audio earphones. These earphones have a frequency response from 0.12 to 40.5 kHz. Both standard and EHF audiometry were used. The subject was seated in front of a computer screen in an audiometric test booth while the automatic test was conducted using the Matrix Laboratory (MATLAB) programming platform. After a stimulus was presented, the computer screen displayed a question asking if the stimulus was perceived or not. After the initial test, two retests were completed, with and without earphone repositioning. Between tests, the participant was instructed to remove and replace the earphones on his or her head. The entire test was conducted with one model of earphones and repeated a week later with the other model. A Friedman test indicated no significant effect of the measurement order. For the HD600 earphones, a Wilcoxon test indicated significantly lower (poorer) reliability of threshold measurement when the earphone was removed at 2 kHz (p = 0.008) and 11 kHz (p = 0.011). For the TDH-39 earphones, a Wilcoxon test indicated significantly lower reliability of threshold measurement when the earphone was removed at 4 kHz (p = 0.014) and 6 kHz (p = 0.019). A Wilcoxon test indicated the differences were higher for the TDH-39 compared to the HD600 when the earphone was removed ($p < 0.001$) and when the earphone was not removed (p = 0.001). From this, it was concluded that the HD600 threshold reliability was significantly lower (poorer) when the earphones were removed at 2 and 11 kHz. At all other frequencies, the reliability was not altered by the earphones being repositioned. The TDH-39 had significantly lower (poorer) reliability at 4 and 6 kHz. There was not a simple correlation of good reliability at low frequencies and poorer reliability at high frequencies. Generally, reliability was better for the HD600 than the TDH-39 when the headphones were removed and when the earphones were not removed. There were reliability differences found between subjects. Depending on earphone model, the position could have a significant effect on hearing threshold measurement at certain frequencies.

Paquier and Koehl (2015) examined the effect headphone transfer function had on the placement of supra-aural and circumaural earphones and if those effects were auditorily discriminable by listeners. Several sound excerpts were used in the study: 3.5 seconds of pink noise; 5 seconds of drums, acoustic guitar, male human voice, and choir voices; and 4 seconds of a symphonic orchestra. Recordings were made using a Neumann KU 11 dummy head that was fit with omnidirectional microphones at the entrance of the blocked ear canal. The four models of earphones used in this study were Sennheiser HD497 supra-aural, Sony MDR CD580 circumaural, Sennheiser HD600 circumaural, and Sony MDR CD2000 circumaural. The earphones were placed and removed from the dummy head by two experimenters as they would normally be fit on a listener. Three recordings were then presented to listeners to determine whether headphone placement differences were noticeable. The listeners were instructed to place the Sony MDR CD2000 earphones on in a way that was comfortable and not to modify that placement for the duration of the test. The listeners were asked to determine which stimulus was different using a three interval three alternative forced choice response paradigm. The recording set was composed of two recordings of the same placement and one recording of another placement, the oddball stimulus. The oddball stimulus could appear in first, second, or third position. After the three stimuli had been listened to in succession, the listener indicated which one of the stimuli was the oddball. The listeners were divided into two experiments: experienced and naïve listeners.

Experiment I was conducted on 10 sound engineering students at the University of Brest. Using the three interval three alternative forced choice response paradigm, answering at random had a one-in-three (33.33%) chance of correctly selecting the oddball stimulus. A *t*-test indicated that average detection rates were statistically different from chance (33.33%) ($p = 0.001$) for all earphones and excerpts. A 2-way ANOVA displayed that earphone effect was statistically significant, $F(3, 108) = 20.199$; $p < 0.0001$. A Fisher least significant difference test determined that all earphones obtained statistically different detection rates from one another ($p < 0.0001$) except for the Sennheiser HD600 and Sony MDR CD2000 ($p = 0.345$). An ANOVA showed that excerpt effect was statistically significant, $F(2, 108) = 60.603$; $p < 0.0001$. A Fisher least significant difference test showed that detection rate was significantly higher with pink noise than the two music excerpts ($p < 0.0001$), while the music excerpts did not have statistically different detection rates. The oddball stimulus was easier to detect for recordings made with pink noise.

Experiment II examined the detectability of the differences in earphone placement by 10 naïve listeners using the same method that was utilized in Experiment I, utilizing Sennheiser HD497 and Sony MDR CD580 earphones. Student *t*-tests indicated that for this sample the average detection rates were statistically higher than chance, except when using Sennheiser HD497 and the symphonic orchestra excerpt. A 2-way ANOVA determined that earphone effect was statistically significant, $F(1, 54) = 42.46$; $p < 0.0001$. An ANOVA displayed that excerpt effect was statistically significant, $F(2, 54) = 15.36$; $p < 0.0001$. A Fisher least significant difference test showed that pink noise detection rate was statistically higher than the two music excerpts ($p < 0.0001$), and the music excerpts did not have statistically significant differences in detection rate ($p = 0.09$). Detection of the oddball stimulus was easier for recordings with pink noise. Spectral variation resulting for earphone placement can be easily discriminated and may bias experiments (Paquier & Koehl, 2015).

Research Rationale

There are currently no published studies directly examining the effects on hearing threshold of self-fitting across the three types of transducers in the same listeners for both conventional and EHF audiometry. This is an area that needs more exploration as it is clinically relevant to most practicing audiologists. The results from this investigation may be used to develop best practices and ensure that test results are reliable.

CHAPTER III

METHODOLOGY

The study was designed to evaluate variability of hearing thresholds between self-fit and audiologist-fit, utilizing TDH-50 supra-aural earphones, Etymotic ER-2 insert earphones, and Sennheiser HDA 200 circumaural earphones. Participants were given informed consent documents outlining the procedures that would be performed if they agreed to participate in the study. The current study was conducted following the University of Northern Colorado Institutional Review Board approval.

Participants

A convenience sample was recruited from the general population utilizing emails, flyers, and Facebook posts. Participants were of both sexes and were aged between 18 and 30 years. Participants were included if they had hearing thresholds between 0 and 20 decibels (dB) hearing level (HL) in the frequency range from 0.5 to 4 kilohertz (kHz). Participants would be excluded if they exhibited any of the following traits: (a) abnormal otoscopy, (b) outer ear piercings that may interfere with the fit of transducers, (c) unable to follow verbal instructions given for audiometric testing and/or placing audiometric transducers (d) limited dexterity that would prevent the ability to properly insert a foam earplug and/or press a response button, (e) graduate and undergraduate students majoring in audiology or audiology and speech and language sciences, (f) formally trained in audiometric testing, or (g) tinnitus symptoms. Hearing thresholds were determined while conducting the first trial of the experiment.

Instrumentation

Audiometer

An Otodynamics Madsen Astera computerized audiometer and a Grason-Stadler GSI Audiostar Pro audiometer were used during the testing procedure to administer the manual Hughson-Westlake method for signal detection. The audiometer was biologically calibrated before each session and had undergone an annual exhaustive calibration prior to data collection.

Transducers

Three types of transducers were used in the experimental procedure: TDH-50 supra-aural earphones, Etymotic ER-2 insert earphones with black couplers and ER1-14A 13 mm disposable foam eartips, and Sennheiser HDA 200 circumaural earphones.

Test Environment

Two sound booths meeting ANSI S3.1-1999, the maximum permissible ambient noise level (MPANL) for audiometric test rooms, were used for the audiometric testing (ANSI, 1999). This was verified using a Type I sound level meter with one-third octave band analyzer. These measurements were obtained at the position of the seated subject at the beginning data collection.

Experimental Procedure

The study was designed to obtain hearing threshold measures for the participants in one ear under the following conditions: when the three types of earphones, insert, supra-aural, and circumaural, were fit by the participant and when fit by the audiologist. The following experimental procedure was implemented.

Air Conduction Hearing Threshold Test

Test Operator

Testing was performed by the researcher, an audiology graduate student with three years of supervised clinical experience and Council for Accreditation in Occupational Hearing Conversation certification.

Listener Response Instructions

The researcher verbally instructed the participant to press the response button when they heard the tone presented by the audiometer. The researcher demonstrated how to adjust the headsets. The instructions for the circumaural and supra-aural earphones were given as follows:

> Put the earphones on so they are comfortable. The objective of this test is to find the quietest level you can hear tones or beeps. You will hear a series of beeps, and I want you to press this response button every time you hear the beeps. The beeps are going to get very quiet, and I need you to press the button even when the beeps are very faint. I will test one ear with different pitched tones.

The instructions for the insert earphones were accompanied by an illustration and given as follows:

> To place the eartip, firmly roll the foam eartip into the smallest diameter possible, similar to a foam earplug. Insert the foam tip deeply into the ear canal. Ideally, the foam tip is inserted fully into the canal and does not extend out of the ear. Allow the foam to expand and seal the ear canal. This picture shows correct and incorrect insertion depth.

Hearing Threshold Measurement

The participant was tested using the manual modified Hughson-Westlake method using five decibel steps at 0.5, 1, 2, 3, 4, 6, 8, 9, 10, 11.2, 12.5, 14, and 16 kHz. The frequency of 0.25

kHz was not included in the current study due to no significant findings in the literature at the frequency and time considerations.

The TDH-50 earphones and the Madsen-Astera audiometer were used to test .5, 1, 2, 3, 4, 6, and 8 kHz, in that order. The Etymotic ER-2 insert earphones with the Madsen Astera audiometer and HDA 200 earphones with the Grason-Stadler GSI Audiostar Pro audiometer were used to test extended high frequencies (EHF). The order of test frequencies was 0.5, 1, 2, 3, 4, 6, 8, 9, 10, 11.2, 12.5, 14, and 16 kHz. Thresholds were recorded at the lowest intensity; a response was elicited on more than half of ascending trials. One ear per participant was tested using counterbalancing across subjects. The test stimulus was a pulsed pure tone.

Experimental Conditions

Thresholds were obtained utilizing three transducers: Etymotic ER-2 insert, Sennheiser HDA 200 circumaural, and TDH-50 supra-aural earphones. Earphone order was counterbalanced across subjects. The thresholds were obtained in two experimental conditions (self-fit and audiologist-fit) with the three transducers listed above. The first condition was earphones fit and removed by the participant. The second condition was earphones fit and removed by the researcher. Following both trials with the first transducer, thresholds were obtained using a transducer that was not employed in the first trial, and a third trial was conducted for the final transducer that was not previously utilized. Table 5 lists the testing conditions and the order in which the subjects were tested.

Table 5

Testing Conditions and Testing Order

Group	Trial					
	1st	2nd	3rd	4th	5th	6th
1	TDH-50 self-fit	TDH-50 audiologist-fit	HDA 200 self-fit	HDA 200 audiologist-fit	ER-2 self-fit	ER-2 audiologist-fit
2	ER-2 self-fit	ER-2 audiologist-fit	HDA 200 self-fit	HDA 200 audiologist-fit	TDH-50 self-fit	TDH-50 audiologist-fit
3	HDA 200 self-fit	HDA 200 audiologist-fit	ER-2 self-fit	ER-2 audiologist-fit	TDH-50 self-fit	TDH-50 audiologist-fit

Data Collection and Analysis

Thresholds were manually recorded on a tabular audiogram during testing and transferred to a Microsoft Excel spreadsheet for analysis. In Statistical Package for Social Sciences (SPSS), version 27, a 2-way repeated measures analysis of variance (ANOVA) was used to detect hearing threshold differences at all frequencies depending on who fit the earphones and which earphones were utilized.

CHAPTER IV

RESULTS

Participants

Participants were recruited from the general northern Colorado geographical region. Twenty-one young adults were eligible to participate and were consented in accordance with the approved Institutional Review Board from the University of Northern Colorado (see Appendix A). One participant was excluded due to a transducer malfunction during the testing session, which left a total subject pool of 20 participants with complete data sets. Forty percent (*n* = 8) of the participants were male and 60% (*n* = 13) were female. The age of the participants ranged from 18 to 29 years with a mean of 22.4 years (*SD* ±2.96 years). All subjects met the inclusion criteria described in Chapter III and had normal hearing sensitivity, thresholds ≤ 20 decibels (dB) hearing level (HL) for 0.5 to 8 kilohertz (kHz). Hearing thresholds ranged from –5 to 20 dB HL from 0.5 to 8 hertz (Hz) when using supra-aural earphones fit by the audiologist with a mean of 4.57 (*SD* ±7.62) dB HL.

Test Environment Ambient Noise Levels

Data collection took place with subjects seated within two different double-walled sound booths (Tracoustics RS254)—one with the Grason-Stadler GSI AudioStar Pro and the other with the Madsen Astera audiometer. One-third octave band ambient noise measurements were taken at the beginning of data collection to ensure the sound booths were compliant with ANSI/Acoustical Society of America (ASA) S3.1-1999 (ANSI, 1999), maximum permissible ambient noise levels (MPANL) or audiometric test rooms. Both audiometric booths met the ambient noise criteria for both insert and supra-aural earphones according to ANSI/ASA S3.1-1999 (ANSI, 1999). Outcomes are summarized in Table 6.

Table 6

Ambient Noise Levels in Sound Booths

1/3 Octave bands (kHz)	MPANL (dB SPL) Ears-covered testing to 0 dB HL for supra-aural earphones	MPANL (dB SPL) Ears-covered testing to 0 dB HL for insert earphones	Ambient noise level (dB SPL)	
			Booth 1	Booth 2
0.125	30	54	Not tested	Not tested
0.25	20	48	Not tested	Not tested
0.5	16.0	16.0	14.0	13.7
0.8	19.0	19.0	16.0	17.2
1	21.0	21.0	19.5	18.4
1.6	25.0	25.0	20.5	20.3
2	29.0	29.0	14.7	15.1
3.15	33.0	33.0	11.6	12.1
4	32.0	32.0	11.6	12.1
6.3	32.0	32.0	11.6	12.1
8	32.0	32.0	11.6	12.1

Note: dB = decibel; kHz = kilohertz; MPANL = maximum permissible ambient noise level; SPL = standard pressure level; HL = hearing level. Adapted from *Maximum Permissible Ambient Noise Levels for Audiometric Test Rooms*, by American National Standard Institute, 1999.

Conventional Audiometric Thresholds

Table 7 summarizes the mean hearing thresholds for the conventional test frequencies tested with three transducers (supra-aural, circumaural, and insert earphones). In general, mean thresholds were consistent between audiologist-fit and self-fit earphones and within the clinical ±10 dB test–retest variability allowance (Carhart & Jerger, 1959; Landry & Green, 1999). The direction of differences was calculated based on the assumption that thresholds would be better when the transducers were fit by the audiologist, that is, self-fit threshold subtracted from audiologist-fit threshold. Therefore, a positive difference reflects that the self-fit threshold was lower (better) than the threshold obtained by the audiologist, and a negative difference reflects that the audiologist-fit threshold was lower (better) than the self-fit threshold.

Mean hearing thresholds were generally consistent between audiologist and self-fit earphones and within the clinical ±10 dB test–retest variability allowance (Carhart & Jerger, 1959; Flamme et al., 2014; Landry & Green, 1999). The hearing threshold mean differences ranged from −1.25 to +3.25 dB and differences were < 1.5 dB for all fitting conditions except when using supra-aural earphones and testing at 4 kHz (3.25 dB). Of the mean differences across all test frequencies, 66% were negative values, reflecting lower audiologist-fit thresholds compared to self-fit thresholds.

Table 7

Mean Hearing Threshold for Conventional Audiometry

Test frequency (kHz)	Fitter	Transducer		
		Supra-aural *M* (*SD*) in dB HL	Insert *M* (*SD*) in dB HL	Circumaural *M* (*SD*) in dB HL
0.5	Audiologist	6.75 (±5.91)	7.00 (±6.37)	4.25 (±6.13)
	Self	8.25 (±6.93)	8.25 (±6.13)	4.25 (±6.54)
	Difference	−1.5 (±1.2)	−1.25 (±0.24)	0.00 (±0.41)
1	Audiologist	4.50 (±6.26)	6.75 (±5.68)	3.50 (±5.87)
	Self	5.00 (±6.07)	8.00 (±6.37)	3.50 (±6.58)
	Difference	−0.5 (±0.19)	−1.25 (±0.69)	0.00 (±0.71)
2	Audiologist	0.50 (±5.83)	6.00 (±4.47)	1.50 (±5.87)
	Self	1.50 (±5.64)	6.00 (±5.03)	2.75 (±6.58)
	Difference	−1.0 (±0.19)	0.00 (±0.56)	−1.25 (±0.71)
3	Audiologist	0.75 (±5.68)	4.75 (±4.99)	1.75 (±6.74)
	Self	1.00 (±5.98)	6.00 (±5.03)	2.50 (±5.5)
	Difference	−0.25 (±0.30)	−1.25 (±0.04)	−0.75 (±1.24)
4	Audiologist	1.75 (±5.68)	5.25 (±4.44)	2.5 (±6.18)
	Self	3.00 (±6.77)	5.5 (±5.1)	3 (±5.48)
	Difference	−1.25 (±1.09)	−0.25 (±0.66)	−0.50 (±0.7)
4	Audiologist	10.5 (±10.74)	7 (±9.09)	4 (±9.68)
	Self	7.25 (±8.66)	6.5 (±8.75)	4.25 (±9.77)
	Difference	3.25 (±2.08)	0.50 (±0.34)	−0.25 (±0.09)
8	Audiologist	7.25 (±6.78)	1.75 (±8.63)	6.5 (±9.05)
	Self	6 (±7.36)	2.5 (±10.94)	6.25 (±9.01)
	Difference	1.25 (±0.58)	−0.75 (±2.31)	0.25 (±0.04)
0.5 – 8	Audiologist	4.57 (±7.62)	5.5 (±6.58)	3.43 (±7.25)
	Self	4.57 (±7.18)	6.12 (±7.49)	3.79 (±7.17)
	Difference	0.00 (±0.44)	−0.62 (±0.91)	−0.36 (±0.08)

Note. dB = decibel; kHz = kilohertz; HL = hearing level. Differences were calculated as self-fit threshold subtracted from audiologist-fit threshold (audiologist-fit – self-fit).

A 2-way analysis of variance (ANOVA) was applied to the conventional hearing threshold measurements obtained with the three earphones for both fitting conditions (self-fit and audiologist-fit). The fitter condition did not significantly affect hearing threshold ($p = 0.515$, $\alpha = 0.05$). The transducer condition had a statistically significant effect on hearing threshold ($p = 0.001$, $\alpha = 0.05$) for conventional test frequencies. These results are displayed in Table 8. A Tukey post hoc test indicated that conventional hearing thresholds (0.5 to 8 kHz) obtained with circumaural earphones were significantly different from thresholds obtained with the supra-aural and insert earphones ($p = 0.001$, $\alpha = 0.05$). It should be noted that mean differences were less than 1 dB and not clinically significant.

Table 8

Two-Way Analysis of Variance for Conventional Audiometric Test Frequencies (0.5 to 8 kilohertz).

Source	Type III *SS*	*df*	*MS*	*F*-value	*p*
Intercept	18246.70	1	18246.70	356.18	0.000
Earphone	678.75	2	339.38	6.625	0.001
Fitter	21.70	1	21.70	0.424	0.515
Error	42827.86	836	51.30		
Total	61775.00	840			

Note. $\alpha = 0.05$.

Extended High Frequency Audiometric Thresholds

Table 9 summarizes the mean hearing thresholds obtained for the extended high frequencies (EHF; 9 to 16 kHz) for circumaural and insert earphones. When comparing self-fit and audiologist-fit mean hearing thresholds, the difference values fell within the clinical benchmark of ±10 dB.

When comparing mean differences for EHF hearing thresholds, all differences were 4.25 dB or lower and 42% favored the audiologist-fitter. These differences are within the test–retest variability range for EHF for this age group (Ahmed et al., 2001; Frank, 2001; Laukli & Mair, 1985; Northern et al., 1971). However, the standard deviations were larger and ranged from ±7.23 to ±16.66 dB than those that were found for conventional audiometric thresholds, which ranged from ±4.99 to ±10.74 dB and suggest more test–retest variability for EHF testing. For the insert earphones, the direction of mean hearing threshold differences was 83% negative and indicated lower (better) audiologist-fit thresholds for all frequencies except for 9 kHz, which had a positive mean difference of 0.35 dB. Mean hearing threshold differences for circumaural earphones were 100% in the positive direction, indicating lower (better) thresholds in the self-fit condition. Standard deviations were ±3.09 or less.

Table 9

Mean Hearing Threshold for Extended High Frequency Audiometry

Test frequency (kHz)	Fitter	*M* hearing threshold Transducer Insert *M* (*SD*) dB HL	 Circumaural *M* (*SD*) dB HL
9	Audiologist	3.60 (±9.33)	5.00 (±11.24)
	Self	3.25 (±8.62)	3.75 (±10.87)
	Difference	0.35 (±0.71)	1.25 (±0.37)
10	Audiologist	1.25 (±9.72)	3.5 (±9.05)
	Self	3.75 (±8.09)	2.75 (±7.69)
	Difference	−2.5 (±1.63)	0.75 (±1.36)
11.2	Audiologist	−1.00 (±9.54)	4.5 (±9.99)
	Self	3.00 (±7.84)	3.75 (±7.23)
	Difference	−4.00 (±1.7)	0.75 (±2.76)
12.5	Audiologist	−3.25 (±11.73)	3.50 (±8.75)
	Self	1.00 (±8.97)	2.50 (±8.81)
	Difference	−4.25 (±3.06)	1.0 (±0.06)
14	Audiologist	−0.75 (±11.96)	6.25 (±15.03)
	Self	0.00 (±14.05)	5.25 (±13.62)
	Difference	−0.75 (±2.09)	1.0 (±1.38)
16	Audiologist	−2.25 (±16.66)	4.00 (±16.43)
	Self	−1.25 (±16.37)	1.50 (±15.57)
	Difference	−1.0 (±0.29)	2.5 (±0.86)
9 – 16	Audiologist	−0.42 (±12.68)	4.46 (±11.90)
	Self	1.63 (±11.08)	3.25 (±10.90)
	Difference	−2.05 dB (±1.60)	1.21 dB (±1.00)

Note. dB = decibel; HL = hearing level; kHz = kilohertz. Differences were calculated as self-fit threshold subtracted from audiologist-fit threshold (audiologist-fit – self-fit).

A 2-way ANOVA was applied to hearing threshold measurements for circumaural and insert earphones and both fitting conditions for the extended test frequency range (9 to 16 kHz). Though not clinically significant (differences of −2.05 to 1.21 dB), the transducer condition had a statistically significant effect ($p = 0.002$, $\alpha = 0.05$) on hearing thresholds between 9 and 16 kHz. The fitter condition did not have a statistically significant effect on hearing thresholds ($p = 0.696$, $\alpha = 0.05$). These results are summarized in Table 10.

Table 10

Two-Way Analysis of Variance for Extended High Frequency Audiometry (9 to 16 kHz)

Source	Type III *SS*	*df*	*MS*	*F*-value	*p*
Intercept	2385.21	1	2385.21	17.50	0.000
Earphone	1267.50	1	1267.50	9.30	0.002
Fitter	20.83	1	20.83	0.153	0.696
Error	65026.46	477			
Total	68700.00	480			

Note. $\alpha = 0.05$.

Similar to conventional audiometry, differences between self-fit and audiologist-fit EHF thresholds were not statistically significant ($p = 0.969$, $\alpha = 0.05$), but there was statistical significance between the insert earphones and circumaural earphones ($p = 0.002$, $\alpha = 0.05$). Although statistical significance was present for some experimental conditions, the differences in hearing thresholds were not clinically significant and suggest that audiologist-fit and self-fit thresholds do not differ for EHF hearing tests conducted in the clinical environment.

Summary

For conventional audiometry, the fitter condition did not have a significant effect on hearing threshold (p = 0.515, α = 0.05); however, transducer condition had a statistically significant effect on hearing threshold (p = 0.001, α = 0.05). Circumaural earphones were significantly different than thresholds obtained with the supra-aural and insert earphones (p = 0.001, α = 0.05) for conventional audiometry. Similarly, differences between self-fit and audiologist-fit EHF thresholds were not statistically significant (p = 0.969, α = 0.05), but there was statistical significance between the insert earphones and circumaural earphones (p = 0.002, α = 0.05).

CHAPTER V

DISCUSSION AND CONCLUSIONS

The purpose of the current study was to investigate the variability in hearing thresholds based upon the type of transducer and person fitting the transducer in individuals with normal hearing sensitivity. This study is the first to evaluate the variability for self-fit and audiologist-fit hearing thresholds obtained with supra-aural, circumaural, and insert earphones for both conventional and extended high frequency (EHF) audiometry in the same subjects.

Comparison to the Literature

Tables 11 through 13 provide comparisons of matched mean hearing threshold outcomes from the current study to the mean hearing thresholds for specific combinations of audiometric frequencies reported in similar studies using similar transducers. The hearing threshold data (see Appendix B) from the current study were extracted using equivalent calculations based on the frequencies and earphones that were used in the referenced study.

Table 11

Comparison of Almeida et al. (2015) to the Current Study

Study	Study population	Subjects (*n*)	*M* participant age (yrs) & (*SD*)	Test frequencies (kHz)	Transducer type	Fitting condition	*M* threshold (dB HL) & (*SD*)	*M* threshold difference between audiologist and self-fit (dB)
Almeida et al. (2015)	Brazilian workers in hearing conservation program; No hearing level pre-requisite	*n* = 324	33.29 years (±10.41)	4, 6, 8	TDH-50	Audiologist	30.47 (±6.9)	10.92 (±0.81)
					TDH-50	Self	19.85 (±7.71)	
Current study	Normal hearing, young adults	*n* = 20	22.4 years (±2.96)	4, 6, 8	TDH-50	Audiologist	6.5 (±7.73)	1.08 (±1.25)
					TDH-50	Self	5.42 (±7.60)	

Note. dB = decibel; HL = hearing level; kHz = kilohertz. Mean difference was calculated by self-fit threshold subtracted from audiologist-fit threshold (audiologist-fit – self-fit).

Table 12

Comparison of Landry and Green (1999) to the Current Study

Study	Study population	Subjects (*n*)	*M* participant age (yrs) & (*SD*)	Test frequencies (kHz)	Transducer type	Fitting condition	*M* threshold (dB HL) & (*SD*)
Landry and Green (1999)	Young adults, no hearing level pre-requisite	20	25.7	0.25, 0.5, 1, 2, 4, 8	TDH-50P	Audiologist	1.47 (±4.87)
				0.25, 0.5, 1, 2, 4, 8	ER-3A	Audiologist	1.25 (±5.52)
Current study	Normal hearing, young adults	20	22.4 (±2.96)	0.5, 1, 2, 4, 8[a]	TDH-50	Audiologist	4.8 (±6.88)
				0.5, 1, 2, 4, 8[a]	ER-2	Audiologist	5.35 (±5.92)

Note. dB = decibel; HL = hearing level; kHz = kilohertz. Mean difference was calculated by self-fit threshold subtracted from audiologist-fit threshold (audiologist-fit – self-fit).

[a] 0.25 kHz was not tested.

Table 13

Comparison of Flamme et al. (2014) to the Current Study

Study	Study population	Subjects (*n*)	*M* participant age (yrs) & (*SD*)	Test frequencies (kHz)	Transducer type	Fitting condition	*M* threshold (dB HL) & (*SD*)
Flamme et al. (2014)	Adults in Kalamazoo, MI, pure tone threshold better than 80 dB HL	527	No *M* data available (20-69)	0.5, 1, 2, 4, 6, 8	TDH-39	Audiologist	−0.66 (±5.19)
Current study	Normal hearing, young adults	20	22.4 years (±2.96)	0.5, 1, 2, 4, 6, 8	TDH-50	Audiologist	3.43 (±7.25)

Note. dB = decibel; HL = hearing level; kHz = kilohertz. Mean difference was calculated by self-fit threshold subtracted from audiologist-fit threshold (audiologist-fit – self-fit).

Mean hearing thresholds obtained by the audiologists were approximately 24 decibels (dB) higher in the Almeida et al. (2015) study population (30.47 dB hearing level [HL]) than for the current study (6.5 dB HL). This same general trend is apparent when comparing the Almeida et al. mean hearing thresholds for self-fit outcomes (19.85 dB HL), which is approximately 14 dB higher than the current study (5.42 dB HL). This discrepancy in mean hearing thresholds is likely due to the presence of workers with hearing loss participating in the Almeida et al. study, whereas the current study excluded subjects with hearing thresholds >20 dB HL for 0.5 to 8 kHz. With TDH-50 supra-aural earphones, mean hearing threshold differences between audiologist and self-fit for 4, 6, and 8 kHz reported by Almeida et al. (10.92 [±0.81]) were higher than the differences reported in the current study (1.08 [±1.25]). In the Almeida et al. study, self-fit mean hearing threshold was significantly (p = 0.001) lower (better) than those obtained when earphones were fit by the audiologist. The larger mean hearing threshold differences between audiologist and self-fit obtained by Almeida et al. (10.92 [±0.81]) also slightly exceeded the standard test–retest variability of ±10 dB that is clinically accepted internationally for conventional audiometry (Flamme et al., 2014; Landry & Green, 1999; Schmuziger et al., 2004). Almeida et al. rationalized the much lower self-fit thresholds and the larger mean difference by proposing the possibility of ear canal collapse and poorer sound transmission due to the shorter stimulus wavelengths at 6 and 8 kHz. They suggested these factors interfered with the audiologist-fit hearing thresholds but not the self-fit thresholds. However, collapsing canals were a factor the researchers allegedly controlled for in the study design (exclusion criteria), and it could be argued that standing wave issues might be present for both self-fit earphones as well as audiologist-fit earphones. The approximately 1 to 2 dB differences found in the current study were not statistically analyzed for 4, 6, and 8 kHz but can be interpreted as minimal differences.

Possible reasons for the discrepancies between the audiologist-fit and self-fit differences in the Almeida et al. (2015) study compared to the current study may relate to differences in the skill of the audiologists placing the TDH-50 earphones on the listener or perhaps variations in the ambient noise conditions, which were not reported by Almeida et al. (2015) but may be higher or more variable when testing onsite in industry as opposed to a quiet clinical location.

Landry and Green (1999) utilized young adults with normal hearing for their study comparing hearing thresholds obtained with insert earphones (ER-3A) and supra-aural earphones (TDH-50P) for testing at 0.25, 0.5, 1, 2, 4, and 8 kHz but did not evaluate self-fit hearing thresholds. The outcomes for Landry and Green are summarized in Table 12 alongside the current study findings for comparable test frequencies.

With TDH-50P supra-aural earphones, mean hearing thresholds and standard deviations from Landry and Green (1999; 1.47 [±4.87] dB HL) were similar to the current study (4.8 [±6.88] dB HL) when testing young adults. Like the supra-aural earphone mean thresholds, Landry and Green had slightly lower mean thresholds for insert earphones (1.25 [±5.52] dB HL) when compared to the current study (5.35 [±5.92] dB HL). Although Landry and Green did not control for hearing loss when recruiting young adult subjects, both studies reported mean hearing thresholds within normal limits (≤ 20 dB HL). The approximately 4 to 7 dB variability reported for both supra-aural and insert earphones in both studies are within ± 10 dB clinical test–retest variability (Carhart & Jerger, 1959; Flamme et al., 2014). Landry and Green included 0.25 kHz and the current study did not. However, it is not likely that hearing threshold variation at 0.25 kHz would differ from other test frequencies (Flamme et al., 2014; Landry & Green, 1999; Schmuziger et al., 2004). The study populations were similar in the two studies and the outcomes when the transducers were fit by the audiologists are generally similar. No comparisons can be made about self-fitting of the transducers since Landry and Green did not include a self-fit condition in their experimental design.

Flamme et al. (2014) recruited adults aged 20 to 69 years of age in the area around Kalamazoo, Michigan, to evaluate test–retest variability of hearing thresholds obtained with supra-aural TDH-39 for testing conventional audiometric thresholds 0.5, 1, 2, 4, 6, and 8 kHz. Table 13 provides a summary of the Flamme et al. in the context of the current study outcomes.

Mean hearing threshold for the Flamme et al. (2014) study was slightly lower for the TDH-39 earphones (−0.66 [±5.19]) when testing 0.5 to 8 kHz when compared to the current study (3.43 [±7.25]) with TDH-50 earphones. Hearing thresholds obtained by Flamme et al. were approximately 4 dB better (lower) than hearing thresholds obtained in the current study. The ±5 to 7 dB of variability in the two studies is within ±10 dB test–retest variability and consistent with previous literature (Carhart & Jerger, 1959; Landry & Green, 1999). The study populations in the studies were somewhat different, as Flamme et al. included participants up to 69 years of age, while the current study included participants up to 29 years of age. Participants in the Flamme et al. (2014) study were screened at 70 dB HL for 0.5, 1, 2, 4, 6, and 8 kHz. If participants responded at 70 dB HL, they were included in the study. If they did not respond, those participants were dismissed from the study (Flamme et al., 2014). The current study's participants had thresholds ≤20 dB HL from 0.5 to 8 kHz. Nevertheless, the outcomes for audiologist-fit hearing thresholds were within approximately 4 dB for both studies. A comparison cannot be made regarding self-fit hearing thresholds as Flamme et al. did not include this condition in their design.

Rodríguez Valiente, Garcia Berrocal, et al. (2014) had a cohort of young adults for whom EHF audiometric hearing thresholds were obtained using HDA 200 circumaural earphones fit by an audiologist. These researchers did not evaluate hearing thresholds when transducers were self-fit. Therefore, self-fit hearing threshold variability cannot be examined in the context of this study. Hearing thresholds were measured in dB sound pressure level (SPL) in the Rodríguez Valiente, Garcia Berrocal, et al. study, while the current study used calibrated decibel HL for hearing threshold measurement. Because of this, the mean hearing thresholds cannot be directly compared as the exact calibration references are unknown. However, the Rodríguez Valiente, Garcia Berrocal, et al. study reported variability of ±12.36 for 8 to 16 kHz, and the current study reported variability at ±11.9 for 8 to 16 kHz when participants were tested with HDA 200 circumaural earphones. Hearing threshold variability for both studies is well within clinically acceptable test–retest variability of ±15 dB for EHF audiometry (Ahmed et al., 2001; Flamme et al., 2014; Frank, 2001; Laukli & Mair, 1985; Northern et al., 1971; Schmuziger et al., 2004).

Frank (2001) evaluated EHF (8 to 16 kHz) hearing threshold variability in 100 young adults aged 18 to 25 years old using HDA 200 circumaural earphones fit by an audiologist. The participants in this study and the current study were similar, as the participants in the Frank study had hearing thresholds ≤15 dB HL for 0.5 to 8 kHz, and the current study's participants had hearing thresholds ≤ 20 dB HL for 0.5 to 8 kHz. The Frank study measured hearing thresholds using dB SPL, and the current study used dB HL for hearing threshold measurement. Due to this difference, it is not possible to directly compare hearing thresholds. Nonetheless, the variability reported by Frank was ±10.86 dB for 8 to 16 kHz, and the current study reported hearing threshold variability of ±10.96 dB for 8 to 16 kHz. Hearing threshold variability is within clinically acceptable test–retest variability of ±20 dB for extended high frequencies in both studies (Ahmed et al., 2001; Flamme et al., 2014; Laukli & Mair, 1985; Northern et al., 1971;

Schmuziger et al., 2004). A comparison cannot be made regarding self-fitting of the transducers since Frank did not incorporate a self-fit condition in the experimental design.

Audiometric Methods

Manual Audiometry

The current study evaluated only manual audiometry; however, audiograms obtained with automatic audiometry are equally as reliable as those obtained with manual audiometry (Ho et al., 2009; Mahomed-Asmail et al., 2016; Sakabe et al., 1978). This suggests that results obtained from the current study may be applicable to automatic audiometry, and results would likely not differ if the current study had been completed utilizing automatic audiometry.

Step Size

A previous study by Paquier et al. (2016) used two decibel steps when determining hearing threshold, which is more precise. The current study utilized five decibel steps in determining threshold, as that is what is widely used and accepted clinically. Moreover, Jervall and Arlinger (1986) concluded that reducing the step size in pure tone audiometry does not produce an improved test–retest reliability but does increase the test time due to the number of threshold crosses needed at the lower level. Findings of the present study were designed to be applied to typical clinical practices to improve efficiency of testing without compromising the reliability of the results (ASHA, 2005).

Ambient Noise Levels

According to ANSI/Acoustical Society of America (ASA) 3.1-1999, R2018 (ANSI, 1999), ambient noise levels must be at or below specified levels to accurately obtain hearing thresholds down to a specified level. This is to ensure that the hearing thresholds are accurate, and the test stimulus is not being masked by ambient noise in the room. If ambient noise in the room is higher than the accepted universal standard, thresholds may be affected by as much as 8 to 14 dB depending on the earphone used and frequency tested (Frank & Williams, 1993).

For the current study, ambient noise levels measured in each booth were below the maximum permissible ambient noise levels (MPANLs) and allowed for accurate threshold measurement at the minimum level of 0 dB HL from 0.5 to 8 kHz (ANSI, 1999; ANSI/ASA S3.1-1999, R2018). Some of the hearing thresholds obtained in the current study were below 0 dB HL. Hearing thresholds for 0.5 to 1.6 kHz were within the tolerance for permissible ambient noise for testing ears covered at 0 dB HL but were not within tolerance for signals below 0 dB HL. This means that a small number of thresholds obtained below 0 dB HL may be questionable depending on the disparity between the actual ambient noise level in the booth at the specific test frequency at the time of testing which is unknown. Clinically, sound booth ambient noise levels are typically verified annually at the time of audiometer calibration and are assumed to be consistent over time unless the environment in which the booth is installed changes. The researcher assumed that ambient noise levels measured in the sound booths at the start of the study were consistent during the period of data collection since the booths were located in a quiet clinical test area that is routinely used for diagnostic hearing testing.

Listener Factors

Listener factors are considerations that must be made based on intrinsic characteristics of the patient or listener. This can include, but are not limited to age, dexterity, hearing status, tinnitus status, biological sex, fitting experience, ear anatomy, and cognitive ability.

Age

The participants in the current study had an age range of 19 to 29 years with a mean of 22.4 years. This does not reflect the typical patient populations visiting audiology clinics, as the majority of patients seen are 65 years or older. Adults 65 years of age or older make up 14% of the United States population at 46 million people, and between 25 and 50% of this population report having a disabling hearing loss (Planey, 2019). The World Health Organization (2018) estimated that 466 million people in the world (6.1%) have a disabling hearing loss. These numbers are expected to rise over the next 10 to 20 years. Approximately 93% (432 million) of these cases are adults with 56% being male and 44% being female. This leaves 7% of the cases to children under 18 years of age.

Approximately 32 million workers are exposed to workplace hazards that may damage hearing (Centers for Disease Control and Prevention, 2019). The current study does not address hearing threshold variability that may occur in older or younger age groups and those with hearing loss.

Landry and Green (1999) found that listeners around the age of 65 years tended to have greater test–retest variability at conventional high frequencies above 1 kHz for both insert and supra-aural earphones. The test–retest differences were 1.35 dB for supra-aural earphones and 2.15 dB for insert earphones, and Landry and Green did not interpret these values as clinically significant. Additionally, there was a positive correlation between age and hearing threshold. As age increases, hearing thresholds also tend to increase. This decrease in hearing acuity is more apparent for the EHFs (Ahmed et al., 2001; Corso, 1959). The effects of aging could not be assessed in the current study as the participants were limited to young adults between the ages of 18 and 28 years.

Another consideration is the age at which a child would be able to self-fit earphones. Future research is needed to evaluate at what developmental age a pediatric patient would be able to follow complex directions and self-fit the various transducers comparable to an audiologist-fit. Children who are developmentally 5 years and older are able to complete a pure tone hearing evaluation similar to audiometric exams given to adults. However, children at 5 years are only beginning to learn the alphabet and how to read and, therefore, would likely be unable to understand the written directions (American Academy of Pediatrics, 2020). These factors may make giving instructions in a written format with images an ineffective way to train these patients to fit earphones, and some may not be able to complete the task even in a different modality. Furthermore, some children may not tolerate supra-aural or circumaural earphones as they can be cumbersome and heavy. In these cases, insert earphones may be a better option (British Society of Audiology, 2011).

Dexterity

Approximately 4,518 people in the United States (1.7%) report having difficulty handling small objects according to the National Health Interview Survey (Centers for Disease Control and Prevention, 2018). Patients within this population may have difficulty handling the foam inserts, rolling them down adequately for insertion, and physically manipulating the ear for insert earphone insertion, while supra-aural or circumaural earphones may not cause the same difficulty (Samelli et al., 2018). This issue was not assessed directly, but it is a factor that should be taken into consideration when evaluating if a patient would be a good candidate for self-fitting earphones. Effective fitting of the earphones is crucial in obtaining accurate and reliable hearing thresholds.

Hearing and Tinnitus Status

The participants in the current study were all young adults with normal, healthy ears. More variability is introduced as more hearing loss is present or if tinnitus is present (Dancer et al., 1976). Despite larger inter-subject hearing threshold variability for conventional and EHFs regardless of earphone type, comparisons over time on an individual basis are reliable and stable (Ahmed et al., 2001; Laukli & Mair, 1985; Rodríguez Valiente, Garcia Berrocal, et al., 2014). This suggests that the results of the current study may be applicable to patients with hearing loss and/or tinnitus. However, patients with hearing loss may have more difficulty obtaining and subjectively judging an effective seal as they may miss some of the auditory cues that normal hearing patients would perceive.

Sex

When comparing hearing thresholds between males and females, females tend to have slightly lower (better) thresholds than their male counterparts across frequencies. This difference becomes more evident in the EHF (Ahmed et al., 2001; Corso, 1959). This was also true for the participants in the current study. While the sexes were not equally represented in the participant pool, males tended to have marginally higher (approximately 5 dB) hearing thresholds than females, except at 3 kHz where the average female threshold was 1.52 dB higher than the male average threshold. Sex alone is not a factor that is expected to have an influence on hearing thresholds or hearing threshold variability. Though not examined in the current study, the presence of thick facial hair such as sideburns or a beard may affect the fitting of earphones if the hair interferes with the seal of circumaural earphones. Ear piercings were a factor that were controlled for in the current study and may add another layer of complication to fitting earphones, especially when piercings interfere with the ear canal opening or those placed on the periphery of the pinna. These piercings may not allow a proper seal to form between the transducer and the ear or may make it difficult to properly position insert earphones. While either sex may have these types of ear piercings, they are more typically encountered with females (Bone et al., 2008; Stieger et al., 2010). Some piercings may not interfere with the placement of the earphones, but some may require removal to create an appropriate seal and allow the comfortable placement of the earphones. This may be a reason to have the patient self-fit the earphones, as they will have the sensation of the earphone placement/seal over the piercings while the audiologist must rely solely on visual fit.

Ear Fitting Experience

A listener's experience fitting devices to their own ears may influence the outcomes of the current study. Most young adults have experience fitting over-the-ear headphones for gaming or music listening. These devices are like circumaural or supra-aural earphones and, consequently, the participants in the current study may have been influenced by their use of these devices which was not controlled for.

With regard to self-fitting insert earphones, patients who have experience fitting formable earplugs or hearing aids to their ears may have a slight advantage when fitting insert earphones over those who are novice to the task. This factor was not tracked, specifically in the current study. However, when given proper instructions, persons with no prior experience with fitting insert earphones (audiometric technicians) have been able to insert the earphones comparable to a trained audiologist (Bell-Lehmkuhler et al., 2009). This suggests that earplug or hearing aid fitting experience may not have influenced the self-fit outcomes for insert earphones in the current study.

Collapsing Canals

Some patients may have ear canals that collapse only when pressure is applied directly to the pinna. This is more common in individuals with small, narrow ear canals, the elderly, and those with protruding pinnae (Chaiklin & McClellan, 1971). This collapse can cause a false high frequency hearing loss due to the ear canal collapsing (Killion & Villchur, 1989). Circumaural earphones do not typically cause collapsed ear canals, unlike supra-aural earphones (Smull et al., 2018). Insert earphones also eliminate the risk of collapsing canals, due to the insert earphones holding the ear canal open rather than putting pressure on the pinna (Killion & Villchur, 1989; Marangoni & Gil, 2009).

Instruction Modality

Instructions were presented orally to participants in the current study, and listeners had normal hearing. Those with hearing loss may require an altered instruction format such as written instructions or closed caption video instructions. These instructions could even be displayed in the waiting room for patients to watch prior to their hearing test appointment. According to the Centers for Disease Control and Prevention (2020a), 12 million Americans have blindness or some form of vision loss. Patients with visual impairment may not be impacted by receiving oral instructions for earphone placement but may have difficulty with written instructions.

Cognition

The current study utilized young adults with the ability to follow oral instructions for earphone fitting. The Centers for Disease Control and Prevention (2020a) stated that more than 5.6 million people in the United States have a cognitive impairment and/or are experiencing cognitive decline which may result in difficulty concentrating on tasks, remembering instructions, making decisions, or responding to stimuli. Patients with a cognitive impairment may not be good candidates for self-fitting of the earphones if the oral instructions are too complex and cannot be followed correctly. In such cases, reinstruction may be necessary throughout testing to ensure that the individual is responding consistently and is focused on the task.

Transducer Considerations

Clinically, it may be more time efficient to utilize circumaural earphones if the audiologist is planning on having the patient fit the earphones and if the evaluation will include both conventional and EHF audiometry. This reduces the amount of contact time and may increase patient comfort without compromising the validity of the test.

The current study used the research grade ER-2 insert earphones in order to test the EHFs, and most audiology clinics would likely only have access to ER-3C audiometric earphones. The ER-3C earphones are calibrated for testing between 0.125 and 8 kHz (Etymotic Research, n.d.). Consequently, using self-fit ER-3C insert earphones would be limited to testing the conventional test frequencies. This practical limitation further supports the use of circumaural earphones clinically.

Slightly lower thresholds were obtained with the insert earphones when compared to the other transducers in the current study. This may be a result of the inserts holding the ear canal open and the sound being delivered closer to the tympanic membrane when compared to supra-aural and circumaural headphones (Killion & Villchur, 1989; Marangoni & Gil, 2009). Additionally, supra-aural earphones may be subject to cushion leak and more physiologic noise resulting in slightly elevated thresholds relative to insert earphones (Wilber et al., 1988).

As mentioned in Chapter II, insert earphones have the advantage of being more sanitary and providing improved infection control when compared to supra-aural and circumaural earphones (Killion & Villchur, 1989). However, the one-time-use foam tips of insert earphones are costly and an additional expense when compared to the other two transducers. To ensure that the insert eartips are seated properly on the probe tube of the earphone, it would be most effective for the audiologist to couple the eartips and the earphone prior to giving the patient the earphone to fit them.

Another consideration is that the HDA 200 circumaural earphones are no longer in production, and audiologists have had to locate and utilize alternative circumaural earphones. The RadioEar DD450 earphones and HDA 300 earphones replicate the physical fit characteristics of the HDA 200 earphones. The DD450 earphones approximate the acoustic characteristics reference equivalent threshold sound pressure levels (RETSPLs) of the HDA 200 earphone very closely, while the HDA 300 earphones have less attenuation, a higher occlusion effect, and different RETSPLs (Frank, 2001; Han & Poulsen, 2009; Smull et al., 2018).

Clinical Implications of Self-Fitting Earphones

If properly instructed, adult patients with adequate dexterity and cognition should be able to properly fit inserts, circumaural or supra-aural earphones. This is especially pertinent given the current global COVID-19 pandemic and the need to reduce close physical contact. Audiologists are often very close to the patient’s face when they are fitting earphones for audiometric evaluation. Having the patient self-fit the earphones would reduce the close contact time and minimize touch contamination as the audiologist would not have to come into physical contact with the patient (ASHA, 2020; Centers for Disease Control and Prevention, 2020b).

Circumaural earphones may be the best choice when earphones are self-fit, as they do not cause collapsing canals, they are cost effective, and relatively easy to self-fit. In addition, they provide the opportunity to measure both conventional and EHF hearing thresholds without changing transducers. These earphones are also easy to disinfect between patients using antimicrobial wipes.

Another test situation that may find benefit by adapting clinical test procedures to allow self-fitting of transducers would be for serial audiometry in workers enrolled in hearing conservation programs. Often workers are tested in groups, and the audiometric technician must fit earphones to several individuals sequentially before starting the automated testing. If future research supports the self-fitting of audiometric earphones by workers enrolled in hearing conservation programs, it has the potential to reduce test time and perhaps improve test–retest reliability since these listeners are already familiar with wearing hearing protection devices such as earplugs and earmuffs.

Future Directions

The current study was completed with a single audiologist fitting the earphones, and it is not possible to determine if these results would be similar for other audiologists. The current study should be repeated with a larger sample of audiologists and audiometric technicians who may be performing conventional air-conduction pure tone audiometry. Children, older adults, and people with hearing loss and tinnitus were not included in the current study. This excludes large populations typically evaluated by audiologists. A replicated study that includes these populations would make the findings more generalizable to those populations. The current study was also completed in an experimental setting and should be repeated in settings such as clinics, schools, workplaces, and hospitals.

Summary

There were no clinically significant differences in hearing thresholds obtained when supra-aural, insert, and circumaural earphones were fit by an audiologist or self-fit by the participant for conventional and EHF audiometry. Because of this, it may be beneficial and time effective to allow patients to self-fit earphones which also facilitates the reduction of close physical contact. Circumaural earphones may be the preferred choice for self-fitting because of the ability to test both conventional and EHF hearing thresholds with a single transducer.

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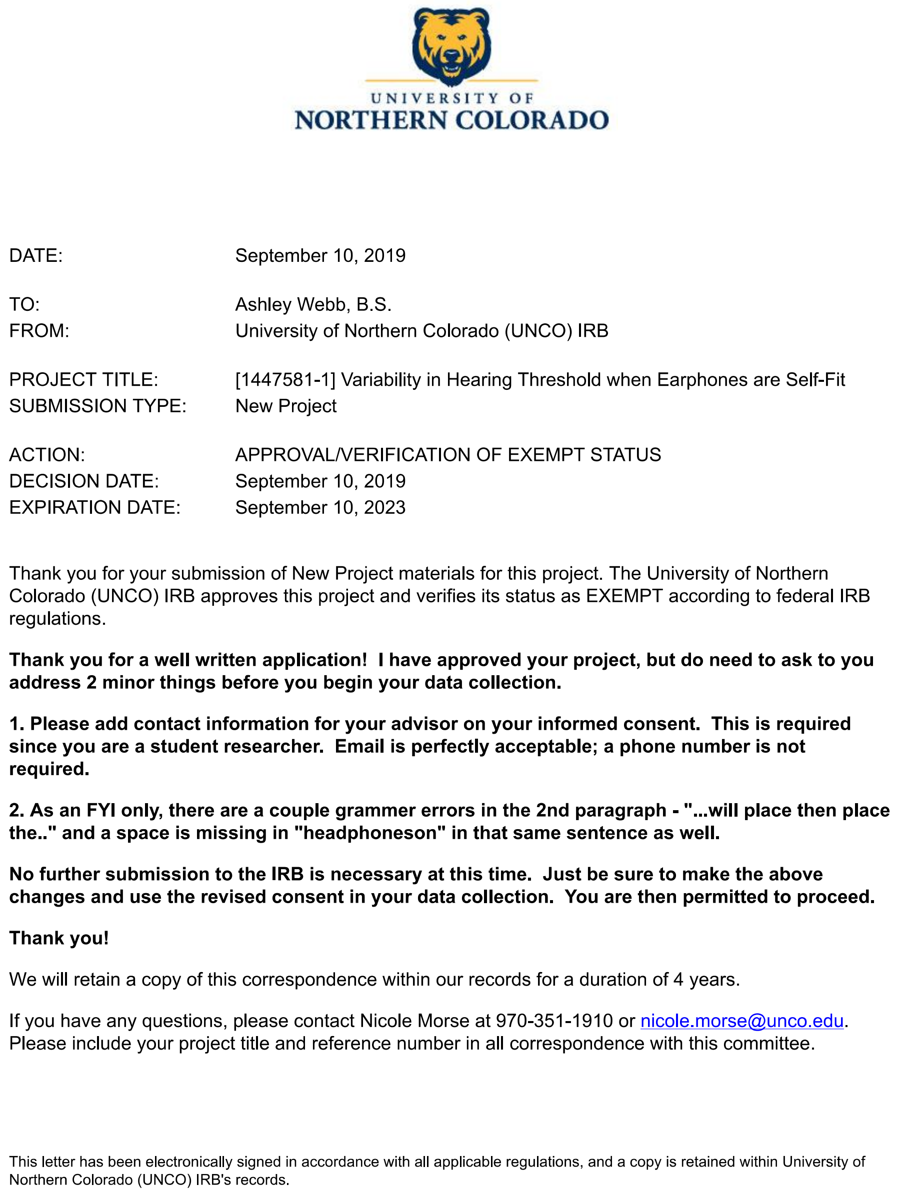
APPENDIX A

INSTITUTIONAL REVIEW BOARD APPROVAL



UNIVERSITY OF
NORTHERN COLORADO

DATE: September 10, 2019

TO: Ashley Webb, B.S.
FROM: University of Northern Colorado (UNCO) IRB

PROJECT TITLE: [1447581-1] Variability in Hearing Threshold when Earphones are Self-Fit
SUBMISSION TYPE: New Project

ACTION: APPROVAL/VERIFICATION OF EXEMPT STATUS
DECISION DATE: September 10, 2019
EXPIRATION DATE: September 10, 2023

Thank you for your submission of New Project materials for this project. The University of Northern Colorado (UNCO) IRB approves this project and verifies its status as EXEMPT according to federal IRB regulations.

Thank you for a well written application! I have approved your project, but do need to ask to you address 2 minor things before you begin your data collection.

1. Please add contact information for your advisor on your informed consent. This is required since you are a student researcher. Email is perfectly acceptable; a phone number is not required.

2. As an FYI only, there are a couple grammer errors in the 2nd paragraph - "...will place then place the.." and a space is missing in "headphoneson" in that same sentence as well.

No further submission to the IRB is necessary at this time. Just be sure to make the above changes and use the revised consent in your data collection. You are then permitted to proceed.

Thank you!

We will retain a copy of this correspondence within our records for a duration of 4 years.

If you have any questions, please contact Nicole Morse at 970-351-1910 or nicole.morse@unco.edu. Please include your project title and reference number in all correspondence with this committee.

This letter has been electronically signed in accordance with all applicable regulations, and a copy is retained within University of Northern Colorado (UNCO) IRB's records.

APPENDIX B

RAW HEARING THRESHOLD DATA

Table 14

Conventional Audiometry Hearing Thresholds for Audiologist-Fit Supra-Aural Earphones

Participant	Age	Sex	Ear	Earphone	Fitter	0.5 kHz	1 kHz	2 kHz	3 kHz	4 kHz	4 kHz	8 kHz
101	18	F	R	Supra-Aural	Audiologist	10	5	5	5	-5	5	0
102	20	M	L	Supra-Aural	Audiologist	5	0	-5	5	5	10	10
103	19	M	R	Supra-Aural	Audiologist	5	5	5	10	-5	10	5
104	25	M	R	Supra-Aural	Audiologist	15	0	0	5	5	15	0
105	21	F	L	Supra-Aural	Audiologist	5	5	0	-10	-5	5	5
106	21	F	R	Supra-Aural	Audiologist	10	10	5	5	5	5	10
107	23	F	L	Supra-Aural	Audiologist	5	0	-10	-5	-5	10	10
108	26	F	R	Supra-Aural	Audiologist	15	10	5	0	0	5	10
109	23	M	L	Supra-Aural	Audiologist	15	15	5	0	5	20	15
110	22	F	R	Supra-Aural	Audiologist	0	-5	-10	0	5	-5	-10
111	20	M	L	Supra-Aural	Audiologist	5	0	-10	0	0	30	5
112	21	M	L	Supra-Aural	Audiologist	5	5	0	0	5	5	10
113	20	F	R	Supra-Aural	Audiologist	0	5	5	5	10	10	10
114	25	M	L	Supra-Aural	Audiologist	5	5	5	-10	-10	5	15
115	28	F	R	Supra-Aural	Audiologist	0	-5	0	10	10	30	5
116	20	M	R	Supra-Aural	Audiologist	10	5	5	-5	10	35	20
117	21	F	L	Supra-Aural	Audiologist	20	20	10	0	5	5	5
119	26	F	R	Supra-Aural	Audiologist	0	0	-5	-5	0	5	15
120	21	F	R	Supra-Aural	Audiologist	5	0	0	0	0	10	5
121	28	F	L	Supra-Aural	Audiologist	0	10	0	5	0	-5	0

Note. kHz = kilohertz.

Table 15

Conventional Audiometry Hearing Thresholds for Self-Fit Supra-Aural Earphones

Participant	Age	Sex	Ear	Earphone	Fitter	0.5 kHz	1 kHz	2 kHz	3 kHz	4 kHz	4 kHz	8 kHz
101	18	F	R	Supra-Aural	Self	15	5	5	5	-5	10	-5
102	20	M	L	Supra-Aural	Self	0	0	0	-5	-5	10	10
103	19	M	R	Supra-Aural	Self	15	10	10	10	10	5	0
104	25	M	R	Supra-Aural	Self	20	5	0	0	10	10	0
105	21	F	L	Supra-Aural	Self	5	0	0	-5	-5	0	0
106	21	F	R	Supra-Aural	Self	5	10	10	5	10	5	15
107	23	F	L	Supra-Aural	Self	5	5	-5	-5	0	0	0
108	26	F	R	Supra-Aural	Self	5	5	5	0	-5	5	10
109	23	M	L	Supra-Aural	Self	15	15	10	5	10	5	20
110	22	F	R	Supra-Aural	Self	0	-5	-5	0	5	0	0
111	20	M	L	Supra-Aural	Self	15	0	-5	5	5	25	15
112	21	M	L	Supra-Aural	Self	10	0	-5	-5	5	5	0
113	20	F	R	Supra-Aural	Self	0	10	5	0	5	10	10
114	25	M	L	Supra-Aural	Self	5	5	-5	-10	-10	0	5
115	28	F	R	Supra-Aural	Self	5	0	0	15	15	25	10
116	20	M	R	Supra-Aural	Self	5	5	5	5	10	20	15
117	21	F	L	Supra-Aural	Self	25	20	10	0	5	0	10
119	26	F	R	Supra-Aural	Self	5	0	-5	0	0	10	0
120	21	F	R	Supra-Aural	Self	5	0	0	-5	0	10	10
121	28	F	L	Supra-Aural	Self	5	10	0	5	0	-10	-5

Note. kHz = kilohertz.

Table 16

Conventional Audiometry Hearing Thresholds for Audiologist-Fit Circumaural Earphones

Participant	Age	Sex	Ear	Earphone	Fitter	0.5 kHz	1 kHz	2 kHz	3 kHz	4 kHz	4 kHz	8 kHz
101	18	F	R	Circumaural	Audiologist	5	5	5	5	0	5	0
102	20	M	L	Circumaural	Audiologist	-5	0	5	-10	0	-10	0
103	19	M	R	Circumaural	Audiologist	5	5	5	10	5	0	-5
104	25	M	R	Circumaural	Audiologist	5	0	-5	0	0	5	0
105	21	F	L	Circumaural	Audiologist	5	5	0	5	0	5	10
106	21	F	R	Circumaural	Audiologist	0	0	5	5	5	-5	5
107	23	F	L	Circumaural	Audiologist	5	5	0	0	0	-5	5
108	26	F	R	Circumaural	Audiologist	0	0	5	-5	-10	0	5
109	23	M	L	Circumaural	Audiologist	10	10	10	0	5	5	20
110	22	F	R	Circumaural	Audiologist	0	-5	-5	0	-5	0	-10
111	20	M	L	Circumaural	Audiologist	5	5	0	5	5	30	30
112	21	M	L	Circumaural	Audiologist	0	10	-5	0	5	5	5
113	20	F	R	Circumaural	Audiologist	0	-5	-10	-5	0	0	5
114	25	M	L	Circumaural	Audiologist	10	5	5	-10	0	-5	10
115	28	F	R	Circumaural	Audiologist	0	5	5	15	15	20	15
116	20	M	R	Circumaural	Audiologist	5	5	5	10	15	20	10
117	21	F	L	Circumaural	Audiologist	25	20	10	5	10	5	15
119	26	F	R	Circumaural	Audiologist	0	-5	-10	-5	0	5	10
120	21	F	R	Circumaural	Audiologist	5	0	0	0	5	5	0
121	28	F	L	Circumaural	Audiologist	5	5	5	10	-5	-5	0

Note. kHz = kilohertz.

Table 17

Extended High Frequency Audiometry Hearing Thresholds for Audiologist-Fit Circumaural Earphones

Participant	Age	Sex	Ear	Earphone	Fitter	9 kHz	10 kHz	11.2 kHz	12.5 kHz	14 kHz	16 kHz
101	18	F	R	Circumaural	Audiologist	-5	-5	0	0	10	10
102	20	M	L	Circumaural	Audiologist	-5	0	10	0	-5	-5
103	19	M	R	Circumaural	Audiologist	-5	-5	-10	-5	0	-5
104	25	M	R	Circumaural	Audiologist	0	10	5	5	0	-20
105	21	F	L	Circumaural	Audiologist	0	0	5	-5	-5	5
106	21	F	R	Circumaural	Audiologist	5	10	-5	0	0	5
107	23	F	L	Circumaural	Audiologist	10	5	0	5	5	5
108	26	F	R	Circumaural	Audiologist	0	-5	-5	-5	-5	0
109	23	M	L	Circumaural	Audiologist	5	-5	0	10	10	10
110	22	F	R	Circumaural	Audiologist	-10	-5	-10	0	-5	-20
111	20	M	L	Circumaural	Audiologist	35	30	30	30	50	45
112	21	M	L	Circumaural	Audiologist	0	10	10	0	0	5
113	20	F	R	Circumaural	Audiologist	5	0	10	0	-5	-15
114	25	M	L	Circumaural	Audiologist	10	-5	-5	-5	10	15
115	28	F	R	Circumaural	Audiologist	30	15	15	20	40	30
116	20	M	R	Circumaural	Audiologist	10	5	5	5	20	20
117	21	F	L	Circumaural	Audiologist	10	10	20	10	0	0
119	26	F	R	Circumaural	Audiologist	10	5	5	0	0	10
120	21	F	R	Circumaural	Audiologist	-5	-5	10	5	-5	-20
121	28	F	L	Circumaural	Audiologist	0	5	0	0	10	5

Note. kHz = kilohertz.

Table 18

Conventional Audiometry Hearing Thresholds for Self-Fit Circumaural Earphones

Participant	Age	Sex	Ear	Earphone	Fitter	0.5 kHz	1 kHz	2 kHz	3 kHz	4 kHz	4 kHz	8 kHz
101	18	F	R	Circumaural	Self	5	10	10	10	0	5	0
102	20	M	L	Circumaural	Self	5	0	0	-5	0	0	10
103	19	M	R	Circumaural	Self	10	10	15	10	10	5	-10
104	25	M	R	Circumaural	Self	10	-5	5	5	0	5	0
105	21	F	L	Circumaural	Self	0	5	5	0	5	0	5
106	21	F	R	Circumaural	Self	0	0	5	0	5	-5	0
107	23	F	L	Circumaural	Self	10	5	0	0	5	0	5
108	26	F	R	Circumaural	Self	0	5	5	0	-5	5	5
109	23	M	L	Circumaural	Self	10	15	10	-5	5	5	25
110	22	F	R	Circumaural	Self	0	-5	-5	5	0	-5	-5
111	20	M	L	Circumaural	Self	5	0	0	5	5	30	25
112	21	M	L	Circumaural	Self	5	5	-5	5	0	0	0
113	20	F	R	Circumaural	Self	-10	-10	-10	-5	-5	5	5
114	25	M	L	Circumaural	Self	5	5	0	0	0	-5	15
115	28	F	R	Circumaural	Self	0	5	0	15	15	20	15
116	20	M	R	Circumaural	Self	10	5	5	5	15	25	10
117	21	F	L	Circumaural	Self	20	15	15	5	5	0	10
119	26	F	R	Circumaural	Self	-5	-5	-5	-5	0	0	10
120	21	F	R	Circumaural	Self	5	5	0	0	0	0	0
121	28	F	L	Circumaural	Self	0	5	5	5	0	-5	0

Note. kHz = kilohertz.

Table 19

Extended High Frequency Audiometry Hearing Thresholds for Self-Fit Circumaural Earphones

Participant	Age	Sex	Ear	Earphone	Fitter	9 kHz	10 kHz	11.2 kHz	12.5 kHz	14 kHz	16 kHz
101	18	F	R	Circumaural	Self	0	-5	0	-5	10	10
102	20	M	L	Circumaural	Self	-5	0	10	5	0	-5
103	19	M	R	Circumaural	Self	0	0	0	0	0	0
104	25	M	R	Circumaural	Self	-5	10	5	5	0	-20
105	21	F	L	Circumaural	Self	-10	-5	0	-10	-5	-10
106	21	F	R	Circumaural	Self	5	10	0	0	0	0
107	23	F	L	Circumaural	Self	5	5	0	10	10	5
108	26	F	R	Circumaural	Self	5	0	0	-10	-10	-5
109	23	M	L	Circumaural	Self	5	-5	0	5	10	10
110	22	F	R	Circumaural	Self	-5	0	0	0	0	-15
111	20	M	L	Circumaural	Self	35	25	25	25	50	35
112	21	M	L	Circumaural	Self	-5	0	10	0	-5	5
113	20	F	R	Circumaural	Self	0	5	5	0	-5	-15
114	25	M	L	Circumaural	Self	15	5	-5	-5	5	15
115	28	F	R	Circumaural	Self	25	15	10	20	30	35
116	20	M	R	Circumaural	Self	10	5	0	0	10	15
117	21	F	L	Circumaural	Self	5	0	15	10	5	-10
119	26	F	R	Circumaural	Self	0	-5	-5	0	0	0
120	21	F	R	Circumaural	Self	-5	0	5	5	-5	-20
121	28	F	L	Circumaural	Self	0	-5	0	-5	5	0

Note. kHz = kilohertz.

Table 20

Conventional Audiometry Hearing Thresholds for Audiologist-Fit Insert Earphones

Participant	Age	Sex	Ear	Earphone	Fitter	0.5 kHz	1 kHz	2 kHz	3 kHz	4 kHz	4 kHz	8 kHz
101	18	F	R	Insert	Audiologist	0	5	10	10	0	0	0
102	20	M	L	Insert	Audiologist	0	0	0	5	5	0	-5
103	19	M	R	Insert	Audiologist	5	5	5	5	5	-10	-20
104	25	M	R	Insert	Audiologist	5	0	5	-5	0	5	-10
105	21	F	L	Insert	Audiologist	5	5	5	5	0	10	5
106	21	F	R	Insert	Audiologist	10	0	0	5	10	0	0
107	23	F	L	Insert	Audiologist	5	10	0	0	0	0	-5
108	26	F	R	Insert	Audiologist	0	5	5	10	0	10	10
109	23	M	L	Insert	Audiologist	20	20	15	0	5	10	0
110	22	F	R	Insert	Audiologist	10	5	5	5	5	5	-5
111	20	M	L	Insert	Audiologist	20	5	5	5	5	30	15
112	21	M	L	Insert	Audiologist	5	10	5	0	10	10	5
113	20	F	R	Insert	Audiologist	5	5	5	5	5	10	0
114	25	M	L	Insert	Audiologist	10	10	5	0	0	0	5
115	28	F	R	Insert	Audiologist	5	5	15	15	10	15	5
116	20	M	R	Insert	Audiologist	15	10	10	10	15	25	15
117	21	F	L	Insert	Audiologist	15	20	10	10	10	5	15
119	26	F	R	Insert	Audiologist	0	0	0	0	5	10	5
120	21	F	R	Insert	Audiologist	0	5	5	0	10	5	0
121	28	F	L	Insert	Audiologist	5	10	10	10	5	0	0

Note. kHz = kilohertz.

Table 21

Extended High Frequency Audiometry Hearing Thresholds for Audiologist-Fit Insert Earphones

Participant	Age	Sex	Ear	Earphone	Fitter	9 kHz	10 kHz	11.2 kHz	12.5 kHz	14 kHz	16 kHz
101	18	F	R	Insert	Audiologist	0	-5	-10	-20	0	5
102	20	M	L	Insert	Audiologist	-10	-5	-5	-10	-15	-5
103	19	M	R	Insert	Audiologist	5	-15	-20	-5	5	-10
104	25	M	R	Insert	Audiologist	0	5	-5	-15	-15	-20
105	21	F	L	Insert	Audiologist	-5	-5	-5	-15	-10	-15
106	21	F	R	Insert	Audiologist	0	-5	-10	-10	-10	-5
107	23	F	L	Insert	Audiologist	-5	-5	0	5	5	-10
108	26	F	R	Insert	Audiologist	10	10	5	-5	-20	-15
109	23	M	L	Insert	Audiologist	0	0	0	-5	0	-10
110	22	F	R	Insert	Audiologist	-5	-5	-5	-5	-10	-15
111	20	M	L	Insert	Audiologist	25	25	20	10	45	35
112	21	M	L	Insert	Audiologist	5	5	10	-5	-15	0
113	20	F	R	Insert	Audiologist	-5	5	0	0	-15	-20
114	25	M	L	Insert	Audiologist	5	0	-10	-15	0	15
115	28	F	R	Insert	Audiologist	25	20	10	30	40	35
116	20	M	R	Insert	Audiologist	15	5	10	5	5	20
117	21	F	L	Insert	Audiologist	5	10	10	15	5	0
119	26	F	R	Insert	Audiologist	5	0	-5	-5	-5	-5
120	21	F	R	Insert	Audiologist	0	-5	-10	-10	-10	-20
121	28	F	L	Insert	Audiologist	0	-10	0	-5	5	-5

Note. kHz = kilohertz.

Table 22

Conventional Audiometry Hearing Thresholds for Self-Fit Insert Earphones

Participant	Age	Sex	Ear	Earphone	Fitter	0.5 kHz	1 kHz	2 kHz	3 kHz	6 kHz	4 kHz	8 kHz
101	18	F	R	Insert	Self	10	5	10	15	0	10	-5
102	20	M	L	Insert	Self	0	0	5	5	0	0	-10
103	19	M	R	Insert	Self	5	5	5	10	5	0	-5
104	25	M	R	Insert	Self	10	0	0	5	5	5	-5
105	21	F	L	Insert	Self	15	10	10	10	5	15	15
106	21	F	R	Insert	Self	10	5	5	5	10	0	-5
107	23	F	L	Insert	Self	5	5	0	0	0	-5	5
108	26	F	R	Insert	Self	5	10	15	10	0	10	15
109	23	M	L	Insert	Self	15	20	15	0	5	-5	10
110	22	F	R	Insert	Self	5	0	0	5	5	0	-10
111	20	M	L	Insert	Self	15	5	0	5	0	25	10
112	21	M	L	Insert	Self	0	10	0	5	10	10	5
113	20	F	R	Insert	Self	0	5	10	5	5	10	0
114	25	M	L	Insert	Self	5	10	0	-5	0	0	5
115	28	F	R	Insert	Self	0	5	5	10	20	15	5
116	20	M	R	Insert	Self	15	10	10	10	10	25	30
117	21	F	L	Insert	Self	20	25	10	5	10	5	15
119	26	F	R	Insert	Self	5	5	5	0	5	10	-10
120	21	F	R	Insert	Self	10	10	5	5	10	0	-5
121	28	F	L	Insert	Self	15	15	10	15	5	0	-10

Note. kHz = kilohertz.

Table 23

Extended High Frequency Audiometry Hearing Thresholds for Self-Fit Insert Earphones

Participant	Age	Sex	Ear	Earphone	Fitter	9 kHz	10 kHz	11.2 kHz	12.5 kHz	14 kHz	16 kHz
101	18	F	R	Insert	Self	0	0	-5	-10	0	0
102	20	M	L	Insert	Self	-10	-5	0	0	-15	-15
103	19	M	R	Insert	Self	5	-5	0	-5	0	-5
104	25	M	R	Insert	Self	-10	0	0	0	-5	-20
105	21	F	L	Insert	Self	0	0	0	5	5	5
106	21	F	R	Insert	Self	0	5	0	0	-10	-10
107	23	F	L	Insert	Self	10	5	0	5	5	-10
108	26	F	R	Insert	Self	0	0	0	-5	-15	-5
109	23	M	L	Insert	Self	5	0	5	10	5	0
110	22	F	R	Insert	Self	-10	-10	-10	-5	-10	-20
111	20	M	L	Insert	Self	20	20	15	5	40	35
112	21	M	L	Insert	Self	10	15	5	0	0	10
113	20	F	R	Insert	Self	0	10	5	0	-10	-20
114	25	M	L	Insert	Self	10	5	0	-5	0	5
115	28	F	R	Insert	Self	20	20	15	30	30	35
116	20	M	R	Insert	Self	5	5	10	5	5	20
117	21	F	L	Insert	Self	10	10	20	10	5	0
119	26	F	R	Insert	Self	5	5	10	-5	-15	-5
120	21	F	R	Insert	Self	0	0	-10	-10	-10	-20
121	28	F	L	Insert	Self	-5	-5	0	-5	-5	-5

Note. kHz = kilohertz.