ACTIVE NOISE REDUCTION HEADPHONE MEASUREMENT: COMPARISON OF PHYSICAL AND PSYCHOPHYSICAL PROTOCOLS AND EFFECTS OF MICROPHONE PLACEMENT

by

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(ABSTRACT)

Currently in the United States, Active Noise Reduction (ANR) headphones cannot be tested and labeled as hearing protection devices (HPDs) due to inherent limitations with the existing psychophysical headphone testing standard, real-ear attenuation at threshold (REAT). This research focused on the use of a standard, for physical, microphone-in-real-ear testing, (MIRE, ANSI S12.42-1995), to determine if MIRE may be appropriately used to measure the *total* attenuation (i.e., passive + active) of ANR headphones. The REAT "Method B, Subject-Fit protocol," ANSI S12.6-1997(R2002), was also used to assess *passive* attenuation (and used for comparison with the MIRE data), as this is the current standard for passive Headphone attenuation testing.

The MIRE protocol currently does not specify a standardized location for measurement microphone placement. Prior research is mixed as to the potential benefits and shortcomings of placing the measurement microphone *outside* versus *inside* the ear canal. This study captured and compared acoustic spectral data at three different microphone locations: in concha, in ear canal-shallow depth, and in ear canal-deep depth (with a probe tube microphone positioned near the tympanic membrane), using human test participants and five ANR headphones of differing design.

Results indicate that the MIRE protocol may be used to supplant the REAT protocol for the measurement of passive attenuation, although differences were observed at the lowest-tested frequency of 125 Hz. Microphone placement analysis revealed no significant difference among the three locations specified, with a noted caveat for the probe tube microphone location at the highest tested frequency of 8000 Hz.

Overall findings may be useful to standards-making committees for evaluating a viable solution and standardized method for testing and labeling ANR headphones for use as hearing protection devices. Microphone placement results may assist the practitioner in determining where to place measurement microphones to best suit their particular needs when using MIRE. Discussion includes an in-depth interpretation of the data, comparisons within and between each protocol, and recommendations for further avenues to explore based on the data presented.

"He that is taught only by himself has a fool for a master."

-H.S. Thompson

DEDICATION

To Mom and Dad

May you both rest in peace

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To Theresa – my light – my life. Thank you for making this chapter in our life so worthwhile, manageable, and enjoyable. Thanks also to my family, friends, and colleagues for their support and encouragement over the years.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

INTRODUCTION

This laboratory-based, empirical research evaluated active noise reduction (ANR) headphones using the ANSI standard S12.42-1995 microphone-in-real-ear, or MIRE protocol. This is a *physical* paradigm used for hearing protection device (HPD) testing. Research efforts focused on determining if this attenuation measurement protocol may be adequately used to determine the total attenuation (i.e., passive + active) of ANR headphones. Since MIRE is a physical protocol, with the human head used as a test fixture, measurement microphones are usually placed in or near the ear canal during testing. Research is mixed as to the potential benefits and shortcomings of placing the measurement microphone outside the ear canal versus inside the ear canal. Since there is no standardized location for microphone placement, this study captured and compared acoustic spectral data at three different microphone locations: in-concha; in ear canal-shallow; and in ear canal-deep (using a probe tube microphone near the tympanic membrane), on five ANR headphones of differing design characteristics. Examples of both circumaural and supra-aural headphones were investigated. The *psychophysical* real-ear attenuation at threshold (REAT), Method B, Subject-Fit protocol, S12.6-1997(R2002), was also used to assess passive attenuation, as this is the current standard for passive Headphone attenuation testing.

Results of this study may be useful in developing an acceptable standard for the measurement of the passive and active components of ANR headphones in lieu of the current 30-year old REAT standard (ANSI S3.19-1974), required by the Environmental Protection Agency (EPA), and which only measures the passive attenuation of

Headphones. It is further hoped that this new standard will lead to EPA labeling guidelines that will allow manufacturers to test and label ANR headphones for general use as EPA-accepted hearing protection devices. Those groups which rely on ANR headphones, such as the military, aviation (commercial and private operations), and industry, may directly benefit from a standardized testing method and a simplified labeling scheme.

The fundamental questions answered by this research may improve the general science of headphone measurement, thereby benefiting not only existing ANR headphone users, but those groups and individuals who may wish to employ such headphones as hearing protection devices but are not legally able to because there is not an acceptable standard for their total attenuation measurement.

This study allowed for MIRE and REAT measurements to each be obtained for a common fit of each ANR headphone (i.e., an average obtained from two fittings of each headphone). The obtained data sets reflect variability due to multiple fits in the same vein as required with current headphone test standards (ANSI S3.19-1974 [EPA required] and ANSI S12.6-1997 (R2002) [EPA-proposed]). Furthermore, differences in ANR device design, inclusive of size, shape, weight, and headband force, were investigated through the use of multiple (5) ANR headphones. These headphones, listed in Appendix A, are believed to be representative of the ‘state of the art’ in ANR noise-canceling devices from leading manufacturers.

The experimental protocol for this research was a substantially revised version of that previously used by (Casali, Mauney, & Burks, 1995) for comparison of MIRE versus REAT procedures with passive earmuffs. That study, however, had very different objectives and did not address ANR devices, nor did it address microphone location issues. The stepwise protocol used for this study is discussed in detail and provides the necessary experimental controls and ordering of conditions so as to avoid extraneous contamination of the results and practice or order effects.

The following text will discuss the current state of the literature regarding passive headphones and ANR headphones, relevant issues regarding physical versus psychophysical testing protocols, previous research related to testing, and findings which impact this study. Goals of this research will be presented, along with an experimental design intended to answer questions posed in the text and meet goals set by the experimenter. This will be followed by an explanation of the results and a discussion of the theoretical implications of this research, with respect to those results.

BACKGROUND

Passive Hearing Protection

Conventional, passive headphones have been used to protect human hearing in loud environments since the mid-1940s. Since that time, headphones have undergone many changes in the form of new materials, sizes, shapes, and techniques for wear and care. Examples of common headphones are circumaural, or closed-back earmuffs, with the earcup cushion covering and creating a seal around each pinna; supra-aural or open-back earmuffs, which sit on top of the pinnae; and earplugs of various types (e.g., foam user-molded earplugs, soft rubber flanged pre-molded earplugs, and custom-molded earplugs).

Passive earmuffs, in general, are more easily donned and doffed and attenuate high-frequency noise better than earplugs. However, without a proper fit, the earcup seal may loose contact between the earmuff and the head around the pinna, thereby allowing unwanted noise to enter under the earcup and into the ear canal. Proper earmuff wear and comfort are affected by jaw and head shape and can impede the use of eyeglasses, hardhats, respirators, and other safety equipment. Earplugs on the other hand, do not usually affect or impede the use of such headgear. Earplugs also generally provide better attenuation of low-frequency noise than do passive earmuffs (Christian, 1999). These headphones are classified as *passive* protectors because noise attenuation is achieved by the structural features and mechanical elements of the protector which block the air conduction pathway to the ear (Casali, 1994). Passive headphones attenuate not only the amplitude of unwanted noise, but also the amplitude of any desirable sounds (e.g., speech and warning signals). Although traditional earmuffs may perform well, often providing about 20-40 dB of sound attenuation at frequencies above about 1000 Hz , they provide less attenuation (0-20 dB) at frequencies from 125 Hz -1000 Hz (Casali & Berger, 1996). It is in this frequency range that researchers believe active noise reduction can play a key role in augmenting passive headphone performance.

Active Noise Reduction

For more than 20 years, "active headphones," or those hearing protection devices which incorporate electronic components and transducers, have been gaining in popularity as a means to protect human hearing in severe noise environments (e.g., extreme industrial settings, military aircraft and armored vehicles, and general and commercial aviation). In addition to providing attenuation in severe noise conditions, active headphones have also been shown to be more comfortable – especially during long-term use, as in general aviation (Gauger, 1998). This is due primarily to the fact that earcup seal compression force does not need to be as great as that of passive headphones since a portion of the attenuation is provided electronically, instead of purely mechanically, as in the case of a passive device.

Active noise reduction is the process of superimposing two sound pressure waves of equal amplitudes, but with a 180° out-of-phase relationship, resulting in destructive wave cancellation (Casali, 1993; Christian, 1999). Figure 1 depicts an original waveform (noise), a 180° out-of-phase "mirror image" of the original waveform, or anti-noise, and the resultant "cancelled" waveform. Due to limits in technology, however, the anti-noise may not have the exact amplitude of the original noise, which is one reason why residual levels of noise remain after cancellation. Figure 2 shows a block diagram of a typical ANR system and how noise enters the system, is processed by the ANR circuitry, and is then presented to the wearer at a more attenuated level than with its passive features alone (Moy, 2001). Although originally conceived (and patented) in 1936 (Lueg, 1936) and successfully demonstrated in the laboratory in 1958 (Meeker, 1958), ANR systems have only been practical since the 1980s with the advent of miniaturized electronics (Casali & Berger, 1996; Cro, 1997). The effectiveness of ANR-based headphones, however, has been the source of debate since the concept was first introduced.

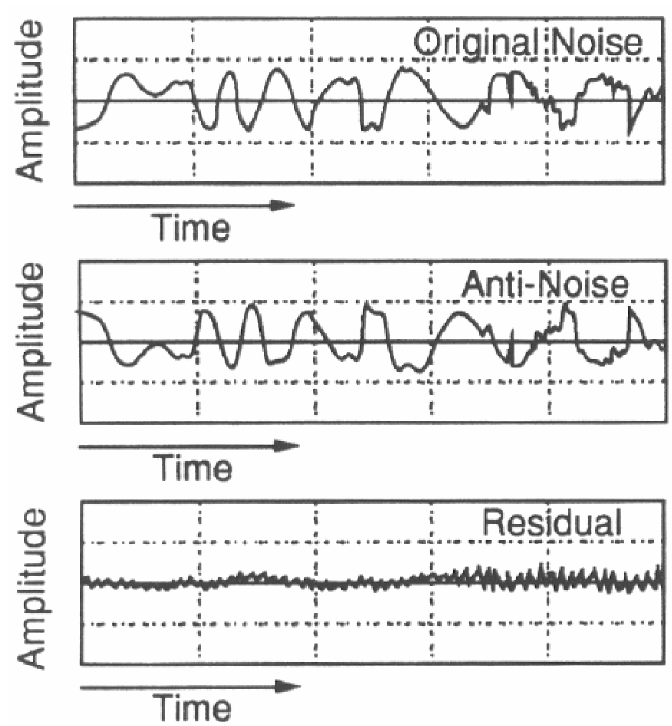

Figure 1. Concept of ANR noise cancellation.

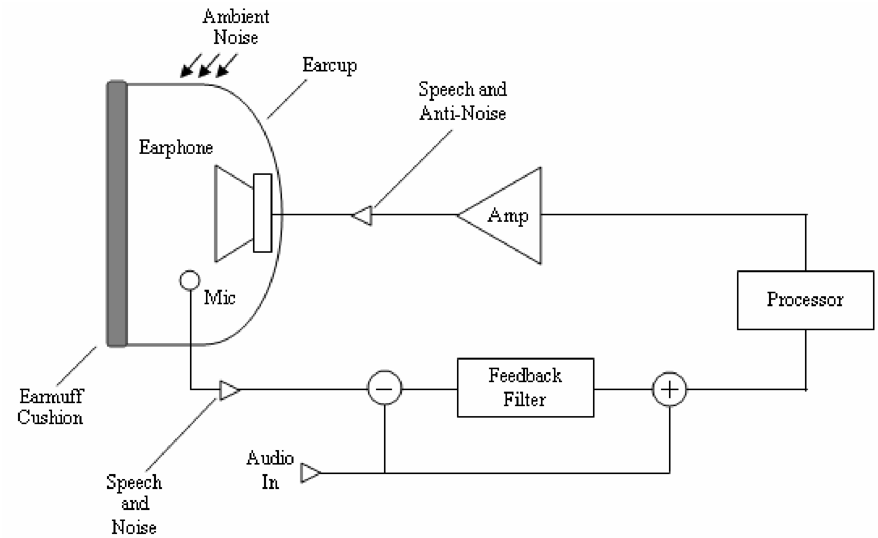

Figure 2. Basic closed-loop ANR circuit.

In order to determine the effectiveness of ANR, one must measure the total attenuation provided by the ANR device. Total attenuation is the sum of the attenuations of the *active* component (i.e., that which cancels noise electronically) and the *passive* component (i.e., that which reduces noise through its physical characteristics) of the device. However, there is no EPA-approved standardized method for determining the "active attenuation contribution" to the overall attenuation (active + passive) properties of ANR devices. It is for this reason that ANR headphones cannot be legally sold in the United States as hearing protection devices. Instead, these devices are marketed as "noise-annoyance-reducing devices." Currently, the REAT protocols standardized in ANSI S3.19-1974 and ANSI S12.6-1997(R2002 Method A [Experimenter Fit] and Method B [Subject Fit]) are the only methods accepted by the EPA for testing the attenuation of hearing protection devices (passive only).

The primary problem with using REAT, however, is that the REAT protocol cannot be applied to ANR headphones to measure the active attenuation component, due in part to the electronic "noise floor" inherent in ANR devices. This noise floor is the broadband residual noise that is audible in a very quiet test chamber. This creates masking in the occluded condition that would erroneously elevate the measured attenuation values when using REAT (Berger, 2002). For example, test results show that REAT exceeds MIRE by 7 dB at 125 Hz and by 2 dB at 250 Hz (Gauger, 1998). While there may be utility in combining these protocols to determine total attenuation of ANR headphones – MIRE for the active component and REAT for the passive component – it was theorized that MIRE (which is a much quicker test than REAT and can be conducted without human subjects) can reasonably supplant REAT for testing total attenuation of ANR headphones.

Such results may provide sufficient evidentiary value to the EPA, thereby allowing standards to be approved that will permit ANR headphones to be tested, labeled (with passive and total attenuation values), and legally sold and used in the U.S. as hearing protection devices.

Headphone Attenuation Measurement

Noise Reduction Rating. The fundamental question that should be asked with respect to hearing protection devices in general is "what amount of protection does each device provide?" In 1979, when the Occupational Safety and Health Administration (OSHA) began rating headphones, they selected the Noise Reduction Rating (NRR) as the preferred method for assessing headphone adequacy for compliance with the Hearing

Conservation Amendment (OSHA, 1983). The NRR is a single-number metric based on spectral attenuation values in nine 1/3-octave frequency bands centered at 125, 250, 500, 1000, 2000, 3150, 4000, 6300, and 8000 Hz. The REAT protocol became the industry-standard method for determining spectral attenuation values for passive headphones in the laboratory.

Noise Reduction vs. Insertion Loss. The two methods primarily used to determine spectral attenuation values are noise reduction (NR) and insertion loss (IL). The NR procedure utilizes two microphones and measurements are made simultaneously, while the protector is present and fit according to the measurement paradigm being used, in the presence of broadband noise (usually pink noise – a sound that falls off steadily into the higher frequencies [at 3 dB per octave], instead of producing all frequencies equally). Generally, one microphone is placed either in the concha or in the ear canal, and the other is placed external to the hearing protector.

To obtain IL measurements, a single microphone is used to obtain two measurements at different points in time, also in the presence of a broadband noise stimulus (again, usually pink). The first measurement is taken with the hearing protector present and fit according to the measurement paradigm being used and the second is taken without the hearing protector in place (assuring that between don and doff the microphone does not move). The microphone is placed under the hearing protector and is usually taped to the floor of the concha or is inserted in the ear canal, depending upon the preference of the experimenter or testing facility.

Transfer function of the open ear. (Pfretzschner & Moreno, 1988) suggest that NR and IL are “equivalent quantities” and that the only differences between them are due to a diffraction effect, such as TFOE, or the transfer function of the open ear. The TFOE is the difference in sound level between the inner and outer microphone locations taken in the NR measurements, only without the headphone present (Casali et al., 1995). Since this effect is not present for IL measurements, in order to make IL and NR "equivalent," NR must be adjusted for the TFOE effect. Pfretzschner and Moreno (1988) also concluded that the TFOE could be used to predict one measurement from another for an "average" human head.

The TFOE is an important metric to measure and account for because it represents an effect that is due to external factors not related to the attenuation of the earmuff. Such factors include the distance between the two measurement microphones (internal and external to the earcup), the resonance of the auricle/concha of the ear, and diffraction effects (Casali et al., 1995). Calculation of the TFOE is made by subtracting the external microphone readings from the internal microphone readings. The resultant correction factor is the TFOE and varies between subject, ears, and frequencies. However, Casali et al. (1995) found that it may be possible to use mean (rather than individual) TFOE factors for correction of attenuation measurements obtained by the NR technique – assuming the TFOE is obtained using a population sample representative of that for which the NR measurements will be obtained. Without the TFOE corrections, NR values will overestimate attenuation by the amount of the TFOE.

Bone conduction and the occlusion effect. The concept of bone conduction implies that sound is transmitted via tissue and bony structures in the head that bypass the normal air-conduction mechanism of sound transmission through the ear canal. In effect, these are flanking pathways that circumvent the noise-blocking features of headphones that cover or occlude the ear canal and are the ultimate limiting factor for a headphone's attenuation ability (Berger, Kieper, & Gauger, 2003; Lancaster & Casali, 2004). The primary bone conduction pathways are: vibration of the ear canal walls, energy transmitted due to excitation of ossicular motion, and direct mechanical excitation of the cochlea (Khanna, Tonndorf, & Queller, 1976). Bone-conducted sounds are enhanced by a low-frequency phenomenon called the occlusion effect (Dempsey, 1990). The occlusion effect occurs when an object (e.g., earplug, earmuff, or other obstruction) completely fills the outer portion of the ear canal. This traps the bone-conducted sound vibrations of a person's own voice in the space between the obstruction and the eardrum. Usually, when people talk, chew, or breath, these vibrations escape through an open ear canal and the person is unaware of their existence. However, when the ear canal is occluded, the vibrations are reflected back toward the eardrum, which increases loudness perception of their own voice. Compared to a completely open ear canal, the occlusion effect may boost the low frequency (usually below 500 Hz) sound pressure in the ear canal by 20 dB or more (Ross, 2004).

When using a headphone, physiological noises such as heartbeat, circulation, and breathing are more prominent, principally because the headphone enhances low frequency bone conduction. For measurement protocols such as REAT, this results in inflated occluded thresholds (and therefore attenuation) at low frequencies. MIRE, on the other hand, cannot account for true bone conduction effects since the measurement microphones measure sound pressure changes in the ear canal and not the sound "heard" through bone conduction (Lancaster & Casali, 2004) .

Real-Ear Attenuation at Threshold (REAT)

Although KEMAR (Knowles Electronics Manikin for Acoustic Research) manikins and other non-human acoustical test fixtures (ATFs) have been used for gathering headphone attenuation data, ATFs are plagued with problems stemming from fit, accurate ear canal representation, less-than-realistic pinnae and artificial flesh, leakage, sound transmission, and the inability to determine self-fit variability (Berger, 1992). Hence, most headphone attenuation data (and all attenuation data required for EPA labeling purposes) are obtained using human participants in the binaural threshold shift methodology, REAT. Because this procedure relies on humans as the "transducers," it is often (incorrectly) referred to as a *subjective* procedure. However, a more appropriate description is *psychophysical*, since it involves real-ear, sensation-based responses. As implemented in the current headphone test standards of the American National Standards Institute (ANSI S3.19-1974 and ANSI S12.6-1997[R2002]), participants track their thresholds for 1/3-octave bands of noise (at center frequencies of 125, 250, 500, 1000, 2000, 3150, 4000, 6300, and 8000 Hz) with (i.e., occluded) and without (i.e., unoccluded) a hearing protector in place. The difference between the two thresholds (i.e., the threshold shift due to the presence of the headphone) represents the insertion loss of the hearing protector. This methodology is recognized as the most accurate method available in that it can account for individual differences in the fit of the devices across the participant sample as well as the human bone conduction effect. For the aforementioned reasons, IL measurements were taken during this study.

However, there are disadvantages associated with REAT, including: overestimation of the low-frequency attenuation of devices due to physiological noise, inter- and intra-subject variability (perceptual-cognitive issues), and the need for extremely quiet test environments. REAT also cannot be used to assess certain augmented headphone technologies (e.g., ANR devices), which results in the data obtained for such devices not being representative of the performance in the conditions for which they were designed. This is a major problem with the current EPA labeling requirement (CFR, 2002), in that it requires data from the ANSI S3.19 standard (ANSI, 1974), which does not accommodate certain augmented headphones. It is also a problem with the anticipated new EPA labeling requirement (the subject of a March, 2003 workshop at the EPA) (Casali & Robinson, 2003) which would likely promulgate ANSI S12.6-1997(R2002) Method B Subject-Fit as the test standard. This means ANR headphones cannot be properly labeled as to their performance in certain noise environments. Hence, there is a desire among some in the headphone testing community to use the MIRE protocol as a potential new standard for ascertaining at least the active component of ANR headphones; if not both active and passive.

ANSI S12.6-1997(R2002) Method B is quite valuable, since research has shown that NRRs computed from existing S3.19-1974 data, as specified by the EPA, overestimate workplace protection for groups of users by as much as 25 dB, depending on the hearing protector selected (Berger, 1993; Franks, Murphy, Harris, Johnson, & Shaw, 2003). Although ANSI adopted this new standard in 1997, the EPA currently does not recognize the new standard. The EPA continues to use the 30-year old S3.19-1974 standard that is no longer supported by ANSI. According to Berger (1993), the current hearing protector NRRs, based upon testing to the outdated S3.19-1974 standard, are of even less accuracy and value than the original, much criticized EPA fuel-economy ratings. The EPA eventually improved the fuel-economy ratings for vehicle manufacturers; however, the procedures for determining hearing protector ratings have not been changed in 30 years.

ANSI S12.6-1997(R2002) Method B data have also been shown to provide a much better indication of achievable results than do existing labeled values (Figure 3). This graph shows that current labeling test procedures result in high attenuation values that in the field, and when using Method B, are considerably lower. “Achievable” means values that are among the higher levels of attenuation attained by groups of informed users in well-managed industrial and military hearing conservation programs (HCPs) (Berger, 1990). Method B has also been shown to be the best choice to predict group performance that is achievable in field conditions (Berger, 1990). This is particularly relevant since it shows that Method B Subject-Fit is a better predictor of “real world” attenuation values than those measured under the current EPA-mandated “Experimenter Fit” protocol (S3.19-1974). Experimenter Fit is considered the ideal or a “best case” fit due to the fact that the experimenter is able to actually see how the earcups are making contact with the head, how they are positioned on the head, and whether there are obstructions under the earcup which could compromise the seal (e.g., hair). The current practice to more closely align laboratory NRR values with real-world values is to de-rate the labeled NRR value by 50% (OSHA, 1983). This has proven to be confusing not only to consumers, but to HCP representatives and OSHA compliance officers as well.

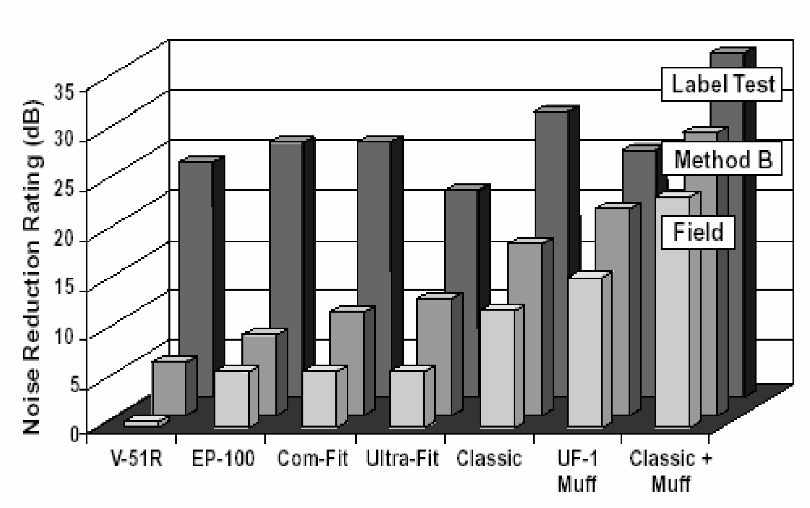

Figure 3. Comparison of labeled data (ANSI S3.19) to field performance and to Method B (ANSI S12.6).

Although REAT, and in particular, REAT Method B, is the preferred method to determine the attenuation levels of passive headphones, this standardized psychoacoustic testing procedure is inappropriate for the determination of the active component of ANR headphones for several reasons. The first, as previously stated, is that the noise floor of ANR headphones may mask the incoming noise stimulus during the occluded portion of the test, which may result in artificially high attenuation estimates. Secondly, as 1/3-octave test band center frequencies dip below about 63 Hz, a range in which some ANR-based headphones can significantly attenuate (with ANR circuit active), results may be unreliable because human hearing sensitivity is minimal at these frequencies (Casali, 1993; Rylands, 1990).

It appears then, that the laboratory testing procedures for ANR devices must consist of an objective, physical (microphone-based) measurement of attenuation (e.g., as per MIL-STD-912) to determine the active plus passive, or "total" physical attenuation.

In this manner, the active component of total attenuation can be determined at each test band. To account for bone conduction and outer ear resonance effects which the physical tests do not, it appears that the psychophysical REAT measurement (Method B) should also be performed to determine the passive attenuation with the ANR circuit off (Casali, 1993; Casali, Mauney, & Burks, 1993).

Microphone in Real-Ear (MIRE)

The microphone-based counterpart to REAT is MIRE. This methodology is standardized in ANSI S12.42-1995 and MIL-STD-912 (USDOD, 1990) and is referred to as *objective* or *physical* since the measurements are microphone-based, requiring no human perception/cognition-biased input. Using MIRE, the attenuation of the active component can be determined by measuring the total physical attenuation with the ANR circuit on, and then passive attenuation with the ANR circuit off. The difference in attenuation between these measurements is the contribution of the ANR system to the total attenuation (Casali & Robinson, 1994). As the name MIRE implies, small microphones (connected to a spectrum analyzer) are used to determine the attenuation levels of headphones. The human head is used as the "test fixture" and the microphones are placed inside the ears (at or near the opening of the ear canal, or sometimes within the canal itself) and IL measurements are performed using relatively high levels of a broadband noise stimulus (usually pink or white noise). This procedure is easily implemented with earmuffs and some supra-aural devices, but can be difficult to implement with earplugs or semi-insert headphones because the wires leading to the microphones must be physically positioned underneath the headphone. Care must be taken to ensure that the earcup cushion produces a tight seal against the head and that the test participant wears earplugs at all times while exposed to the test stimulus. Even with very small wires, earcup cushion seals can easily be broken, not only undermining measurement efforts, but also exposing the participant to the high levels of noise introduced during the test.

Advantages of MIRE testing are that the results are not contaminated by physiological noise, as would be the result if the REAT protocol were used to test the active component of ANR devices. In other words, the masking effect of the ANR circuitry that may artificially elevate attenuation levels using REAT is of no consequence when using MIRE since actual insertion loss (difference) is what is being measured instead of the sound level perceived under the headphone. The MIRE process is also much quicker than REAT (roughly five minutes versus up to one hour for each headphone) and, since MIRE measurements are performed at elevated noise levels, there is no requirement for extremely quiet ambient noise conditions (Casali et al., 1995). MIRE can also be used to test individual ear attenuation, while sound field REAT cannot. Also, because real human heads are used as test fixtures, MIRE measurements can account for individual differences in the fit of the devices across the participant sample, just as REAT measurements do. However, MIRE, as previously mentioned, cannot account for bone conduction (and thus may overestimate attenuation at mid-to-higher frequencies) and also requires special equipment (miniature microphones, microphone power supplies, and a spectrum analyzer).

With regard to bone conduction, MIRE measurements (both IL and NR) are not expected to show a strong occlusion effect, especially when the microphone is mounted in the concha of the participant, rather than near the tympanic membrane. The occlusion effect enhances bone conduction transmission but not the physical metrics of the waveform because these are measured with microphones which transduce air pressure changes in the outer ear (Casali et al., 1995). In-ear canal microphones, however, are susceptible to this effect because the walls of the ear canal provide an influence of enhanced bone conduction of sounds below about 2000 Hz (Berger & Kerivan, 1983). The fact that bone conduction pathways are not accounted for in MIRE is a disadvantage from an accuracy standpoint because these pathways do influence overall exposure since they constitute flanking paths around the headphone (Casali et al., 1995).

ANR headphone testing and labeling issues. As previously discussed, at present, standardized attenuation data and NRRs are not available for ANR headphones. Also, as stated, MIRE testing may be used to measure the passive (ANR off) and total (ANR on) attenuation of ANR-based headphones, and then active attenuation levels may be calculated from the difference of these two measurements. REAT or MIRE testing can be used to quantify (for labeling purposes) the *passive* component of the total attenuation, but the choice of method can affect the data (Casali, 2005).

MIRE attenuation (as determined by insertion loss) at low frequencies is generally lower than REAT attenuation due to the physiological noise masking effects on occluded thresholds that occur in REAT testing. Looked at in another way, it could be said that REAT overestimates the low frequency attenuation of headphones. Since the human head is used only as a 'test fixture' in MIRE testing, with the participant not being required to provide responses to noise stimulus, these physiological effects do not adversely impact the insertion loss levels measured for each headphone. Conversely, MIRE, unlike REAT, does not account for the bone conduction path (again, bone conduction, as a flanking path, limits the performance of all headphones and thus is an important factor when quantifying their attenuation). This is an issue that may be addressed by studying various microphone placement or measurement strategies. Finally, passive attenuation is often decreased in the middle frequencies (from about 1000-4000 Hz) when the ANR circuit is turned on (i.e., the electronics produces and/or amplifies noise which increases the noise level under the protector). The effects of the ANR circuitry may create masking effects that are reflected in REAT IL measurements, but they do create a significant effect for the MIRE microphones.

ANR attenuation performance: MIRE and REAT. MIRE and REAT attenuation for a typical circumaural ANR earmuff is shown in Figure 4 (Robinson & Casali, 1995). Readily apparent in the figure is the difference between the MIRE and REAT attenuation at 125 and 250 Hz. As mentioned earlier, this difference is due to physiological noise masking the test stimulus during occluded trials of the REAT test (but not during the unoccluded trials). Also evident in the figure is the slight reduction in total attenuation at 1000 and 2000 Hz when the ANR circuit is turned on.

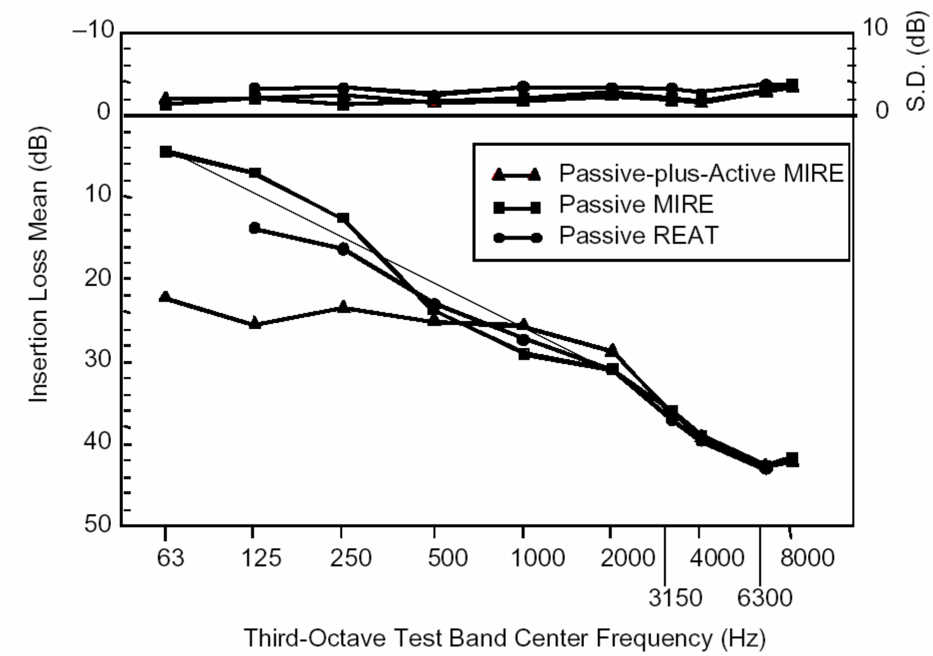

Figure 4. Attenuation of the NCT PA-3000 closed-back ANR headphone.

While the differences are real and measurable, how significant are they when the attenuation spectra are used to calculate a single-number rating such as the NRR? In part to answer this question, (Casali et al., 1995) performed both REAT (1/3-Octave Band and Pure Tone) and MIRE tests on six different conventional, passive earmuffs. To remove the effect of re-fitting the muff, both REAT and MIRE tests were performed for each fitting of the earmuffs. In addition, both insertion loss and noise reduction MIRE measurements were performed with the NR data corrected for TFOE – essentially resulting in an IL measurement. To allow NRRs to be calculated for each test and device, 10 participants were tested in three trials as required by existing REAT test standards. An example of this type of design is shown in Figure 5.

The spectral attenuation and NRRs for two representative examples of the six earmuffs tested appear in Figures 6 through 9. As can be seen, there was no difference between NRRs calculated using either the MIRE-IL or MIRE-NR method (as would be expected since the NR measurement was corrected for measured TFOE). In addition, the differences between the NRRs calculated using the MIRE data and the REAT data suggest that MIRE data can be used to generate an NRR-like rating for the passive component of at least some augmented hearing protectors (Casali et al., 1995).

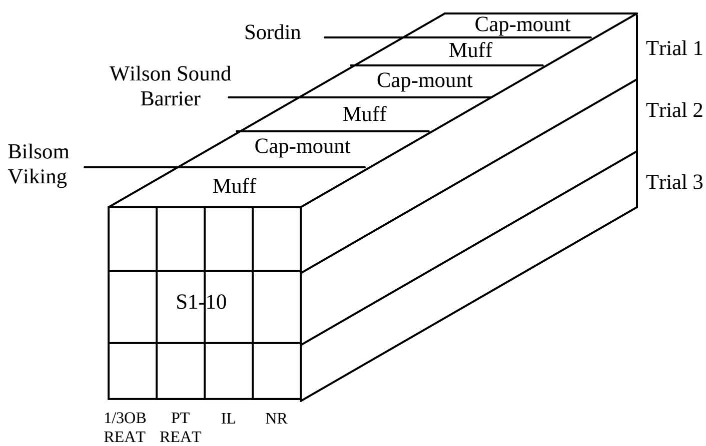

Figure 5. Example of experimental design comparing Passive HPDs.

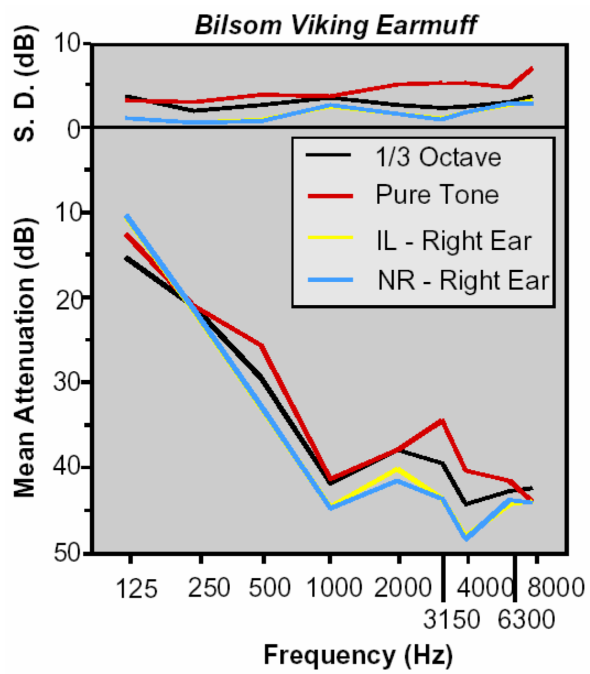

Figure 6. Spectral attenuation of the Bilsom Viking earmuff testing using REAT, MIRE-IL, and MIRE-NR.

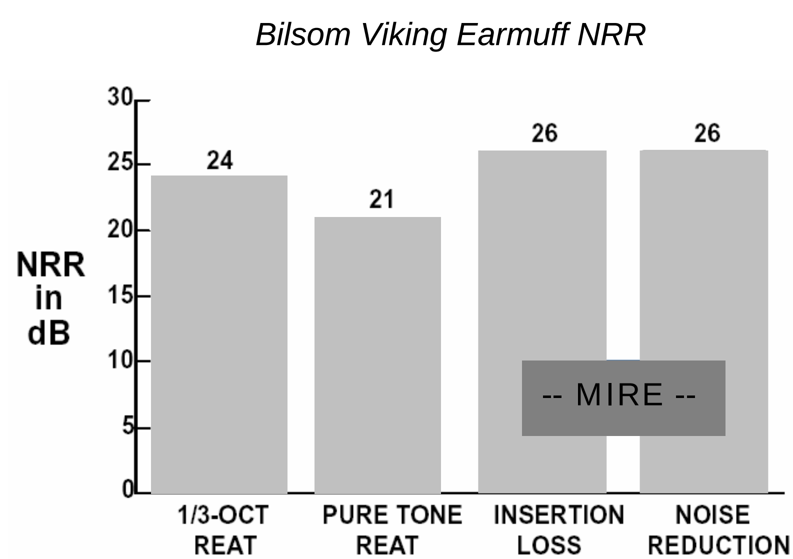

Figure 7. NRRs calculated for the Bilsom Viking earmuff tested using REAT, MIRE-IL, and MIRE-NR.

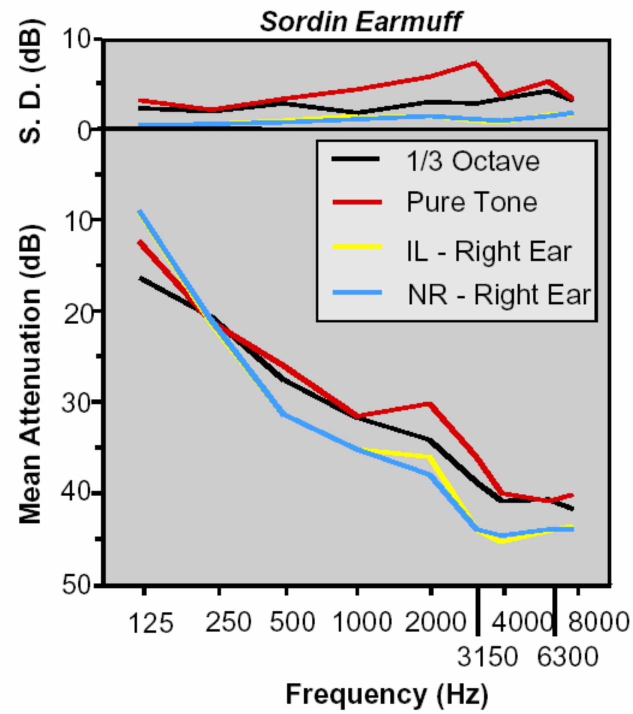

Figure 8. Spectral attenuation of the Sordin earmuff tested using REAT, MIRE-IL, and MIRE-NR.

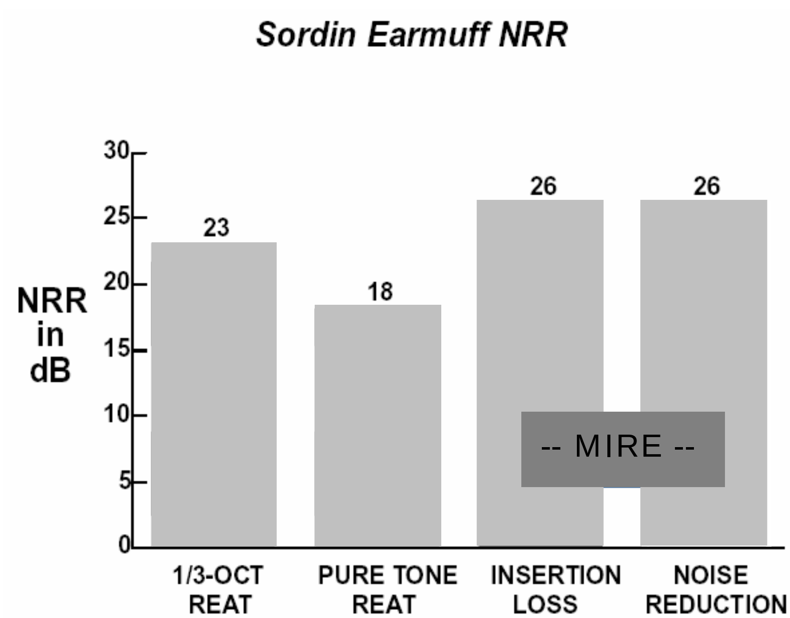

Figure 9. NRRs calculated for the Sordin earmuff tested using REAT, MIRE-IL, and MIRE-NR.

Real-ear attenuation at threshold protocols are the “gold standard” in hearing protection testing, even though it is recognized that REAT protocols will overestimate the low-frequency attenuation of headphones. Despite this disadvantage, REAT is generally believed to best reflect headphone attenuation on a sample of humans, as compared to any of the other methods. If manufacturers of ANR-based devices wish to sell their products as hearing protectors, however, they are presently penalized since only the passive performance of the devices can be characterized; that is, using the REAT protocol of ANSI S3.19-1974 as required by the EPA. As stated, there is currently no legally-acceptable method for these manufacturers to express the active (or the total) performance of their ANR products. However, based on the results of the studies cited above as well as the results of studies by other researchers, it *should* be possible to develop such a performance rating using REAT to characterize an ANR device’s passive component performance and MIRE to determine the active component.   A rating labeling scheme could then be devised which provides attenuation values for each component (passive and total) and a brief explanation of each.

Furthermore, through additional empirical investigations, or perhaps simply through thorough statistical scrutiny of the data, it may be determined whether using MIRE for the passive attenuation component of ANR headphones can reasonably supplant REAT, perhaps with some post-hoc data correction. If so, considerable time savings could result for those who test headphones as well as those who administer hearing conservation programs within their organizations, since the MIRE test is less time-consuming and is more repeatable than REAT.

ANR attenuation performance: Effects of measurement microphone location. Typically, MIRE attenuation measurements, whether they are for passive or ANR headphones, are conducted with a miniature microphone affixed to some portion of the outer ear (under the earcup) via double-sided tape. Some researchers (Casali, Mauney, & Burks, 1995) have located the microphone on the floor of the concha, and in using this approach, the data have demonstrated good MIRE test-retest reliability. Other researchers have located the microphone slightly inside the ear canal, just below its rim, mounted on a small earplug (Gauger, 1998). In-ear canal placement can be both "shallow" (i.e., microphone fitted on an earplug inserted just past the opening) and "deep" (i.e., microphone fitted to a probe tube and inserted deeper into the ear canal) to determine the outer ear resonance and bone conduction effects as well as spectral differences at these locations. Illustrations of these microphone placements appear later in the text. It is apparent that there is not a definitive, agreed-upon specification for microphone placement in the prevailing MIRE standards (MIL-STD-912, 1990; ANSI S12.42,1995) and there is no extant empirical data set which lends guidance as to which microphone placement is the better one, i.e., in the ear canal-shallow, in the ear canal-deep, in the concha area, or perhaps in some other location. One goal of this research was to provide such data.

While microphone placement differences may not matter for passive devices, there is reason to believe that microphone placement may in fact be important for obtaining measurement sensitivity to differences between ANR systems. For instance, the degree of active noise cancellation may be different at one microphone placement versus another, since the gradient of the destructive superposition effect changes as the measurement microphone moves away from the ANR microphone (inside the earcup). With this in mind, "optimal" ANR designs should affect high amounts of noise cancellation throughout the volume under the earcup, while less effective designs would demonstrate cancellation primarily in the region of the ANR system's microphone location. If this premise is true, then it provides support for the attenuation measurement microphone being located as close to the tympanic membrane as possible (deeper inside the ear canal), because that is the location where cancellation of noise is most important. A tympanic measurement microphone location is the most distal from the ANR microphone in most ANR headphone designs, and again, as the distance away from the ANR microphone increases, cancellation typically decreases.

At present, it is unknown whether differences (statistical or practical) in measurement microphone placement (i.e., in-concha, shallow canal or deep canal) will be sensitive to differences in ANR designs. However, because attenuation measurement standards are being revised to accommodate ANR devices, with the EPA calling for input toward the development of ANR device attenuation labeling regulations, it is very important that this question be answered so that appropriate recommendations can be made for the specification of measurement microphone location in the upcoming standards and regulations (Casali & Robinson, 2003).

It is for this reason that three microphone placements for MIRE measurements were compared for the different ANR devices in this study, representing those mentioned above; that is, in-concha, in ear canal-shallow, and in ear canal-deep. It is theorized that ear canal resonance, tissue and bone conduction, and microphone distance from the ANR-circuitry are factors that may influence attenuation. Evaluating microphone placement in these three key locations provides not only valuable insight as to the significance of these physiological effects, but also the importance of microphone location to capture noise that may have circumvented the ANR system.

Acceptance and Proper Use of Headphones

Comfort. As widely accepted in the literature (Arezes & Miguel, 2002; Berger, 1990, 1998; Casali, 1993; Gauger, 1998; Park & Casali, 1991), comfort and acceptability are key factors in the successful fielding and utilization of any headphone. Whether a headphone is effective is not determined solely by the level of protection it can provide. If the headphone is uncomfortable, impedes the task, or creates a greater safety hazard because it attenuates desired sounds (e.g., speech and warning signals) along with the unwanted noise, the device may be worn improperly (to increase comfort or allow speech and signals to be heard), or not worn at all. Employees have even modified headphones to improve comfort at the expense of protection. These modifications include springing earmuff headbands to reduce the tension, cutting flanges off of pre-molded inserts, drilling holes through plugs or muffs, or deliberately obtaining HPDs that were either larger (muffs) or smaller (plugs) than required (Berger, 1980).

It is, of course, very important to determine the attenuation properties of headphones, whether they be passive or active devices. Additionally, it is very important to understand how a headphone may be worn, in what environment it is worn (e.g., hot, cold, dusty, greasy), and the duration of wear. Many general aviation pilots, for example, wear ANR communications headphones for many hours at a time. Similarly, workers who are exposed to high levels of noise in the workplace may wear passive headphones throughout their shift. If a headphone is uncomfortable, the wearer may periodically remove it or, in the case of an earmuff, move it to a more comfortable location (e.g., resting on the head, around the neck, or any location away from the ears). In either instance, a significant reduction in actual hearing protection may result because the periods not worn result in 0 dB protection in a time-weighted average (average noise exposure over the course of an 8-hour work shift).

For example, if not worn for 15 minutes during a total exposure time of 1 hour (i.e., worn 75% of the time), the effective protection provided by a high attenuation (30 dB) hearing protector is only 6 dB. This effectively means that a high attenuation protector is really only providing the protection of a low attenuation (6 dB) protector worn for the full hour of exposure (Figure 10, Example a). Similar evidence has been shown for longer exposure times. Assume that total exposure was for 6 hours (accounting for breaks, lunch, and rest periods away from noise exposure during an 8-hour day). If not worn for 5 minutes during this 6-hour period (i.e., worn 98.6% of the time), the effective protection provided by a 30 dB hearing protector is only 18 dB (Figure 10, Example b); making the effective protective value 12 dB less than expected (OSHS, 2003). Noise exposure, even for a brief period of time, can be detrimental to human hearing; yet, if a hearing protector is uncomfortable, regardless of its attenuation value, it will either not be worn, it will not be worn properly, or it will be repeatedly removed – thereby seriously compromising its effectiveness. Berger (1998) suggested that headphone selection should consist not only of manufacturer’s specification sheets and price lists, but also by comparing different headphones for their comfort level and wearability.

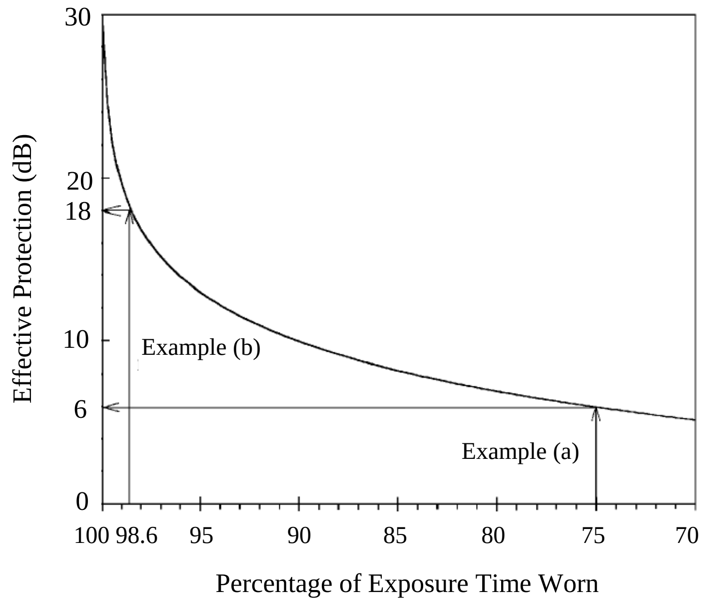

Figure 10. Reduction in effective protection provided by a high attenuation headphone with decreased wearing time during noise exposure.

Wearing an ANR-based earmuff incorrectly can create additional problems. For example, in some devices, if the seal is broken around the ear, the compensation circuitry may "saturate" when exposed to the ambient noise and artifacts can be produced through the earphones, increasing exposure levels. In this case, some ANR devices may exhibit "squeal." This can occur when the wearer lifts the earcup away from the head or rests it on the pinnae in an attempt to hear sounds outside the muff or to achieve greater levels of comfort.

A potential advantage of ANR is evidenced by subjects who anecdotally indicate that they feel more "comfortable" with the noise reduction provided by ANR headphones (versus passive), particularly for loud, low-frequency rumbles or intense intrusive noises such as sirens (Casali & Berger, 1996). With supra-aural ANR headphones, comfort advantages over passive earmuffs may be even greater due to their lower weight and reduced headband force. This is because ANR headphones attenuate incoming noise electronically (in part), therefore not requiring large-volume earcups or the same amount of earcup cushion compression as with passive devices to establish the same (or better) low-frequency attenuation. However, since supra-aural headphones lack any appreciable passive attenuation (Cro, 1997), comfort, in this case, should not be the primary determining factor. The earcups of circumaural ANR headphones, on the other hand (at least in most designs), are intended to provide fairly good passive attenuation.

Perceived levels of comfort are generally determined using subjective measurement techniques (Christian, 1999; Park & Casali, 1991). The Comfort and Acceptability Rating Scale developed by (Casali, Lam, & Epps, 1987) (see Appendix B), is an example of a validated method for determining headphone comfort (Arezes & Miguel, 2002; Lancaster & Casali, 2004). The scale is a multidimensional bipolar rating scale designed to assess and quantify the wearer's subjective feelings with respect to a particular headphone. Using a Likert-type scale, numerical values are assigned to each response and are summed to compute the comfort index (CI) for a particular headphone. Statistical analysis can then be performed on the CI data to determine if differences in comfort exist between headphones.

Design characteristics. Laboratory research has shown that proper selection and use of headphones can provide effective protection for wearers exposed to potentially harmful noises (Arezes & Miguel, 2002; Casali & Grenell, 1988). Field research, on the other hand, has shown that protection afforded by headphones in actual field use or "real world" environments, routinely falls short of laboratory-derived data reported by manufacturers (Berger, 1988; Berger, 1991; Frank & Roald, 2004; Park & Casali, 1991; Pfretzschner & Moreno, 1988). These studies have identified a number of factors that may attribute to this discrepancy, such as physical activity, wear time, and various headphone design characteristics. Comparisons have been made between these factors and their effects on hearing protector attenuation with results ranging from reductions in attenuation caused by physical activity and headband force, to earmuff cushion type not having a significant effect on attenuation (Casali & Grenell, 1988; Casali & Grenell, 1990).

The Casali and Grenell (1990) study also revealed that pressure exerted on the head (band-force of the headphone) is an important consideration for assessment of comfort and acceptability of earmuffs. Berger and Mitchell (1989) determined that peak-pressure loading, particularly where the circumaural earcup cushion exerts pressure on sensitive areas of the flesh, may be a more critical determinant of comfort than overall cushion force. While the measurement and apparatus of this particular metric were beyond the current research scope, headband force measurements were within the purview of this effort. As such, this research focused on headband force as it directly related to comfort by correlating this earmuff design characteristic with levels of comfort as rated by each participant for a given headphone (using the Comfort Index).

RESEARCH GOALS

The goals and related hypotheses established for this research are as follows:

Goal 1: Comparison of passive attenuation using REAT and MIRE test protocols

Determine the differences between the passive attenuation of several ANR-based circumaural hearing protector earcup designs (e.g., with different occluded volumes and/or cushion seals) measured using both REAT and MIRE protocols.

Hypothesis. There is no significant difference between the attenuation values obtained from each measurement paradigm; i.e., REAT and MIRE for each headphone type.

Goal 2: Determine numerical spectral corrections for MIRE, if necessary

If necessary, determine numerical spectral corrections for MIRE data such that the less expensive, less time-consuming, and more objective MIRE measurements closely approximate the "gold-standard" REAT measurements that are now required in current ANSI and ISO headphone test standards.

Goal 3: Evaluation of MIRE measurement microphone placement

Determine which location of the MIRE attenuation measurement microphone (i.e., either in-concha, in the ear canal-shallow, or in the ear canal-deep) yields better sensitivity to differences in designs among ANR headphones as to noise cancellation effectiveness.

Hypothesis. A significant difference exists between the IL measurements taken at the three microphone placement locations (i.e., in-concha, in-ear canal shallow, and in-ear canal deep). It is hypothesized that the deep microphone placement will yield increased noise cancellation effectiveness, due in part to ear canal characteristics and the decreasing gradient of the soundwave superposition as distance from the earcup increased.

Goal 4: Determine subjective comfort for each headphone

Determine the levels of comfort for each headphone, via the Comfort Index (Casali et al., 1987), and solicit information that may be useful to manufacturers with respect to certain design characteristics that may influence comfort.

Hypothesis. A significant difference exists between headphones with high headband force values and those with low headband force values with respect to comfort index. Higher headband force will yield higher levels of discomfort. Information gleaned from subjective evaluation may be useful to manufacturers in the design of future headphones or redesign of existing products.

Goal 5: Make empirically-based recommendations for use of REAT vs. MIRE

Make recommendations based on the empirical evidence collected regarding REAT versus MIRE testing protocols with primary relevance to ANR headphone attenuation measurement.

Hypothesis. It is hypothesized that the MIRE protocol may reasonably supplant the existing REAT protocol for testing passive attenuation of ANR-based headphones. That is, no significant difference exists between the spectral attenuation results from REAT and MIRE for passive attenuation measurement.

Goal 6: Recommendations for rating labeling scheme

Make recommendations as to a rating labeling scheme using the MIRE data (or a combination of REAT and MIRE data).

Hypothesis. An attenuation rating labeling scheme similar to the EPA fuel-rating paradigm, previously discussed in the literature review section, may simplify attenuation labeling for consumers of ANR-based headphones since existing labeling does not include the contribution of active attenuation.

METHODOLOGY

Experimental Design

This research was based on a full factorial, within-subject design. The dependent variable for MIRE was attenuation via insertion loss (in dB) in 1/3-octave bands centered at 63, 125, 250, 500, 1000, 2000, 4000, and 8000 Hz, in octave band steps. The dependent variable for REAT was attenuation via insertion loss (in dB) in 1/3-octave bands centered at 125, 250, 500, 1000, 2000, 4000, and 8000 Hz, in octave band steps. In all cases, both REAT and MIRE data were obtained for each of two common fits of each headphone on each participant. This was done so that differences in quality of fit would not confound the REAT vs. MIRE comparisons. The experimental design matrix (Figure 11) illustrates the focus on determining the differences between MIRE- and REAT-obtained attenuation for the active and passive attenuation components of each headphone. The three different microphone locations for MIRE consisted of in the concha, in the ear canal (shallow-fit), and in the ear canal (deep-insert using a probe tube microphone). Microphone was not a factor during the REAT tests, since those measurements were psychophysical, not physical.

Independent Variables. The two levels of Measurement Protocol were *REAT* and *MIRE*. The three levels of Microphone Location were *in-concha (with open canal), shallow* with occluded canal (using a earplug-mounted microphone), and *deep* with open canal (using the probe tube microphone). The five levels of Headphone Type were *Sennheiser HMEC300 NoiseGard*, *Bose Aviation Headset X*, *Bose QuietComfort 2*, *Sennheiser HDC451 NoiseGard*, and *Lightspeed Aviation Thirty 3G*. Participant assignment to condition is shown in each cell (Figure 11). During the experimental trials, presentation order of headphones was randomized across participants.

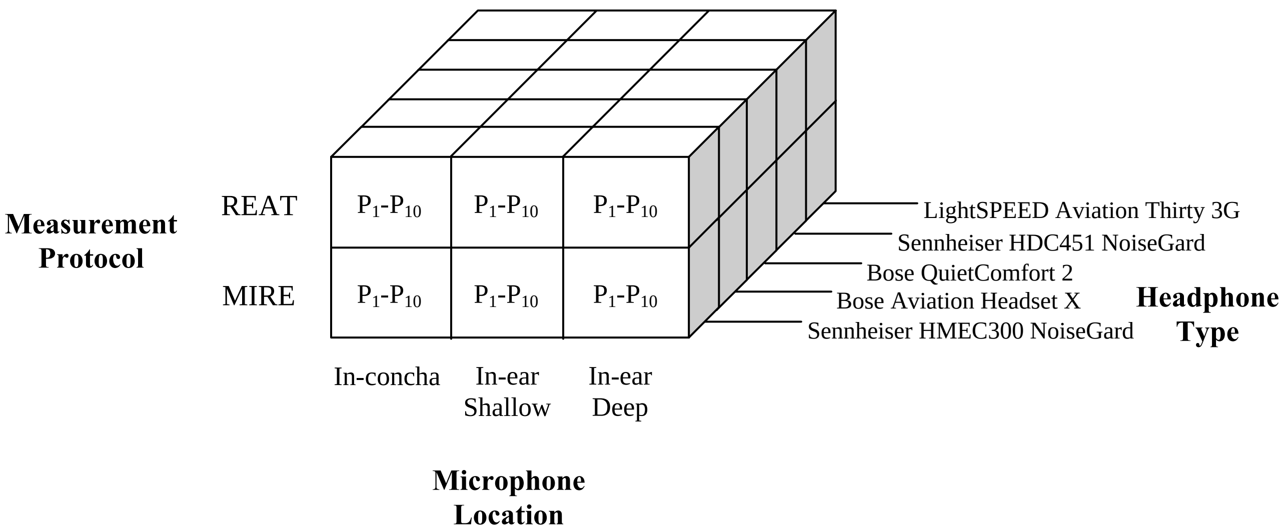

Figure 11. Within-subject experimental design matrix for comparison of two attenuation measurement protocols and three microphone locations using five different ANR headphones. Participant (P) assignment shown.

As mentioned earlier, both REAT and MIRE IL data were obtained for each of two unique fits of all headphones under observation. This was done to eliminate quality of fit as an uncontrolled source of variance when comparing the passive REAT and MIRE attenuation data, as well as when comparing microphone locations.

Microphone Location

As discussed previously, three microphone locations were evaluated with measurements obtained at each for two fits of each earmuff: 1) in-concha, with open canal (see Figure 12), 2) in ear canal-shallow, with occluded canal (swim plug-mounted microphone, see Figure 13), and 3) deep-insert, with open canal (probe tube microphone, see Figure 14). The in-concha microphone was a Knowles model 3132. The in ear canal-shallow microphones were miniature Panasonic microphones mounted to AEARO Ultrafit™ child swim earplugs with the stems removed. The probe tube microphone was the type typically used for testing hearing aid devices and consisted of a Knowles model EM3068 microphone attached to an ER-7 silastic probe tube. The probe tube was a very soft, flexible rubber-like material that fit over the microphone port on the miniature microphone; essentially extending the microphone port the length of the probe tube. Although difference measurements (i.e., insertion loss) were taken with each microphone, all microphones were calibrated before each testing session to ensure proper functionality. The probe tube microphone was calibrated with and without the probe tube attached.

Measurement microphones were affixed to the concha via double-sided foam tape and low-adhesion cloth tape was used to secure all microphone wires to the side of each participant's neck. The shallow microphone was mounted on a swim plug (Children's Ultrafit™ from AEARO Company) with the stem removed, and inserted into the ear canal, stopping just inside the entrance and facing the tragus. The probe tube was attached to the miniature microphone and the probe tube itself was inserted into the ear canal. Once the tympanic membrane was reached, as indicated by the participant, the probe tube was backed outward about 5 mm and the microphone was fixed to the floor of the concha using foam tape under the microphone.

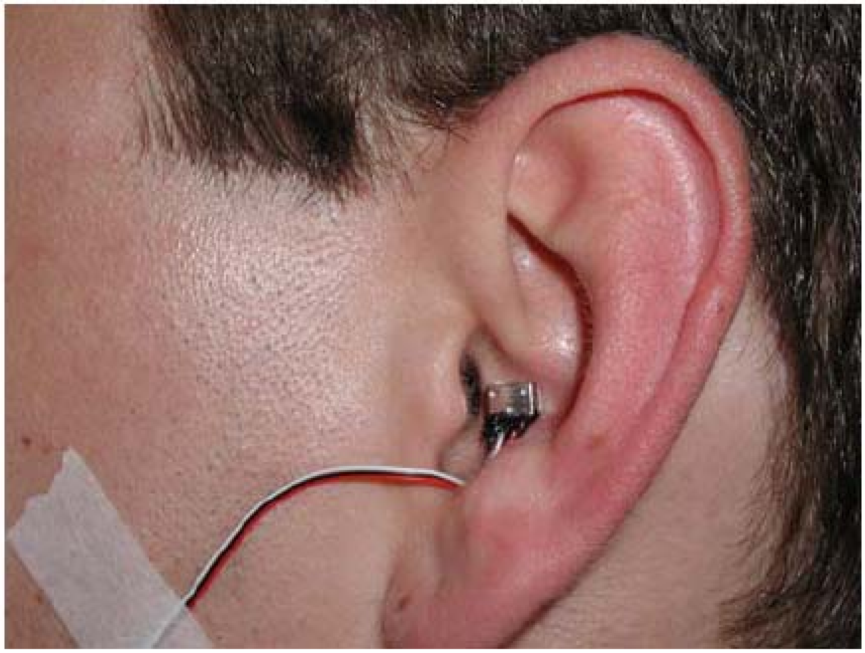

Figure 12. Microphone placement for the in-concha location (note open ear canal).

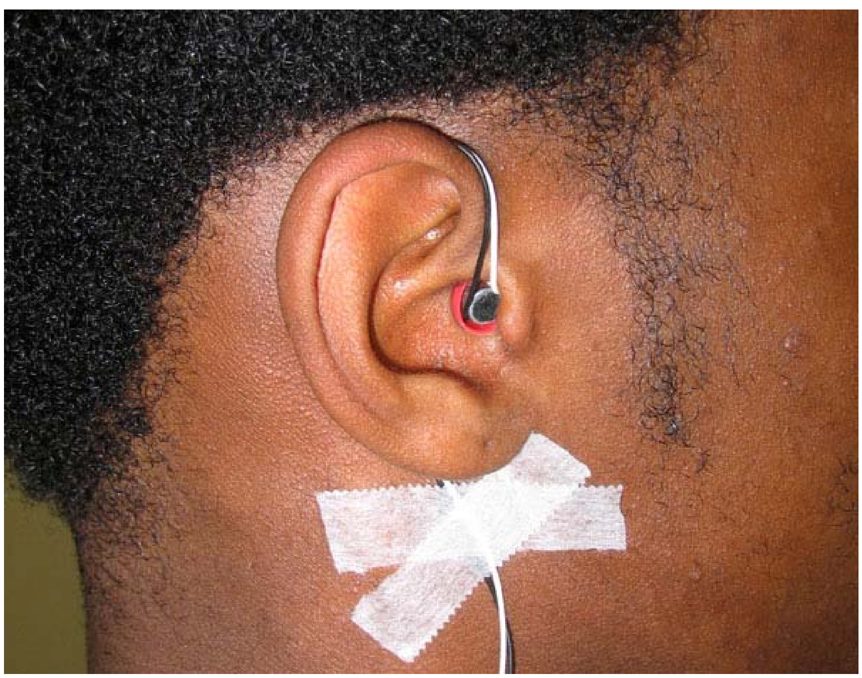

Figure 13. In ear canal-shallow microphone mounted on truncated “swim” plug.

Figure 14. In ear canal-deep microphone location. (Note clear probe tube inserted into ear canal. This stops just short of the tympanic membrane).

Headphones

Figure 15 shows the five different ANR headphones used for this research. They are a) Bose Aviation Headset X, b) Bose QuietComfort 2, c) Lightspeed Aviation Thirty 3G, d) Sennheiser HDC451 NoiseGard, and e) Sennheiser HMEC300 NoiseGard. These headphones were representative of the latest technology in ANR noise-annoyance-reducing, music-reproduction headphones (b, d) or communications headphones, designed for the aviation cockpit environment (a, c, e). Detailed descriptions of each headphone may be found in Appendix A. Headband force, measured in Newtons (N) was directly measured in the laboratory with an INSPEC earmuff headband force measurement apparatus (Figure 16). Each headphone was placed on the measurement apparatus according to specifications in (Casali, Robinson, & Hankins, 2000), with respect to earcup separation and placement on the apparatus. Earcup cushions were allowed to fully compress and digital measurement readouts were annotated. Each headphone was measured twice and an average force value was computed for each headphone.

(a) Bose Aviation Headset X (circumaural)

(b) Bose QuietComfort 2 (lightweight circumaural)

(c) LightSPEED Aviation Thirty 3G (circumaural)

(d) Sennheiser HDC451 NoiseGard (lightweight supra-aural)

(e) Sennheiser HMEC300 NoiseGard (circumaural)

Figure 15. Examples of the five ANR headphones used during the research.

Figure 16. INSPEC earmuff headband force measurement apparatus.

Apparatus

This research was conducted at the Auditory Systems Laboratory (ASL) in the Grado Department of Industrial and Systems Engineering, of the Virginia Polytechnic Institute and State University, in Blacksburg, Virginia. The reverberant sound chamber used in this study was housed within a sound-isolated room with double exterior walls and an acoustic door (Figures 17 and 18). Instrumentation for stimulus presentation and data capture included an IBM PC with custom software for controlling a 4-channel Norwegian-Electronics 828 Hearing Protector Attenuation Test System (at the experimenter's station) and a set of three frequency-response-matched TEP-2 loudspeakers; with the firing axis of one speaker being in each of the three room planes (inside the reverberant chamber). The functional block diagram of the experimental environment is shown in Figure 19. A complete glossary of photographs depicting the experimental environment and all testing apparatus may be found in Appendix C. More detail regarding apparatus specifications may be found in the Virginia Tech Auditory Systems Laboratory calibration manual (Casali & Lancaster, 2004).

Figure 17. Experimenter's station and exterior view of the reverberant chamber within the sound-isolated Auditory Systems Laboratory.

Figure 18. Interior view of the reverberant chamber with seated subject.

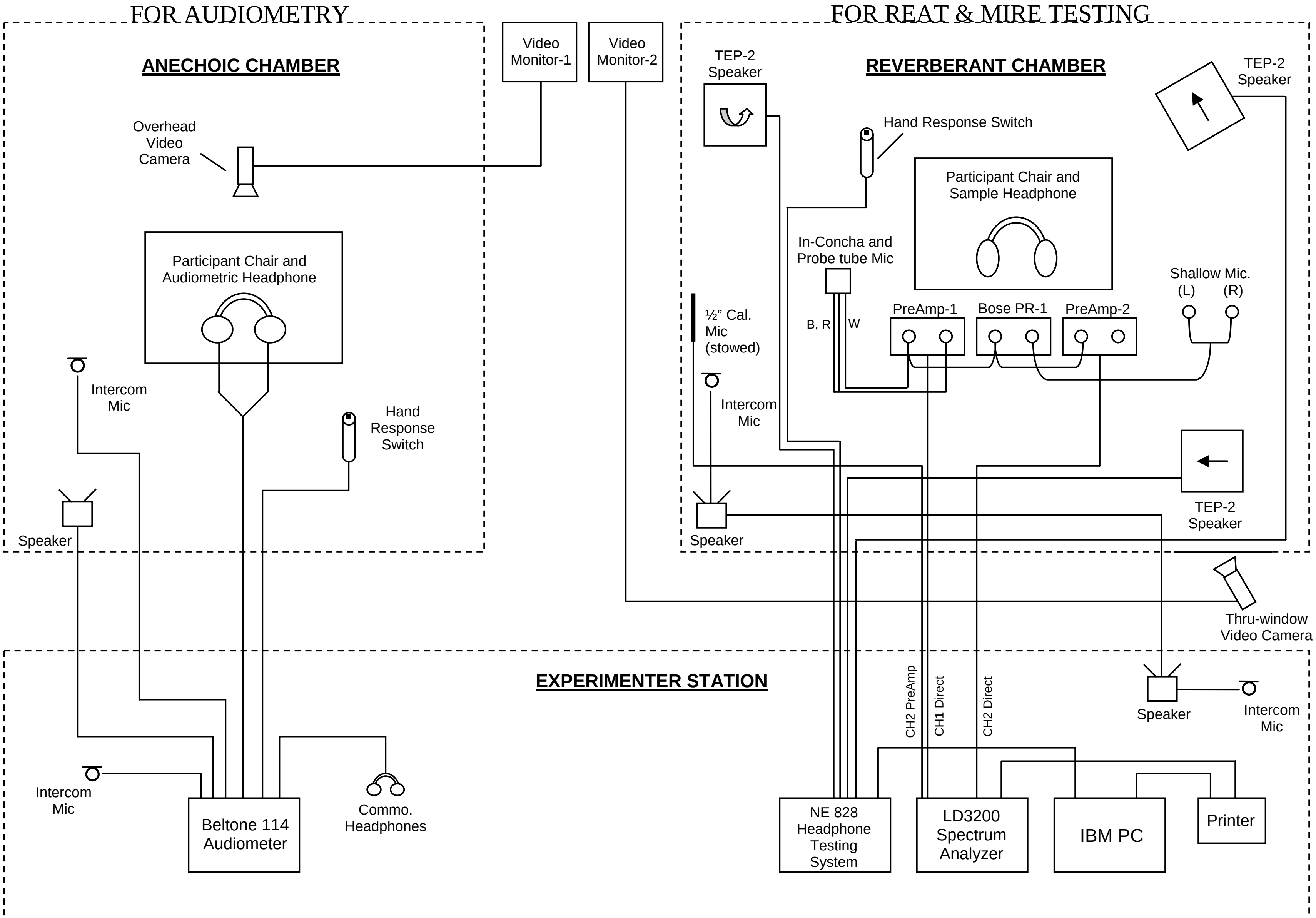

Figure 19. Functional block diagram of experimental environment and apparatus (not to scale).

Measurement

REAT tests were conducted using a variant of Békésy tracking, which incorporated computer software-imposed safeguards to achieve validity and reliability of threshold (Casali et al., 2000). Békésy tracking is a type of method of adjustment where the listener pushes a button as long as he or she can hear the tone and lets go when he or she stops hearing the tone, so the level goes up and down around threshold. In Békésy tracking, the frequency of the tone changes during the course of the test so that thresholds can be estimated at many frequencies (Gelfand, 1998).   Participants tracked their hearing thresholds to the 1/3-octave band stimuli using a silent, thumb-actuated hand switch. Participants depressed the hand switch button and held it down when they thought they heard the pulsed-tones and released the button when they thought they no longer heard the tones. All thresholds were computer-scored and recorded to the computer. The threshold pairs for open-ear and occluded-ear measurements at each frequency were differenced to obtain the insertion loss for that frequency band during a given trial.

MIRE tests were conducted using pink noise generated by the NE828 test system. Stimuli were presented at 90 dBA to ensure sufficient signal-to-noise floor headroom (10 dB) to accommodate the attenuation provided by all devices under study (ANSI, 1995). Sufficient signal headroom is important because if the headroom is not high enough, the true attenuation capability of a headphone with high attenuation characteristics may not be accurately evaluated. Because these measurements needed to allow each participant to perform REAT tests while the in-concha and probe tube microphones (both open ear canal) were present for the MIRE tests, all MIRE measurements were conducted in 90 dBA pink noise for only 30-seconds per trial, ensuring that no hazard to the participant's hearing occurred. This process provided an exposure level well below the OSHA "criterion level" of 90 dBA time-weighted average for an 8-hour day, and thus was deemed safe for participants in the unoccluded REAT trials.

<u>Participants</u>

Ten volunteers from the Blacksburg, Virginia area, consisting of 6 males and 4 females, with an average age of 23.1, participated in this within-subject study. The number of participants was specified in the two testing standards used for this study, ANSI S12.6-1997(R2002) and ANSI S12.42-1995. Five additional participants were recruited, screened, and deemed "pre-qualified" in the event of participant drop-out during the study. Per ANSI S12.6-1997(R2002) "Method B," participants were "naïve subjects," meaning that they had no prior experience with using passive headphones or ANR headphones (i.e., in commercial, aviation, industry, military, or any other setting). However, basic familiarity with these devices did not preclude prospective individuals from participating in the research, since most people are familiar, if only knowing of their existence, with hearing protection devices. All participants were compensated for time spent in the laboratory at a rate of $8.00 per hour.

Experimental descriptions, procedures, and participant consent forms were reviewed and approved by the Virginia Tech Internal Review Board (IRB) in accordance with IRB standards and procedures for the utilization of human participants for investigative research prior to the commencement of any experimentation (see Appendix D). The Informed Consent form was read and signed by each participant before any screening, pre-testing, or experimentation took place (see Appendix E). Participant screening forms may be found in Appendix F.

Pre-Experimental Procedures

After reading and signing the informed consent, each participant underwent the following procedures, which are governed by the VT-ASL's quality assurance manual (Hankins, Robinson, & Casali, 2000). These audiometric criteria met (or exceeded) the requirements of ANSI S3.19-1974 and ANSI S12.6-1997(R2002), which are the U.S. standards for REAT protocols:

- Undergo an otoscopic examination to determine any potential ear canal anomalies.
- Undergo a pure-tone audiometric examination using a standard Beltone 114 clinical audiometer. This exam required hearing threshold levels, in either ear, no greater than 25 dBHL at 125, 250, 500, 1000, 2000, 3000, 4000, 6000, and 8000 Hz (per ANSI S12.6-1997[R2002]).
- Undergo 1/3-octave band open ear threshold variability tests, over a minimum of five trials (of which two were 'practice trials') at each test band to establish a range of trial-to-trial variability on 3 consecutive trials of not greater than 6 dB using modified Békésy tracking (with reliability checks and computer scoring), as described earlier.

Prior to conducting experiments, and per (Casali et al., 2000), a diffuse sound field uniformity test was conducted inside the reverberant chamber at 6 positions ($\pm$ 6 inches) about the participant's head center position. The six positions were front, back, left, right, up, and down. A total of six equivalent continuous sound level (L_{eq}) measurements were obtained over 60-second periods using a Larson-Davis (LD) 3200 series real-time spectrum analyzer, an LD 2559 microphone, and an LD 900B preamplifier. L_{eq} equals the continuous sound level which, when integrated over a specific time, would result in the same energy as a variable sound integrated over the same time (Earshen, 1986).

The four azimuth measurements were made with the microphone diaphragm 6 in. from the center of the room corresponding to the desired azimuth. For the two elevation measurements, the microphone was placed at the center of the room and adjusted ± 6 in. to obtain the up or down position. The room was configured exactly as it was for the experiments, only without the participant or chair present. The 1/3-octave band measurements were obtained using a steady (i.e., not pulsed) pink noise test signal at a broadband level of 90 dBA. Values were within recommended allowances, per ANSI S12.6-1997(R2002); that is no greater than 2 dB for left and right differences and no greater than 6 dB difference for all others. Results of the test are shown in Table 1.

TABLE 1. Reverberant Chamber Diffuse Sound Field Uniformity Test

1/3 OB Center (Hz)	dB Right -15, 0, 0	dB Left 15, 0, 0	Δ* **R-L**	dB Up 0, 0, 15	dB Down 0, 0, -15	dB Front 0, -15, 0	dB Back 0, 15, 0	Δ** **6-Pos**
125	52.0	51.3	**0.7**	51.4	51.5	51.0	51.1	**1.0**
250	51.5	52.7	**1.2**	52.6	52.1	51.3	52.2	**1.4**
500	55.3	55.3	**0.0**	55.1	55.4	54.4	54.4	**1.0**
1000	54.9	54.8	**0.1**	54.4	54.7	54.4	54.6	**0.5**
2000	52.4	52.0	**0.4**	52.3	52.3	52.3	52.0	**0.4**
3150	51.9	51.8	**0.1**	52.0	52.5	51.4	51.9	**1.1**
4000	53.1	53.5	**0.4**	53.6	53.4	53.5	53.2	**0.4**
6300	52.1	52.2	**0.1**	52.0	52.4	52.0	52.3	**0.4**
8000	51.3	51.4	**0.1**	51.4	51.6	51.5	51.8	**0.1**

* Absolute value dB difference between right and left microphone locations (no greater than 2 dB maximum).
** Maximum absolute value dB difference between all pairs of the six microphone locations (no greater than 6 dB maximum).

Experimental Procedures

Test method. The ten audiometrically qualified participants underwent the following procedures during experimental trials conducted during May and June, 2005. These procedures were performed with each participant using each headphone. Participants used one headphone per experimental session and there was a total of five experimental sessions per participant. A total of fifty experimental sessions were conducted (ten subjects x five headphones).

- Verbal instructions were given to the participants for proper use of the thumb-operated control switch for use during the REAT tests. This was followed with a demonstration by the experimenter. Participants were allowed to practice using the control switch. All questions were answered and the experimenter determined when the participant had sufficiently demonstrated acceptable use of the control switch.

- MIRE active and passive attenuation tests were performed on the left ear only (Casali et al., 1995), per modified ANSI S12.42-1995 (i.e., open ear, headphone power off, headphone power on), using three different microphone locations (in-concha, in ear canal-shallow, and in ear canal-deep).
- REAT passive attenuation tests, per ANSI S12.6-1997(R2002) Method B Subject-Fit, were performed.
- Comfort Index Rating Scales were completed by each participant after each experimental session.

Test sequence. Specific steps for the aforementioned tests were as follows:

- Ensured that the participant was not suffering from any physical condition that might affect his/her hearing immediately prior to each session (e.g., head cold, ear canal anomaly found during otoscopic exam). All participants were pre-qualified based on audiogram performance, requiring pure tone threshold to meet ANSI S12.6-1997(R2002).
- Connected test-specific microphones as prescribed in test sequence.
- Seat the participant in the test booth.
- Performed the steps outlined in Table 2 for the headphone assigned to that session.

- Upon completion of each session, participants moved to the experimenter’s station and completed the Comfort and Acceptability Rating Scale for the headphone just used (while wearing the headphone).
- Each participant was thanked, compensated, and escorted from the laboratory.

TABLE 2. Experimental Stepwise Procedures Summary

	SUBJECT:	Headphone:		DATE:
	Step by Subj#			
	Odd#	Even#	MEASUREMENT	Done
Shallow 1	1	19	REAT unoccluded	
	2	20	Fit Microphone	
	3	21	MIRE unoccluded	
	4	22	Fit sample -- wait 30 seconds	
	5	23	MIRE + passive	
	6	24	MIRE + active	
	7	25	Remove sample	
Shallow 2	8	26	MIRE unoccluded	
	9	27	Fit sample -- wait 30 seconds	
	10	28	MIRE + active	
	11	29	MIRE + passive	
	12	30	Remove sample and mic	
Deep 1	13	1	Fit Mic. Doc ear used & probe length.	
	14	2	REAT unoccluded with mic	
	15	3	MIRE unoccluded	
	16	4	Fit sample -- wait 30 seconds	
	17	5	REAT occluded	
	18	6	MIRE + passive	
	19	7	MIRE + active	
	20	8	MIRE noise floor test (with ANR off)	
	21	9	MIRE noise floor test (with ANR on)	
	22	10	Remove sample	
Deep 2	23	11	Fit sample -- wait 30 seconds	
	24	12	MIRE + active	
	25	13	MIRE + passive	
	26	14	REAT occluded	
	27	15	Remove sample	
	28	16	REAT unoccluded with mic	
	29	17	MIRE unoccluded	
	30	18	Remove microphone	
Concha 1	31	31	Fit Microphone	
	32	32	MIRE unoccluded	
	33	33	Fit sample -- wait 30 seconds	
	34	34	MIRE + passive	
	35	35	MIRE + active	
	36	36	Remove Sample	
Concha 2	37	37	MIRE unoccluded	
	38	38	Fit sample -- wait 30 seconds	
	39	39	MIRE + active	
	40	40	MIRE + passive	
	41	41	REAT occluded	
	42	42	Remove sample and mic	
	43	43	REAT unoccluded without mic	

Experimental Stepwise Procedures. As summarized in Table 2, the following detailed steps were performed with each participant, for each headphone, during each experimental session. The experimenter calibrated each microphone and captured noise floor spectra inside the reverberant chamber. Upon arrival, the participant was asked if they had any condition (e.g., head cold) that could potentially affect their hearing. If a condition existed, they were asked to reschedule the experimental session. If no condition existed, an otoscopic examination was administered. If the otoscopic exam discovered excessive amounts of earwax, the participant was informed they should reschedule the experimental session for a later time after the blockage had been removed. Instructions were given to either purchase over-the-counter ear wax removal solutions or to consult with a physician.

Each participant was assigned a participant number (from 1-10). Odd-numbered and even-numbered participants began each session with different microphone placements as shown in Table 2. This assisted in controlling for order bias with respect to microphone placement. Since all participants underwent all steps in Table 2, only one set (odd-numbered) will be described in detail here.

When ready to proceed with the experimental session, participants were seated in the reverberant chamber with the door closed for five minutes to allow their ears to adjust to the ambient acoustics. After this acclimation period, the participant was administered the REAT unoccluded test. The participant then exited the chamber and sat at the experimenter’s station, where the experimenter carefully inserted the shallow microphones (mounted on swim earplugs) and secured the electrical wires to the participant’s cheek and neck with tape. The participant was escorted back into the chamber, the experimenter connected the microphone wires to the pre-amp boxes (see Figure 19 for details), and the MIRE unoccluded test was administered. The first sample of the headphone was then donned (by the participant) and 30 seconds passed to allow for proper cushion seal before the MIRE-passive (ANR off) test was conducted. The experimenter then entered the chamber and switched the ANR circuitry on and the MIRE-active test was given. The headphone was then removed by the experimenter (to ensure that microphone placement was not disturbed). Another MIRE unoccluded test was given, followed by the participant donning the second sample of the same headphone. The experimenter switched the ANR circuitry on, and after 30 seconds, the MIRE-active test was given. The experimenter then switched the ANR circuitry off and the MIRE-passive test was given. The experimenter removed the headphone, disconnected the microphone wires from the pre-amp boxes, and escorted the participant to the experimenter's station.

The shallow microphones were carefully removed by the experimenter and the deep probe tube microphone was inserted into the participant's left ear. The soft probe tube was carefully inserted into the participant's ear canal until the tip of the probe tube touched the tympanic membrane. This produced a distinct sound for the participant, who then indicated this to the experimenter. The probe tube was then backed away from the tympanic membrane by about five mm and the microphone, attached to the outer-ear end of the probe tube, was secured to the floor of the participant's concha with double-sided foam tape. The wires leading to the probe tube microphone were securely attached to the participant's cheek and neck with tape. The participant was led back into the chamber and connected to the pre-amp boxes. This microphone fitting procedure is step 13 for the odd-numbered participants and step 1 for the even-numbered participants.

The REAT unoccluded test was performed, followed by the MIRE unoccluded test. The participant then donned the first sample of the headphone, and after 30 seconds, the REAT occluded test was performed. The MIRE-passive test was then given, followed by the MIRE-active test, after the experimenter switched the ANR circuitry on. Another set of MIRE-passive and MIRE-active tests were then performed, only this time with no noise stimulus presented. This was done to obtain data for a noise floor test to ensure that instrument and room noise floor was not high enough (i.e., 10 dB above noise floor in each 1/3-octave band) to affect the measurement over the range in which the ANR circuitry was performing. The experimenter then removed the headphone and the participant donned the second headphone sample. The experimenter switched the ANR circuitry on, and after 30 seconds, a MIRE-active test was performed. The experimenter then turned the ANR circuitry off and a MIRE-passive test was performed, followed by a REAT occluded test. The experimenter then removed the headphone and a REAT unoccluded test was performed, followed by a MIRE unoccluded test. The experimenter then disconnected the microphone wires from the pre-amp boxes, and escorted the participant to the experimenter’s station. The experimenter carefully removed the probe tube microphone and attached the concha microphone to the floor of the participant’s left concha using double-sided foam tape. The wires leading to the concha microphone were securely attached to the participant’s cheek and neck with tape. The participant was led back into the chamber and connected to the pre-amp boxes.

The MIRE unoccluded test was performed. The participant then donned the first sample of the headphone and the experimenter switched the ANR circuitry on. After 30 seconds, the MIRE-active test was performed. The experimenter switched the ANR circuitry off and the MIRE-passive test was performed, followed by the REAT occluded test. The experimenter then removed the headphone, disconnected the microphone wires from the pre-amp boxes, and escorted the participant to the experimenter's station. The experimenter carefully removed the concha microphone from the participant's ear. The participant was then asked to complete the headphone comfort index survey, while wearing the headphone they had just used during the experimental session. Upon completion, the participant was paid, thanked, and escorted from the laboratory. The experimenter cleaned each microphone and headphone with isopropyl alcohol, inspected all wires and connectors, calibrated all microphones, and captured noise floor spectra from each microphone in preparation for the next participant.

DATA REDUCTION

Equipment Malfunction

During the data reduction phase, it was determined that an equipment malfunction occurred with the Lightspeed Aviation Thirty 3G headphone (Headphone 5) during the testing phase, due to no fault of the headphone itself. This malfunction created acoustic artifacts in the data, which created erroneous spectral attenuation values for this headphone. Consequently, this headphone's data were dropped from all data analyses involving spectral attenuation. Data from this headphone were still used, however, for the headband force and comfort index rating analyses, since the malfunction had nothing to do with these variables.

Objective Measures

Attenuation values in dB from each experimental session were collected using both REAT and MIRE protocols and reduced for later analysis. Additionally, data from each protocol were combined into a REAT vs. MIRE data set for comparison between protocols. Passive insertion loss values were measured in the passive-only mode for each headphone. That is, the ANR circuitry was not activated. Total insertion loss values were measured with the ANR circuitry activated. That is, Total IL represented the passive plus active attenuation of each headphone. Active insertion loss values were computed by differencing the Total IL values from the Passive IL values. The data collected represented a complete data set, with no missing values. SAS, version 8, by the SAS Institute, Inc., was used for all data analyses involving spectral data. The alpha level for all analyses was set at 0.05.

REAT. As described earlier, this protocol used a Norwegian Electronics (NE) 828 hearing protector testing system connected to an IBM Personal Computer (386 PS2) running DOS 6.22. Psychophysical responses to stimulus presentation, as measured in dB at threshold (1/3-octave bands of noise), were automatically collected by the NE828 within each experimental condition and were recorded to the PC hard drive. These data were stored in a format that did not lend themselves to electronic conversion to other formats, such as a spreadsheet. Instead, the values for each condition were printed in hardcopy form and compiled for each participant's session. Upon completion of the experimentation phase, these data were transcribed from hardcopy into an MS Excel spreadsheet (see Appendix G). Mean attenuation values were then computed at each test frequency. These mean values were then used to determine statistical significance.

MIRE. For measurement, this protocol utilized the LD3200 series real-time spectrum analyzer connected to a microphone located under each headphone's left earcup (i.e., for concha, shallow, and deep microphones) to capture noise spectra during each condition. Shallow microphones were under both earcups, but only left-ear values were used for analysis. This was done because only the left ear was used for the in-concha and deep probe tube microphones and a by-ear comparison was not a goal of this study. However, since both shallow microphones were available and because these data were easy to collect, right-ear data were also collected and kept for future use. The NE828 hearing protector testing system was used for stimulus presentation (90 dBA pink noise). Data captured for each condition were stored in the LD3200 internal memory and digitally written to external electronic media. Mean attenuation values were computed at each test frequency. These values were then used to determine statistical significance.

REAT vs. MIRE. This data set was a combination of the REAT and MIRE data sets previously discussed. That is, REAT Passive IL data and MIRE Passive IL data were compared at each frequency. Since REAT used 7 frequencies and MIRE 8 (63Hz was included for the MIRE test) and since REAT is passive-only, this data set was comprised of the REAT Passive data and the MIRE Passive-only Insertion Loss data at the 7 frequencies common to both (i.e., 125, 500, 1000, 2000, 4000, 6000, and 8000 Hz).

Headband Force. This data set was captured using the INSPEC earmuff headband force measurement apparatus (per ANSI S3.19-1974) and the force values (in Newtons) were manually entered into an MS Excel spreadsheet (Appendix G). Data were used for regression analysis and comparison across headphones.

<u>Subjective Measures</u>

The Comfort and Acceptability Rating Scale data were transcribed from the participant rating scale forms into an MS Excel spreadsheet (Appendix G). The 7-point Likert-type rating scale was comprised of twelve questions with values ranging from 1 (poor or lowest) to 7 (best or highest). This provided for a range of possible scores from 12 (all ‘poor’ or ‘lowest’ responses) to 84 (all ‘high’ or ‘best’ responses). A Comfort Index score was calculated for each participant and each headphone. The resultant data set with averaged CI values was used for regression analysis to predict comfort from headband force. Comparisons across headphones were conducted using a one-way, non-parametric ANOVA.

DATA ANALYSIS AND RESULTS

<u>MANOVA Results</u>

A MANOVA was conducted separately on each of the three data sets (i.e., MIRE-only, REAT-only, and REAT vs. MIRE) collected from the experiment. This was done since the data collected were repeated measures and since sphericity assumptions are not made in the MANOVA, this test is considered to be "exact" for repeated measures designs, while the univariate approach can only be considered "approximate" (Vasey & Thayer, 1987).

The dependent variables included in the overall MIRE model were Passive Insertion Loss (Passive_IL), Active Insertion Loss (Active_IL) and Total Insertion Loss (Total_IL). Independent variables included in the model were Headphone, Microphone, Frequency, and all interaction combinations. Statistical significance (at $p < 0.05$) was observed in Headphone, Microphone, Frequency, Headphone-by-Frequency, Microphone-by-Frequency, and Headphone-by-Microphone-by-Frequency in the overall MANOVA model using the Wilk's *Lambda* test (Table 3).

The dependent variable included in the overall REAT model was Passive Insertion Loss (Passive_IL). Independent variables included in the model were Headphone, Microphone, Frequency, and all interaction combinations. Statistical significance was observed in Headphone, Frequency, and Headphone-by-Frequency in the overall MANOVA model using the Wilk's *Lambda* test (Table 4).

For the combination REAT vs. MIRE data set, the dependent variable included in the overall REAT vs. MIRE model was Passive Insertion Loss (Passive_IL).

Independent variables included in the model were Headphone, Microphone, Frequency, Protocol (for REAT vs. MIRE), and all interaction combinations. Significance was observed in Headphone, Frequency, Protocol, Headphone-by-Frequency, Microphone-by-Frequency, Microphone-by-Protocol, Frequency-by-Protocol, Headphone-by-Microphone-by-Frequency, Headphone-by-Microphone-by-Protocol, Headphone-by-Frequency-by-Protocol, Microphone-by-Frequency-by-Protocol, and Headphone-by-Microphone-by-Frequency-by-Protocol in the overall MANOVA model using the Wilk's *Lambda* test (Table 5).

TABLE 3. MIRE MANOVA Table

Source	Wilk's *Lambda*	*F*-Value	Num DF	Den DF	*Pr* > *F*
Headphone (H)	0.01	83.61	6	52	<.0001*
Microphone (M)	0.50	3.63	4	34	0.0144*
Frequency (F)	0.00	199.25	14	124	<.0001*
H x M	0.85	0.77	12	106	0.6839
H x F	0.00	137.88	42	376	<.0001*
M x F	0.33	6.65	28	250	<.0001*
H x M x F	0.51	3.56	84	754	<.0001*

* Statistically significant effect at $p \leq 0.05$.

TABLE 4. REAT MANOVA Table

Source	Wilk's *Lambda*	*F*-Value	Num DF	Den DF	*Pr* > *F*
Headphone (H)	0.07	120.24	3	27	<.0001*
Microphone (M)	0.99	0.10	1	9	0.7535
Frequency (F)	0.04	237.75	6	54	<.0001*
H x M	0.88	1.25	3	27	0.3125
H x F	0.14	57.00	18	162	<.0001*
M x F	0.88	1.20	6	54	0.3217
H x M x F	0.91	0.85	18	162	0.6339

* Statistically significant effect at $p \leq 0.05$.

TABLE 5. REAT vs. MIRE MANOVA Table

Source	Wilk's *Lambda*	*F*-Value	Num DF	Den DF	*Pr > F*
Headphone (H)	0.05	157.80	3	27	<.0001*
Microphone (M)	0.54	7.77	1	9	0.0211*
Frequency (F)	0.02	419.69	6	54	<.0001*
Protocol (P)	0.05	161.15	1	9	<.0001*
H x M	0.93	0.65	3	27	0.5879
H x F	0.08	108.09	18	162	<.0001*
H x P	0.74	3.18	3	27	0.2098
M x F	0.30	21.25	6	54	<.0001*
M x P	0.51	8.72	1	9	0.0161*
F x P	0.39	14.29	6	54	<.0001*
H x M x F	0.78	2.52	18	162	0.0012*
H x M x P	0.63	5.28	3	27	0.0054*
H x F x P	0.40	13.61	18	162	<.0001*
M x F x P	0.58	6.44	6	54	<.0001*
H x M x F x P	0.80	2.23	18	162	0.0045*

* Statistically significant effect at $p \leq 0.05$.

ANOVA Results for Main Effects and Interactions

Based upon the MANOVA results, individual ANOVAs were conducted on each of the dependent variables in each data set. *Only those significant main effects and interactions found in the ANOVAs that were also significant in the MANOVA were reported.* This was done because individual ANOVAs do not provide adequate protection against making Type I errors (i.e., when a true null hypothesis is rejected), when multiple dependent variables are analyzed separately. Performing the MANOVA first ensures that if significant differences are found between population means, the researcher may be confident that real differences actually exist and ANOVAs can then be used to determine where the differences actually occur (Johnson, 1998).

Per (Keppel, 1991) and (Huck, 2000), significant higher-order interactions were decomposed and evaluated first, using software analysis (described in detail below), followed by significant first-order interactions and main effects. Simple effects tests were conducted manually on significant two- and three-way interactions to determine how the main effect of one factor differed at each level of another. That is, if factors A and B, for example, interact, one interpretation is a lack of additivity. This stems from the linear model representation of the factorial treatment and design structure. Conversely, if two factors act independently on the outcome of an experiment, their contributions are additive. Factor A makes its contribution independent of Factor B and you can add the two up to assess their joint effect. If an interaction between A and B is present, this additivity no longer applies. You must know the particular level of factor B to assess the effects of factor A and vice versa (Schabenberger, Gregoire, & Kong, 2000).

The method used to determine these effects is called slicing. This is a term and a function developed by SAS, the company responsible for the SAS statistical analysis software used in this study. Slicing is essentially simple effect or simple main effects testing. A slice implies breaking the data set into separate parts and running one-way ANOVAs for each location. For example, the significant three-way interaction Headphone-by-Microphone-by-Frequency in the MIRE Passive-only data set was sliced as such. The statistical model included the dependent variable Passive_IL and the independent variables included headphone, microphone, and frequency and all interaction combinations. SAS then compared each two-way combination to look for significant interaction.

Post-hoc analysis using the Tukey-Kramer test was conducted on significant main effects with more than two levels. This test was chosen because of its ability to better control error rate and generate 95% confidence intervals better than other post-hoc tests, such as Newman-Keuls. Results of these analyses follow.

The dependent variables included in the overall MIRE ANOVA model were Passive Insertion Loss (Passive_IL), Active Insertion Loss (Active_IL), and Total Insertion Loss (Total_IL). Independent variables included in the model were Headphone, Microphone, Frequency, and all interaction combinations. Results of all the post-ANOVA tests follow. Specific output (non-significant) from effects tests are listed in Appendix G.

MIRE Passive Insertion Loss.. Significant differences, via ANOVA, were observed in Headphone ($F_{3,27} = 155.02$, $p < 0.0001$), Microphone ($F_{2,18} = 7.54$, $p = 0.0042$), Frequency ($F_{7,63} = 515.82$, $p < 0.0001$), Headphone-by-Frequency ($F_{21,189} = 145.97$, $p < 0.0001$), Microphone-by-Frequency ($F_{14,126} = 15.25$, $p < 0.0001$), and Headphone-by-Microphone-by-Frequency ($F_{42,378} = 6.81$, $p < 0.0001$) for the dependent variable Passive_IL. The ANOVA summary table for MIRE Passive_IL is provided in Table 6.

Further analysis of the three-way interaction Headphone-by-Microphone-by-Frequency revealed no significance ($F_{42,864} = 0.74$, $p = 0.8832$). Appendix G provides ANOVA tables for all non-significant higher-order interactions. Since the higher-order interaction showed no level-dependent significance across any factor of interest, the two-way interactions and main effects from the overall design were analyzed to determine loci of significance.

Results of the Headphone-by-Frequency interaction analysis revealed that the simple main effect of Headphone was significant for all frequencies (63 Hz, $F_{3,21} = 16.22$, $p < 0.0001$; 125 Hz, $F_{3,21} = 51.87$, $p < 0.0001$; 250 Hz, $F_{3,21} = 112.25$, $p < 0.0001$; 500 Hz, $F_{3,21} = 287.92$, $p < 0.0001$; 1000 Hz, $F_{3,21} = 478.88$, $p < 0.0001$; 2000 Hz, $F_{3,21} =$

369.51, $p < 0.0001$; 4000 Hz, $F_{3,21} = 283.38$, $p < 0.0001$; and 8000 Hz, $F_{3,21} = 119.58$, $p < 0.0001$), see Figure 20.

Overall, the Sennheiser HMEC300 NoiseGard provided significantly greater insertion loss from the lowest frequency of 63 Hz, thru 2000 Hz, becoming non-significant at the remaining frequencies. The Bose Aviation Headset X outperformed all other headphones at frequencies greater than 4000 Hz. Surprisingly, the supra-aural Sennheiser HDC451 NoiseGard performed as well as the circumaural headphones at the very lowest frequencies (63 Hz thru 250 Hz). However, at all frequencies up to and including 2000 Hz, the Sennheiser HDC451 NoiseGard provided nearly zero passive attenuation and achieved only 10 dB attenuation at its most effective frequency of 8000 Hz.

Results of the Microphone-by-Frequency interaction analysis revealed that the simple main effect of Frequency was significant ($F_{7,14} = 118.61$, $p < 0.0001$) only at the highest-tested frequency of 8000 Hz, see Figure 21. This significance appeared only at the deep microphone location, with the deep microphone insertion loss level being significantly lower (19.7 dB) than both the concha (25.9 dB) and shallow (25.2 dB) microphone locations.

Post-hoc analysis using the Tukey-Kramer test was conducted on the main effects of Headphone, Microphone, and Frequency. For the main effect of Headphone, the Sennheiser HMEC300 NoiseGard headphone provided the greatest amount of passive insertion loss averaged across frequency (23.5 dB), followed by the Bose Aviation Headset X (17.3 dB), Bose Quiet Comfort 2 (11.6 dB), and Sennheiser HDC451

NoiseGard (2.4 dB), respectively. All headphones were significantly different from one another, see Figure 22.

For the main effect of Microphone, the deep microphone measured significantly lower sound levels (13.1 dB) than both the concha (14.1 dB) and shallow (13.9 dB) microphone locations. The concha and shallow positions were not significantly different from each other, see Figure 23.

For the main effect of Frequency, significant differences were observed across all frequencies with the exception of 63 Hz and 125 Hz. These frequencies were significantly different than all of the other frequencies, but were not significantly different from each other, see Figure 24. Levels of insertion loss increased as frequency increased, decreasing slightly at 8000 Hz (24.1 dB).

TABLE 6. MIRE *Passive Insertion Loss* ANOVA Table

Source	df	SS	MS	*F*-Value	*Pr > F*
Headphone (H)	3	58050.90	19350.30	155.02	<.0001*
H x Subject (S) (Error)	27	2270.36	124.82		
Microphone (M)	2	181.40	90.70	7.54	0.0042*
M x S (Error)	18	216.40	12.02		
Frequency (F)	7	86656.10	12379.44	515.82	<.0001*
F x S (Error)	63	1511.97	24.0		
H x M	6	71.0	11.83	1.35	0.2525
H x M x S (Error)	72	539.63	7.50		
H x F	21	25597.27	1218.92	145.97	<.0001*
H x F x S (Error)	189	1578.22	8.35		
M x F	14	821.13	58.65	15.25	<.0001*
M x F x S (Error)	126	484.45	3.84		
H x M x F	42	488.34	11.63	6.81	<.0001*
H x M x F x S (Error)	378	645.29	1.71		

* Statistically significant effect at $p \leq 0.05$, and also significant in MANOVA.

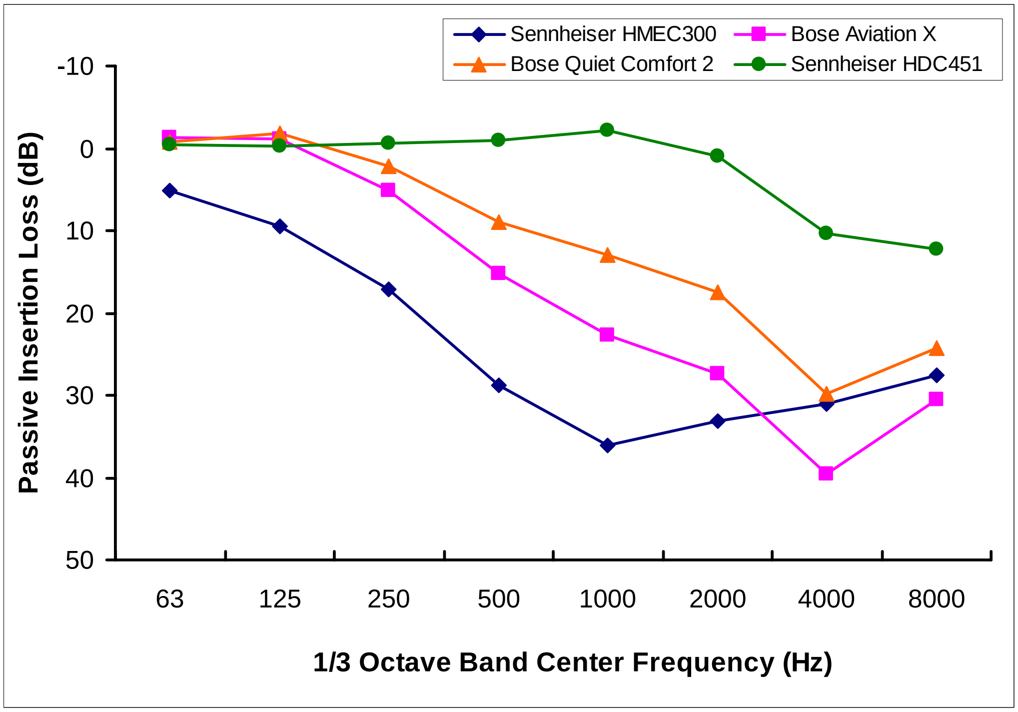

Figure 20. Headphone-by-Frequency interaction for *MIRE Passive Insertion Loss* dependent measure.

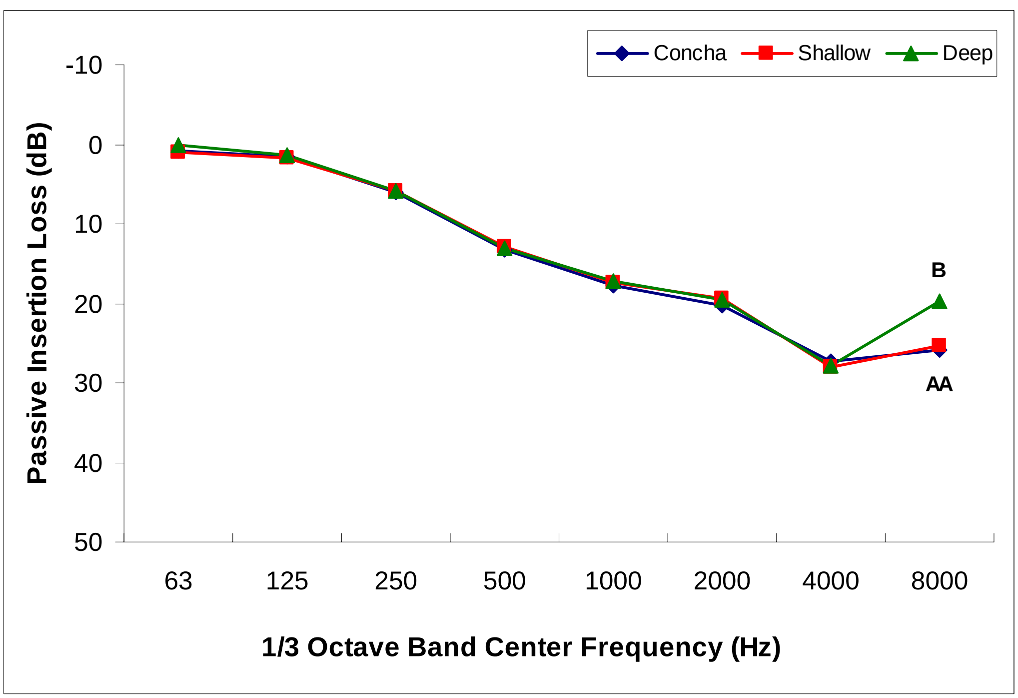

Figure 21. Microphone-by-Frequency interaction *for MIRE Passive Insertion Loss* dependent measure (Means with different letters are significantly different at $p \leq 0.05$).

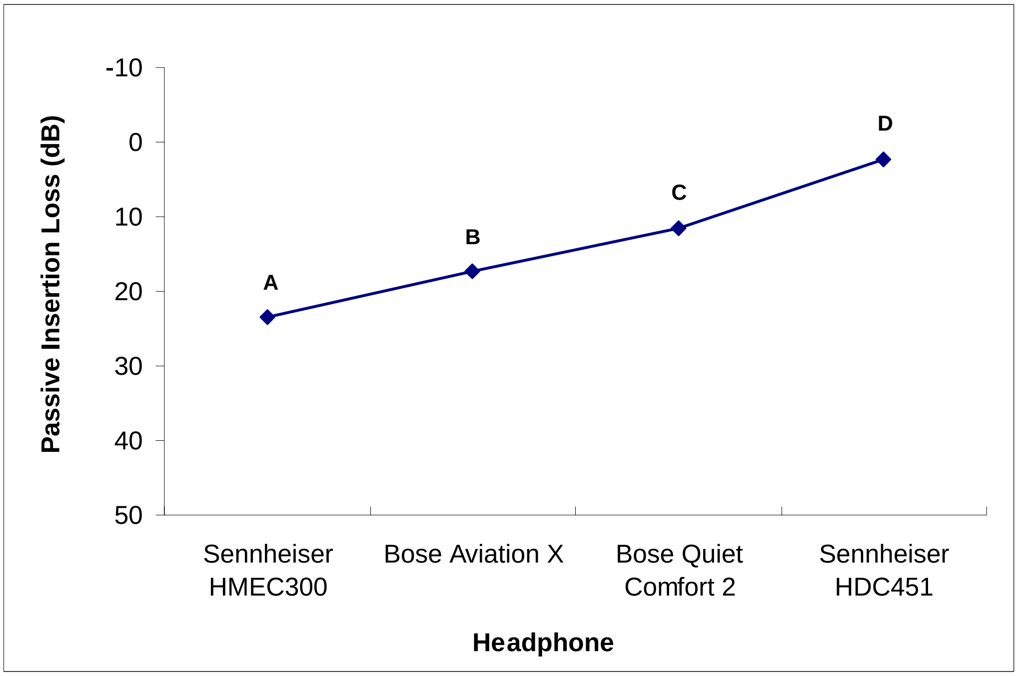

Figure 22. Headphone main effect for *MIRE Passive Insertion Loss* dependent measure (Means with different letters are significantly different at $p \leq 0.05$).

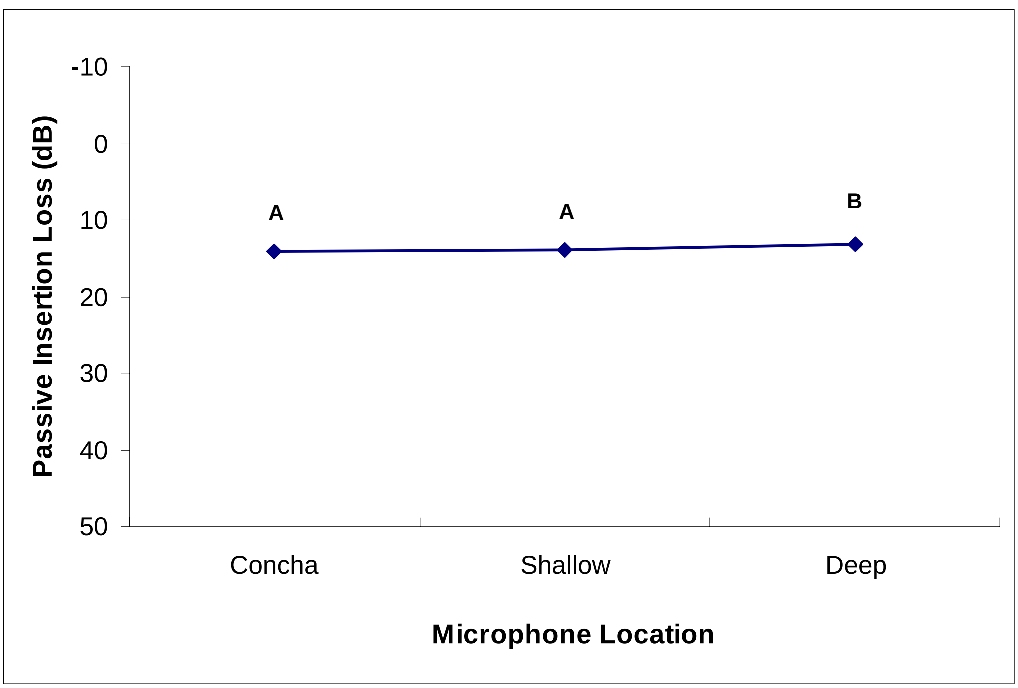

Figure 23. Microphone main effect for *MIRE Passive Insertion Loss* dependent measure (Means with different letters are significantly different at $p \leq 0.05$).

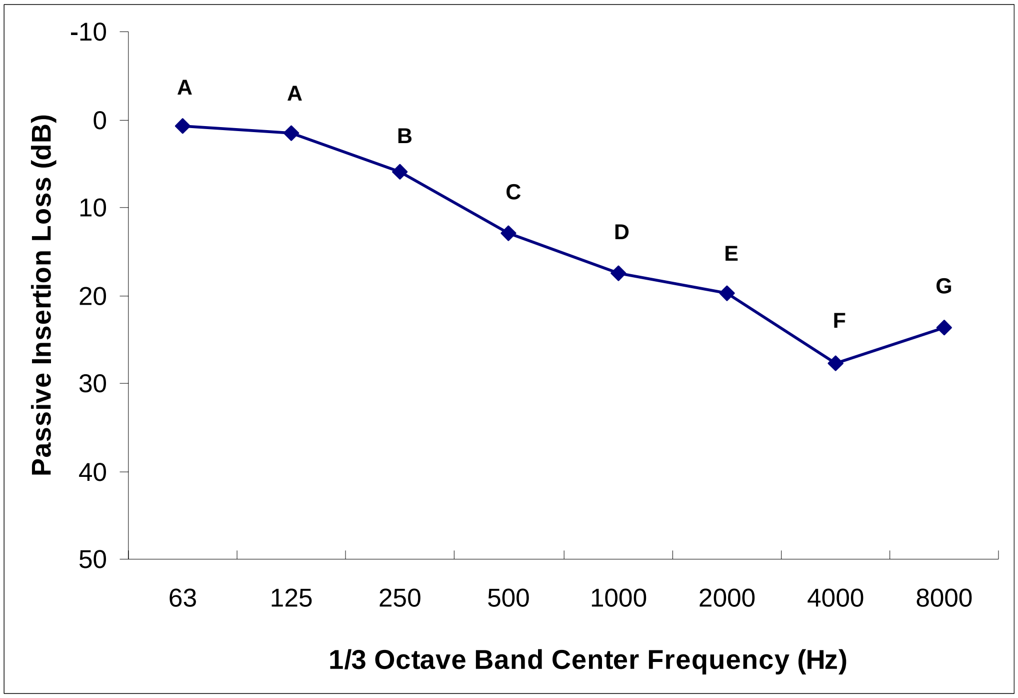

Figure 24. Frequency main effect for *MIRE Passive Insertion Loss* dependent measure (Means with different letters are significantly different at $p \leq 0.05$).

MIRE Total Insertion Loss. Significant differences, via ANOVA, were observed in Headphone ($F_{3,27} = 141.12$, $p < 0.0001$), Microphone ($F_{2,18} = 6.72$, $p = 0.0066$), Frequency ($F_{7,63} = 221.80$, $p < 0.0001$), Headphone-by-Frequency ($F_{21,189} = 118.57$, $p < 0.0001$), Microphone-by-Frequency ($F_{14,126} = 12.59$, $p < 0.0001$), and Headphone-by-Microphone-by-Frequency ($F_{42,378} = 4.81$, $p < 0.0001$) for the dependent variable Total_IL. The ANOVA summary table for MIRE Total_IL is provided in Table 7.

TABLE 7. MIRE *Total Insertion Loss* ANOVA Table

Source	df	SS	MS	*F*-Value	*Pr > F*
Headphone (H)	3	67619.13	22539.71	141.12	<.0001*
H x Subject (S) (Error)	27	4312.59	159.73		
Microphone (M)	2	154.33	77.17	6.72	0.0066*
M x S (Error)	18	206.70	11.48		
Frequency (F)	7	21745.22	3106.46	221.80	<.0001*
F x S (Error)	63	882.36	14.00		
H x M	6	98.90	16.48	1.15	0.3444
H x M x S (Error)	54	771.17	14.28		
H x F	21	17678.62	841.84	118.57	<.0001*
H x F x S (Error)	189	1341.92	7.10		
M x F	14	770.02	55.00	12.59	<.0001*
M x F x S (Error)	126	550.23	4.37		
H x M x F	42	420.43	10.01	4.81	<.0001*
H x M x F x S (Error)	378	787.16	2.10		

* Statistically significant effect at $p \leq 0.05$, and also significant in MANOVA.

Simple effects analysis of the three-way interaction Headphone-by-Microphone-by-Frequency revealed no significance ($F_{42,864} = 0.53$, $p = 0.9945$). Appendix G provides ANOVA tables for all non-significant higher-order interactions. Since this higher-order interaction showed no level-dependent significance across any factor of interest, the two-way interactions and main effects from the overall design were analyzed to determine loci of significance.

The Headphone-by-Frequency interaction analysis revealed that the simple main effect of Headphone was significant for all frequencies (63 Hz, $F_{3,21} = 107.65$, $p < 0.0001$; 125 Hz, $F_{3,21} = 118.58$, $p < 0.0001$; 250 Hz, $F_{3,21} = 70.59$, $p < 0.0001$; 500 Hz, $F_{3,21} = 58.95$, $p < 0.0001$; 1000 Hz, $F_{3,21} = 282.50$, $p < 0.0001$; 2000 Hz, $F_{3,21}$ 328.37, $p < 0.0001$; 4000 Hz, $F_{3,21} = 361.51$, $p < 0.0001$; and 8000 Hz, $F_{3,21} = 147.79$, $p < 0.0001$), Figure 25.

Compared with MIRE passive insertion loss, MIRE total insertion loss was generally increased in the lower frequencies (63 Hz – 1000 Hz) across all headphones.

The Sennheiser HMEC300 NoiseGard provided the highest overall insertion loss, although performed only average at 4000 Hz and above. The Bose Aviation Headset X outperformed all other headphones at frequencies greater than 4000 Hz. The Sennheiser HDC451 NoiseGard provided the least overall insertion loss at all frequencies. This result was expected, however, since the Sennheiser HDC451 NoiseGard is a lightweight, supra-aural headphone (which does not seal around the pinnae – allowing noise to enter around the headphone earpads), unlike the other heavier, circumaural headphones. The circumaural headphone which provided the least overall insertion loss of the devices tested was the Bose Quiet Comfort 2. It is interesting to note the more than doubled (compared with the next closest headphone) insertion loss value at 1000 Hz provided by the Sennheiser HMEC300 NoiseGard headphone (see Figure 25). This relatively large difference appears to be an anomalous characteristic specific to this particular headphone and frequency and appears to overcome the typical ANR "deficit" at this frequency.

Results of the Microphone-by-Frequency interaction analysis revealed that the simple main effect of Frequency was significant ($F_{7,14} = 28.44$, $p < 0.0001$) only at the highest-tested frequency of 8000 Hz, see Figure 26. This significance appeared only at the deep microphone location, with the deep microphone insertion loss level being significantly lower (18.9 dB) than both the concha and shallow microphone locations (both 24.5 dB) at 8000 Hz.

Post-hoc analysis using the Tukey-Kramer test was conducted on the main effects of Headphone, Microphone, and Frequency. For the main effect of Headphone, the Sennheiser HMEC300 NoiseGard headphone provided the greatest level of total insertion loss averaged across frequency (26.7 dB) followed by the Bose Aviation Headset X (23.5

dB), Bose Quiet Comfort 2 (15.7 dB), and Sennheiser HDC451 NoiseGard (4.9 dB), respectively. All headphones were significantly different from one another on this metric, see Figure 27.

For the main effect of Microphone, the deep microphone measured significantly lower insertion loss levels (17.1 dB), on average, than both the concha (18.1 dB) and shallow (17.8 dB) microphone locations. The concha and shallow positions were not significantly different from each other, see Figure 28.

For the main effect of Frequency, significant differences were observed across all frequencies with the exception of 125, 250, 500, and 1000 Hz. These frequencies were significantly different from all others, but were not significantly different from each other, see Figure 29.

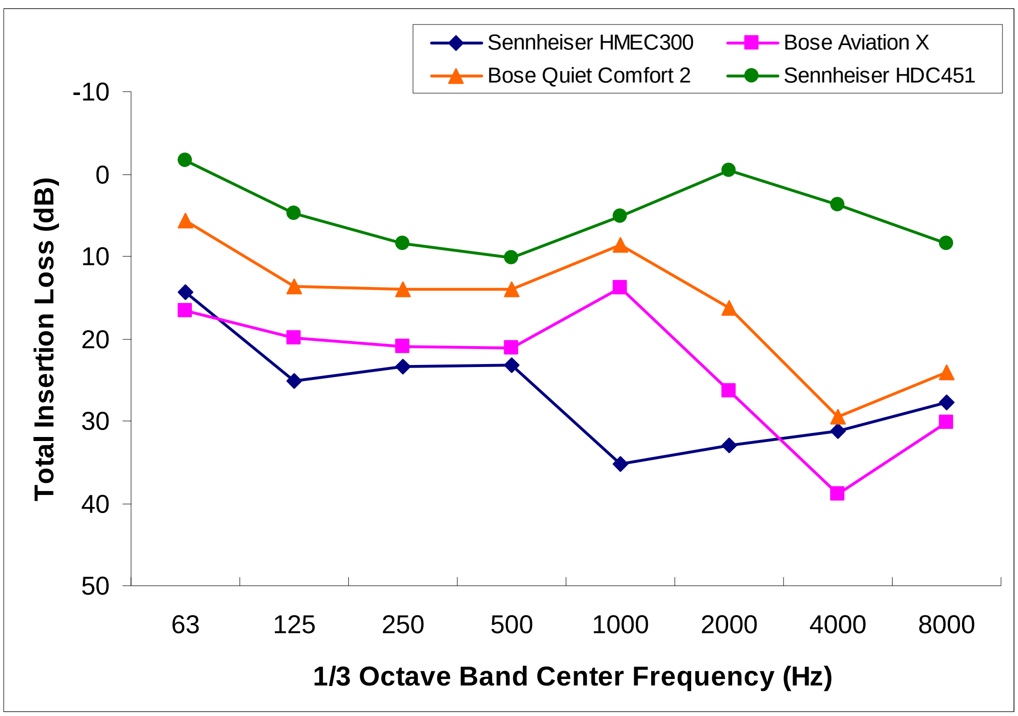

Figure 25. Headphone-by-Frequency interaction for *MIRE Total Insertion Loss* dependent measure.

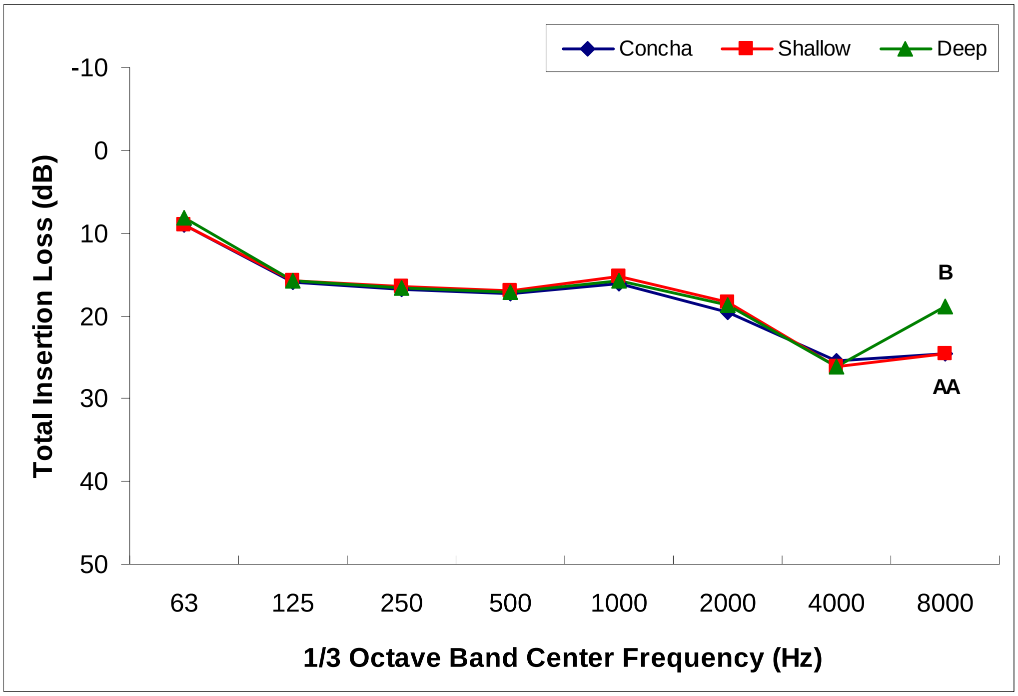

Figure 26. Microphone-by-Frequency interaction for *MIRE Total Insertion Loss* dependent measure (Means with different letters are significantly different at $p \leq 0.05$).

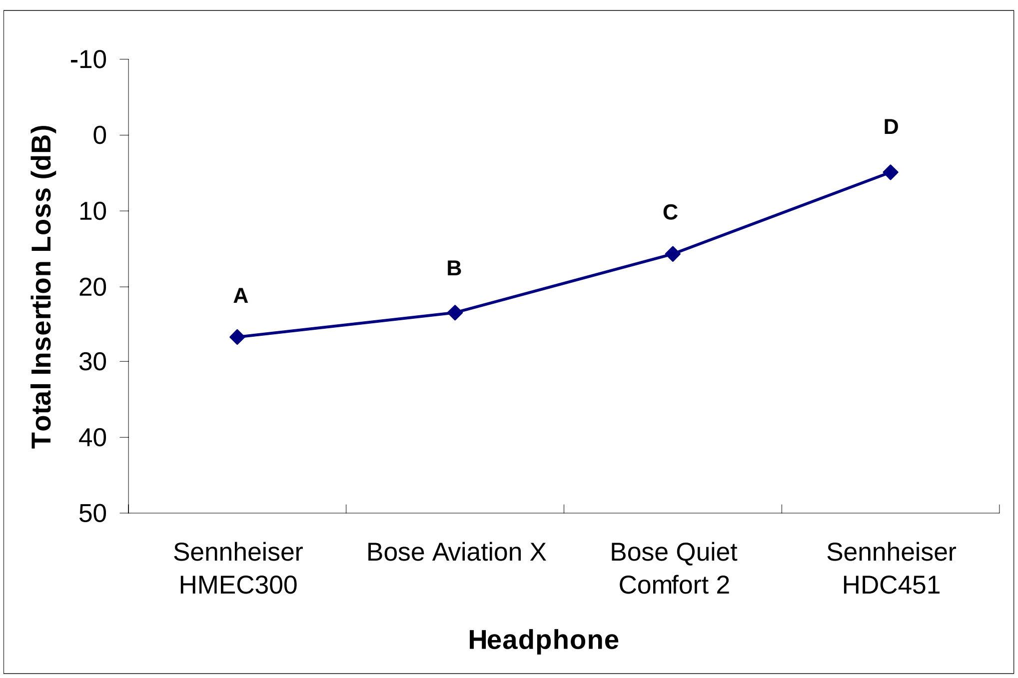

Figure 27. Headphone main effect for *MIRE Total Insertion Loss* dependent measure (Means with different letters are significantly different at $p \leq 0.05$).

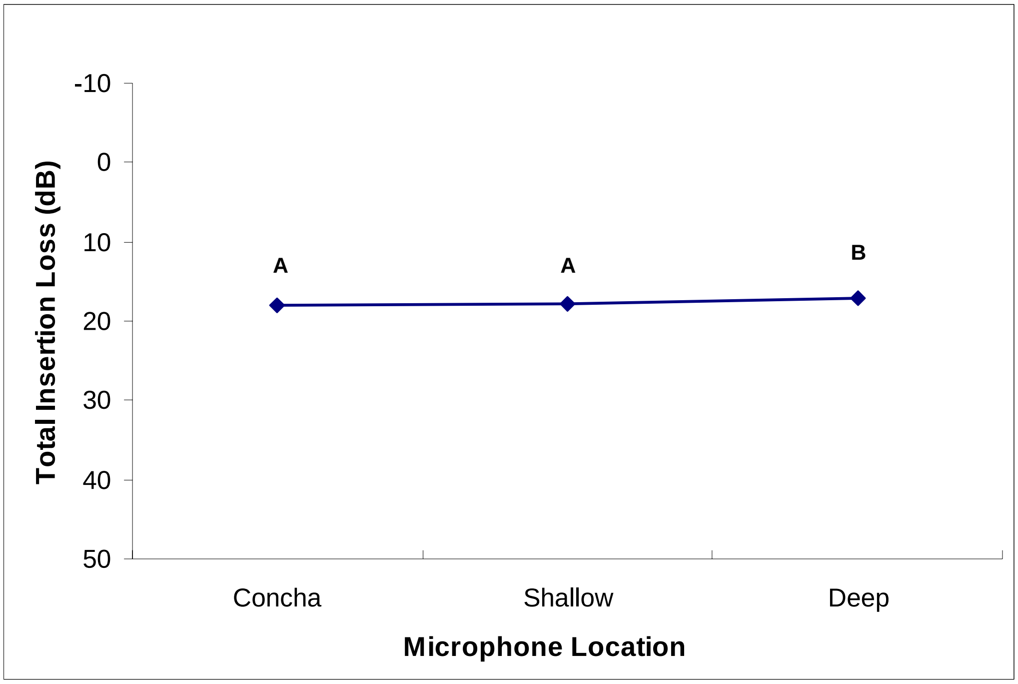

Figure 28. Microphone main effect for *MIRE Total Insertion Loss* dependent measure (Means with different letters are significantly different at $p \leq 0.05$).

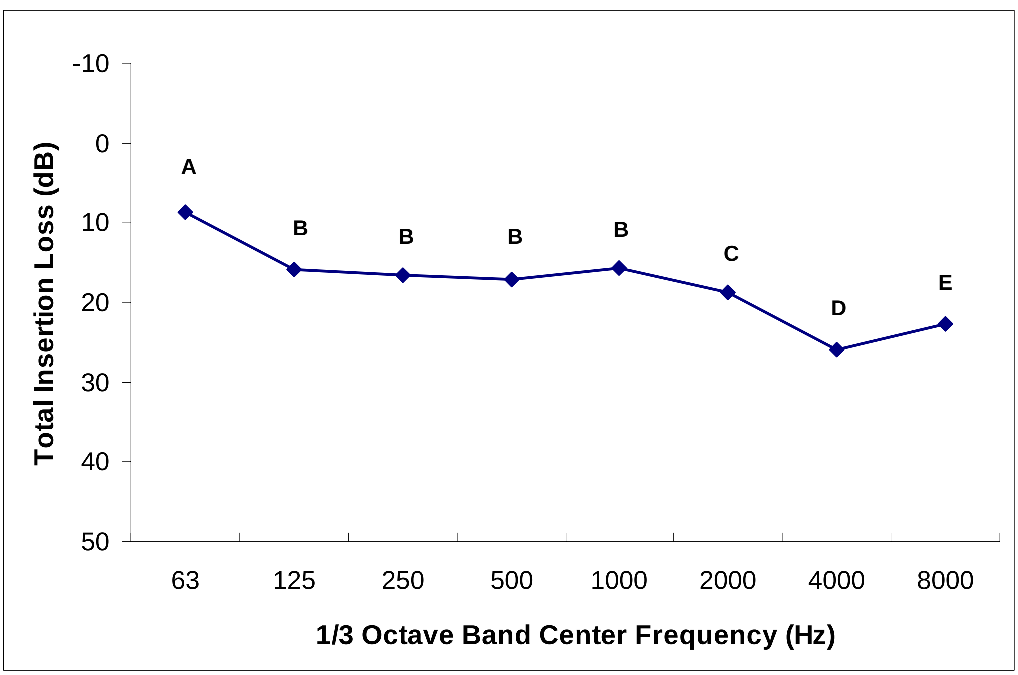

Figure 29. Frequency main effect for *MIRE Total Insertion Loss* dependent measure (Means with different letters are significantly different at $p \leq 0.05$).

MIRE Active Insertion Loss. As previously stated, active insertion loss was a calculated value (i.e., not directly measured) determined by the difference between total and passive insertion loss values (both of which were measured). Significant differences, via ANOVA, were observed in Headphone ($F_{3,27}$ = 52.12, p < 0.0001), Frequency ($F_{7,63}$ = 236.12, p < 0.0001), and Headphone-by-Frequency ($F_{21,189}$ = 156.93, p < 0.0001) for the dependent variable Active_IL in dB. The ANOVA summary table for MIRE Active_IL is provided in Table 8.

TABLE 8. MIRE *Active Insertion Loss* ANOVA Table

Source	df	SS	MS	*F*-Value	*Pr > F*
Headphone (H)	3	1924.10	641.37	52.12	<.0001*
H x Subject (S) (Error)	27	332.25	12.31		
Microphone (M)	2	1.48	0.74	0.41	0.6665
M x S (Error)	18	32.10	1.78		
Frequency (F)	7	34130.17	4875.74	236.12	<.0001*
F x S (Error)	63	1300.93	20.65		
H x M	6	15.03	2.51	1.02	0.4230
H x M x S (Error)	54	132.77	2.46		
H x F	21	18793.66	894.94	156.93	<.0001*
H x F x S (Error)	189	1077.84	5.70		
M x F	14	23.67	1.69	1.15	0.3230
M x F x S (Error)	126	185.43	1.47		
H x M x F	42	42.09	1.00	0.88	0.6794
H x M x F x S (Error)	378	428.70	1.13		

* Statistically significant effect at $p \leq 0.05$ and also significant in MANOVA.

Results of the Headphone-by-Frequency interaction analysis revealed that the simple main effect of Headphone was significant for all frequencies except 2000 Hz (63 Hz, $F_{3,21}$ = 449.83, p < 0.0001; 125 Hz, $F_{3,21}$ = 321.65, p < 0.0001; 250 Hz, $F_{3,21}$ = 116.76, p < 0.0001; 500 Hz, $F_{3,21}$ = 358.49, p < 0.0001; 1000 Hz, $F_{3,21}$ = 341.74, p < 0.0001; 4000 Hz, $F_{3,21}$ = 71.10, p < 0.0001; and 8000 Hz, $F_{3,21}$ = 22.18, p < 0.0001), see Figure 30. As expected, insertion loss was generally increased in the lower frequencies, slightly decreased in the mid frequencies, and remained level in the higher frequencies across the circumaural headphones. However, the supra-aural headphone performance was reversed; that is, increasing in the low-mid frequencies and decreasing much more gradually in the higher frequencies, before matching circumaural performance at 2000 Hz.

Post-hoc analyses using the Tukey-Kramer test were conducted on the main effects of Headphone and Frequency. For the main effect of Headphone, the Bose Aviation Headset X provided the greatest level of active insertion loss averaged across frequency (6.3 dB), followed by the Bose Quiet Comfort 2 (4.1 dB), Sennheiser HMEC300 NoiseGard (3.0 dB), and Sennheiser HDC451 NoiseGard (2.5 dB), respectively. All headphones were significantly different from one another with the exception of the Sennheiser HMEC300 NoiseGard and Sennheiser HDC451 NoiseGard headphones. Although significantly different than the others, these two headphones did not differ significantly from one another, see Figure 31.

For the main effect of Frequency, significant differences were observed across all frequencies with the exception of 1000, 2000, 4000, and 8000 Hz. These frequencies were significantly different than all others, but were not significantly different from each other, see Figure 32. Additionally, significant positive attenuation effect (i.e., insertion loss) was observed in the lower frequency range (63-500 Hz), with the greatest attenuation occurring at 125 Hz.

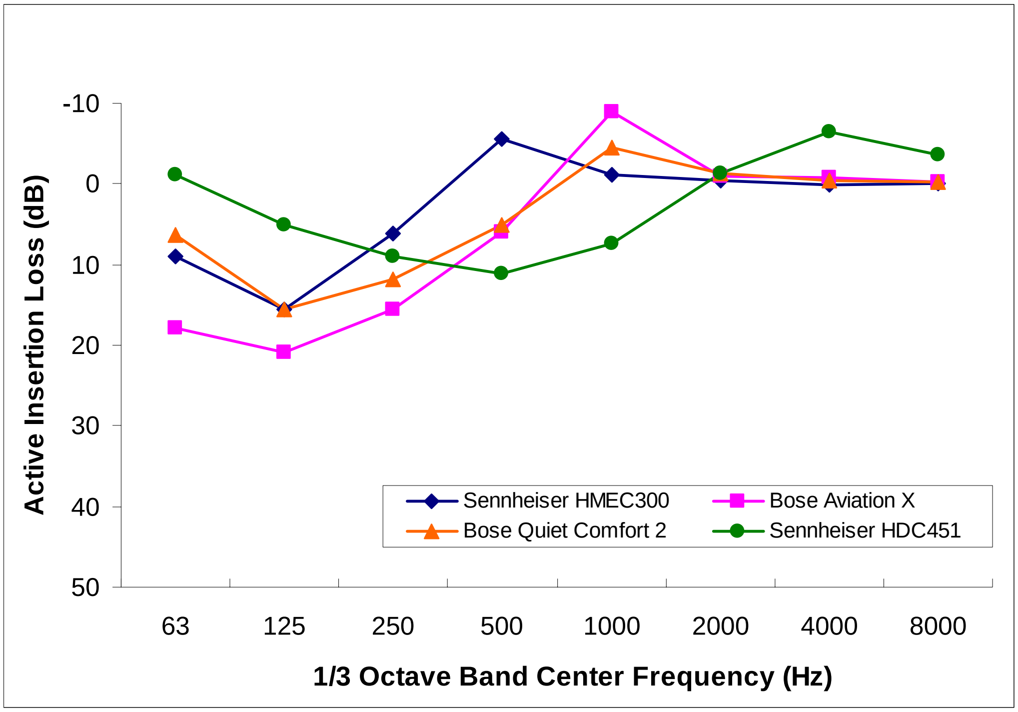

Figure 30. Headphone-by-Frequency interaction for *MIRE Active Insertion Loss* dependent measure.

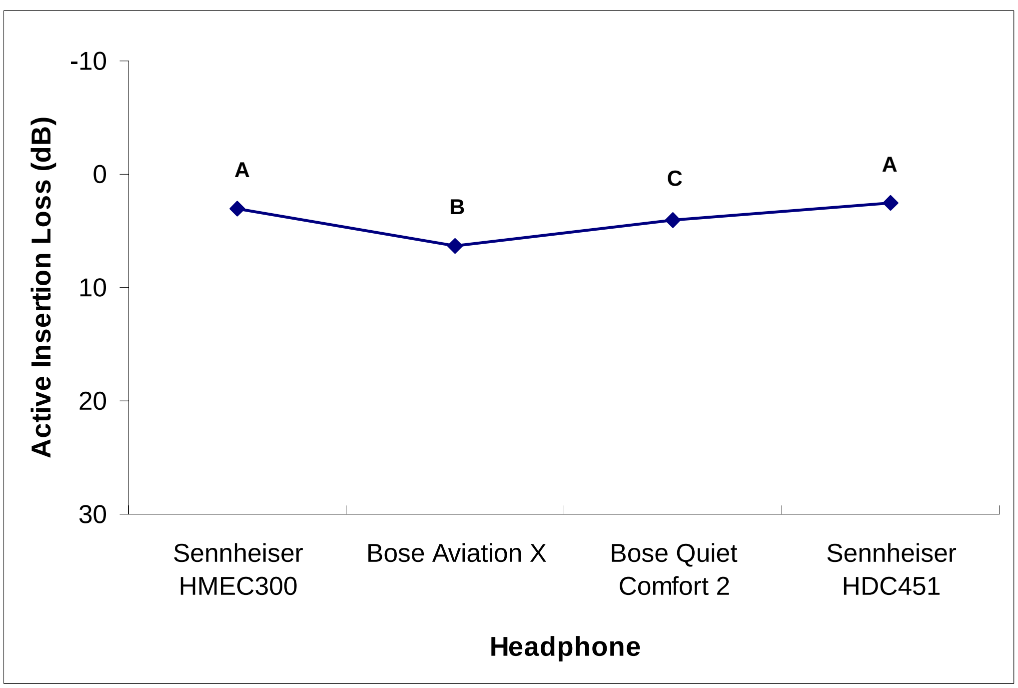

Figure 31. Headphone main effect for *MIRE Active Insertion Loss* dependent measure (Means with different letters are significantly different at $p \leq 0.05$).

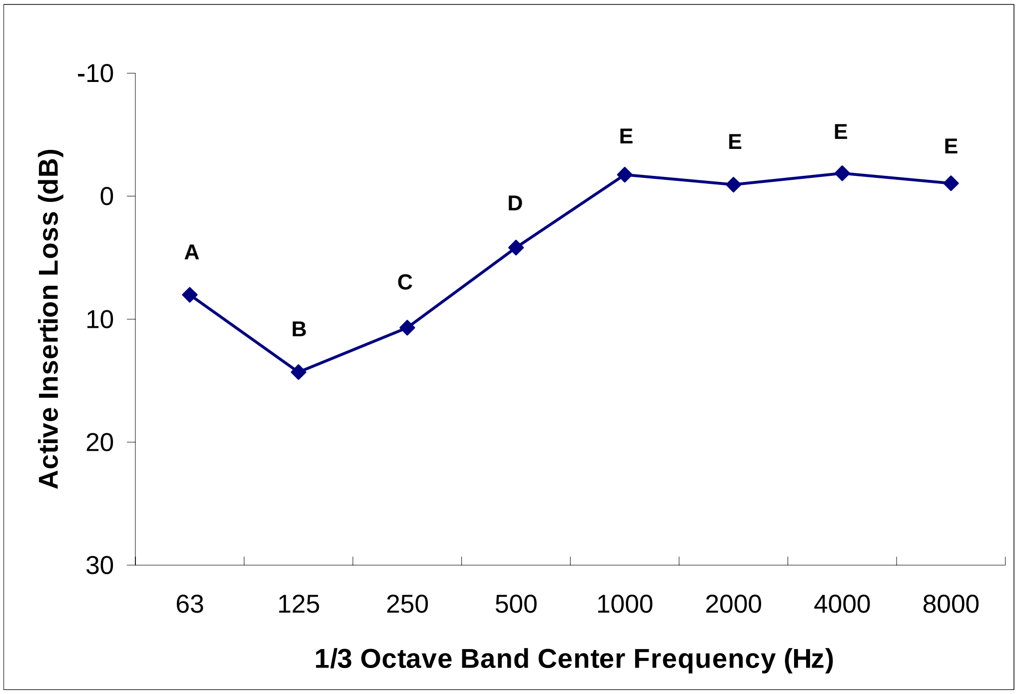

Figure 32. Frequency main effect for *MIRE Active Insertion Loss* dependent measure (Means with different letters are significantly different at $p \leq 0.05$).

REAT Passive Insertion Loss. The dependent variable included in the overall REAT model was Passive Insertion Loss (Passive_IL) in dB. Independent variables included in the model were Headphone, Microphone, Frequency, and all interaction combinations. Since REAT is a psychophysical testing protocol, it was known apriori that REAT tests with the shallow microphone could not be conducted since the shallow microphone configuration occluded the test participant's ear canal (i.e., the shallow microphone was mounted on a swim plug inserted in the ear canal during MIRE testing). Therefore, the REAT tests were only done with the concha and deep microphones in place for the MIRE tests.

Additionally, the REAT signal generation and test stimuli control apparatus (i.e., the NE828) did not allow for testing at 63 Hz. Therefore, only results from frequencies

125, 250, 500, 1000, 2000, 4000, and 8000 Hz were obtained; this was in keeping with the requirements of the current REAT test standard, ANSI S12.6-1997(R2002), Method B. All levels of Headphone remained the same as those used for MIRE.

Significant differences, via ANOVA, were observed in Headphone ($F_{3,27}$ = 120.24, $p < 0.0001$), Frequency ($F_{6,54}$ = 237.75, $p < 0.0001$), and Headphone-by-Frequency ($F_{18,162}$ = 57.00, $p < 0.0001$) for the dependent variable Passive_IL. The ANOVA summary table for REAT Passive_IL is provided in Table 9.

TABLE 9. REAT *Passive Insertion Loss* ANOVA Table

Source	df	SS	MS	*F*-Value	*Pr* > *F*
Headphone (H)	3	34328.45	11442.82	120.24	<.0001*
H x Subject (S) (Error)	27	2569.55	95.17		
Microphone (M)	1	0.73	0.73	0.10	0.7535
M x S (Error)	9	62.56	6.95		
Frequency (F)	6	32234.87	5372.48	237.75	<.0001*
F x S (Error)	54	1220.23	22.59		
H x M	3	46.39	15.46	1.25	0.31
H x M x S (Error)	27	335.03	12.41		
H x F	18	11377.15	632.10	57.00	<.0001*
H x F x S (Error)	162	1796.51	11.10		
M x F	6	33.90	5.65	1.20	0.3217
M x F x S (Error)	54	254.78	4.72		
H x M x F	18	98.70	5.48	0.85	0.6339
H x M x F x S (Error)	162	1039.64	6.42		

* Statistically significant effect at $p \leq 0.05$ and also significant in MANOVA.

Results of the Headphone-by-Frequency interaction analysis revealed that the simple main effect of Headphone was significant for all frequencies (125 Hz, $F_{3,18}$ = 16.91, $p < 0.0001$; 250 Hz, $F_{3,18}$ = 35.56, $p < 0.0001$; 500 Hz, $F_{3,18}$ = 106.98, $p < 0.0001$; 1000 Hz, $F_{3,18}$ = 160.22, $p < 0.0001$; 2000 Hz, $F_{3,18}$ = 144.65, $p < 0.0001$; 4000 Hz, $F_{3,18}$ = 182.30, $p < 0.0001$; and 8000 Hz, $F_{3,18}$ = 106.69, $p < 0.0001$), see Figure 33. For the circumaural headphones, the Sennheiser HMEC300 NoiseGard performed significantly better than the other headphones, up to 4000 Hz. The Bose Aviation Headset X outperformed all other headphones at frequencies greater than 4000 Hz.

All headphones followed the general trend of exhibiting increasing passive insertion loss as frequency increased. Insertion loss decreased above 4000 Hz for all circumaural headphones except the Sennheiser HMEC300 NoiseGard. The insertion loss for this headphone decreased only slightly (0.4 dB) between 4000 and 8000 Hz. Again, as previously seen via MIRE measurements, the supra-aural Sennheiser HDC451 NoiseGard provided very little (~3 dB) passive attenuation at all frequencies up to and including 2000 Hz, achieving only 10 dB attenuation at its most effective frequency of 8000 Hz.

Post-hoc analysis using the Tukey-Kramer test was conducted on the main effect of Headphone and Frequency. For the main effect of Headphone, the Sennheiser HMEC300 NoiseGard headphone provided the greatest level of passive insertion loss averaged across frequency (26.9 dB), followed by the Bose Aviation Headset X (21.4 dB), Bose Quiet Comfort 2 (15.5 dB), and Sennheiser HDC451 NoiseGard (5.8 dB), respectively. All headphones were significantly different from one another, see Figure 34.

For the main effect of Frequency, significant differences were observed between the lowest, middle, and highest frequencies, see Figure 35. 125 and 250 Hz were not significantly different from each other, but were significantly different than all other frequencies. 1000 and 2000 Hz were not significantly different from each other, but were significantly different than all other frequencies. Similarly, 4000 and 8000 Hz were not significantly different from each other, but were significantly different than all other frequencies. Levels of insertion loss increased as frequency increased (6.4 dB to 27.7 dB, respectively); only decreasing slightly at 8000 Hz (26.1 dB).

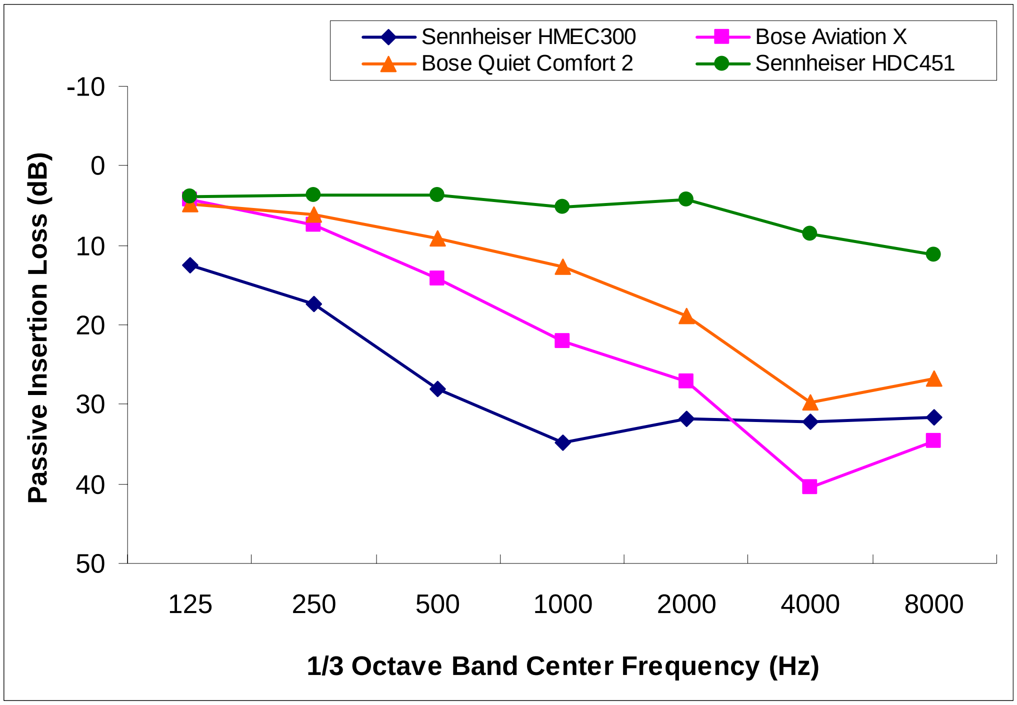

Figure 33. Headphone-by-Frequency interaction for *REAT Passive Insertion Loss* dependent measure.

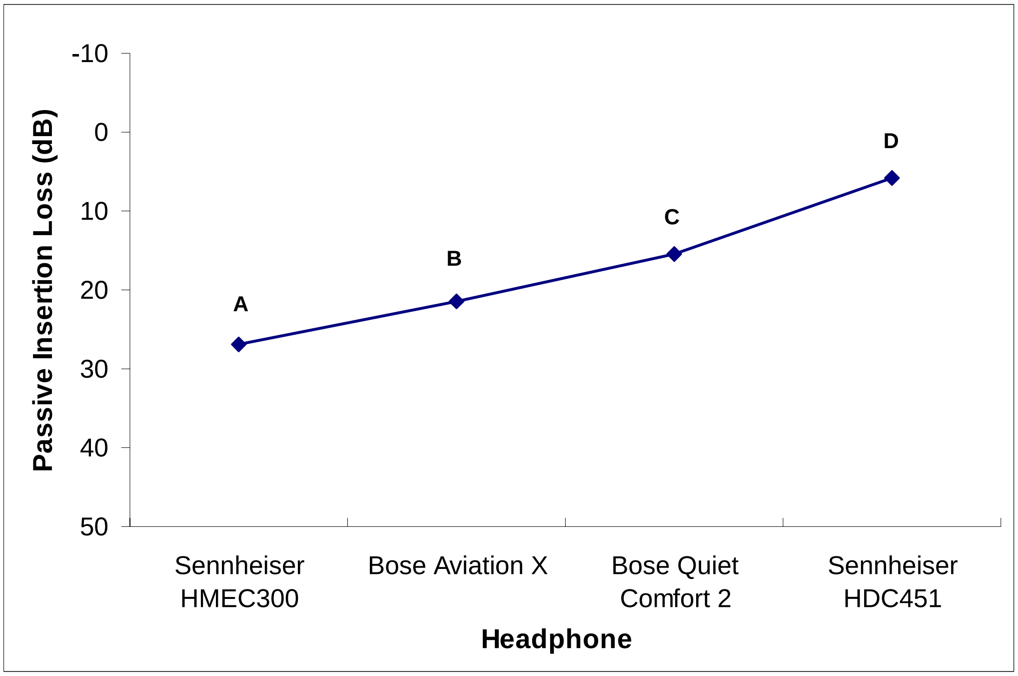

Figure 34. Headphone main effect for *REAT Passive Insertion Loss* dependent measure (Means with different letters are significantly different at $p \leq 0.05$).

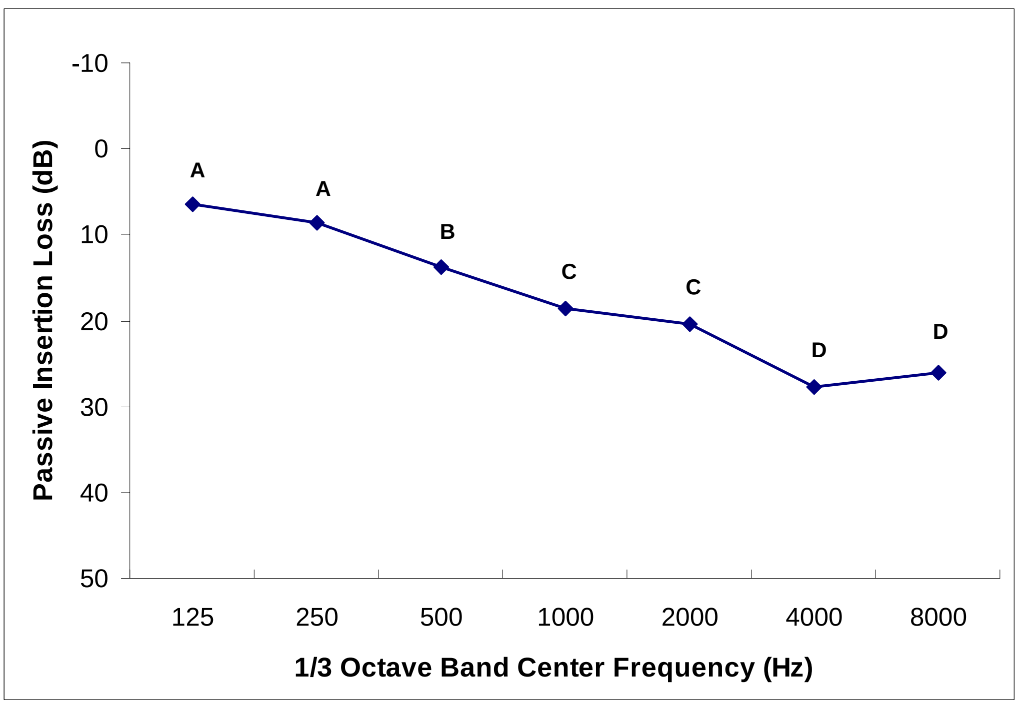

Figure 35. Frequency main effect for *REAT Passive Insertion Loss* dependent measure (Means with different letters are significantly different at $p \leq 0.05$).

REAT vs. MIRE Passive Insertion Loss. The dependent variable included in the overall REAT vs. MIRE model was Passive Insertion Loss (Passive_IL). Independent variables included in the model were Headphone, Microphone, Frequency, Protocol, and all interaction combinations. For reasons previously stated in the REAT-only analysis, only REAT data obtained with the MIRE microphones located in the concha and deep microphone positions were reported. Also, all frequencies tested in the MIRE-only condition were included, again, with the exception of 63 Hz.

Significant differences, via ANOVA, were observed in Headphone ($F_{3,27}$ = 157.80, $p < 0.0001$), Microphone ($F_{1,9} = 7.77$, $p < 0.0211$), Frequency ($F_{6,54} = 419.69$, $p <$ 0.0001), Protocol ($F_{1,9} = 161.15$, $p = 0.0074$), Headphone-by-Frequency ($F_{18,162} = 108.09$, $p < 0.0001$), Microphone-by-Frequency ($F_{6,54}$ 21.25, $p < 0.0001$), Microphone-by-Protocol ($F_{1,9} = 8.72$, $p = 0.0161$), Frequency-by-Protocol ($F_{6,54} = 14.29$, $p < 0.0001$), Headphone-by-Microphone-by-Frequency ($F_{18,162} = 2.52$, $p = 0.0012$), Headphone-by-Microphone-by-Protocol ($F_{3,27} = 5.28$, $p = 0.0054$), Headphone-by-Frequency-by-Protocol ($F_{18,162} = 13.61$, $p < 0.0001$), Microphone-by-Frequency-by-Protocol ($F_{6,54}$ = 6.44, $p < 0.0001$), and Headphone-by-Frequency-by-Microphone-by-Protocol ($F_{18,162}$ = 2.23, $p = 0.0045$) for the dependent variable Passive_IL. The ANOVA summary table for Passive_IL is provided in Table 10.

TABLE 10. REAT vs. MIRE *Passive Insertion Loss* ANOVA Table

Source	df	SS	MS	*F*-value	*Pr > F*
Headphone (H)	3	75235.49	25078.50	157.80	<.0001*
H x Subject (S)	27	4290.99	158.93		
Microphone (M)	1	86.27	86.27	7.77	0.0211*
M x S (Error)	9	99.90	11.10		
Frequency (F)	6	72659.61	12109.94	419.69	<.0001*
F x S (Error)	54	1558.15	28.85		
Protocol (P)	1	1032.70	1032.70	161.15	<.0001*
P x S (Error)	9	57.68	6.41		
H x M	3	30.44	10.15	0.65	0.5879
H x M x S (Error)	27	419.43	15.53		
H x F	18	23398.65	1299.93	108.09	<.0001*
H x F x S (Error)	162	1948.24	12.03		
H x P	3	154.40	51.47	3.18	0.3098
H x P x S (Error)	27	436.62	16.17		
M x F	6	457.56	76.26	21.25	<.0001*
M x F x S (Error)	54	193.77	3.59		
M x P	1	65.30	65.30	8.72	0.0161*
M x P x S (Error)	9	67.37	7.49		
F x P	6	739.68	123.28	14.29	<.0001*
F x P x S (Error)	54	465.88	8.63		
H x M x F	18	247.50	13.75	2.52	0.0012*
H x M x F x S (Error)	162	885.25	5.46		
H x M x P	3	71.15	23.72	5.28	0.0054*
H x M x P x S (Error)	27	121.29	4.49		
H x F x P	18	1279.63	71.10	13.61	<.0001*
H x F x P x S (Error)	162	846.37	5.22		
M x F x P	6	235.52	39.25	6.44	<.0001*
M x F x P x S (Error)	54	329.33	6.10		
H x F x M x P	18	123.69	6.87	2.23	0.0045*
H x F x M x P x S (Error)	162	500.05	3.10		

* Statistically significant effect at $p \leq 0.05$ and also significant in MANOVA.

Results of the higher-order interaction analyses for Headphone-by-Microphone-by-Frequency ($F_{18,1064} = 0.64$, $p = 0.8666$), Headphone-by-Microphone-by-Protocol ($F_{3,1104} = 0.22$, $p = 0.8814$), Microphone-by-Frequency-by-Protocol ($F_{6,1092} = 0.36$, $p = 0.9051$) and Headphone-by-Frequency-by-Microphone-by-Protocol ($F_{24,1008} = 0.79$, $p = 0.7487$) revealed no significance. Appendix G provides ANOVA tables for all non-significant higher-order interactions.

However, significance was observed in the Headphone-by-Frequency-by-Protocol three-way interaction ($F_{18,1064} = 3.72$, $p < 0.0001$). To attempt to isolate the source or sources of the higher-order interaction significance, in terms of simple effects, an analysis of simple effects was conducted manually by decomposing the three-way interaction into multiple *simple interactions* (two-way interactions not associated with the two-way interactions in the overall design) (Keppel, 1991). This process consisted of assessing the interactions between any two of the independent variables separately at each level of the third independent variable.

For example, the Headphone-by-Frequency *simple interaction* at the Protocol level of REAT was conducted. No significance was observed ($F_{18,162} = 0.61$). The Headphone-by-Frequency *simple interaction* at the Protocol level of MIRE was then conducted.

Again, no significance was observed ($F_{18,162} = 0.68$). The Protocol-by-Frequency *simple interaction* at the level of each Headphone was then conducted. No significance was observed for the Sennheiser HMEC300 NoiseGard ($F_{6,162} = 0.07$), Bose Aviation Headset X ($F_{6,162} = 0.08$), Bose QuietComfort 2 ($F_{6,162} = 0.07$), or Sennheiser HDC451 NoiseGard ($F_{6,162} = 0.11$). Finally, the Headphone-by-Protocol *simple interaction* at the level of each Frequency was conducted. No significance was observed for 125 Hz ($F_{3,162} = 0.01$), 250 Hz ($F_{3,162} = 0.02$), 500 Hz ($F_{3,162} = 0.08$), 1000 Hz ($F_{3,162} = 0.17$), 2000 Hz ($F_{3,162} = 0.03$), 4000 Hz ($F_{3,162} = 0.01$), or 8000 Hz ($F_{3,162} = 0.08$). Tables for the analysis of simple effects are listed in Appendix G. Since the analysis of simple effects showed no level-dependent significance across any factor of interest, the two-way interactions and main effects from the overall design were analyzed to determine loci of significance.

Results of the Headphone-by-Frequency interaction analysis revealed that the simple main effect of Headphone was significant for all frequencies (125 Hz, $F_{3,18} =$

41.71, $p < 0.0001$; 250 Hz, $F_{3,18} = 89.38$, $p < 0.0001$; 500 Hz, $F_{3,18} = 244.81$, $p < 0.0001$; 1000 Hz, $F_{3,18} = 385.14$, $p < 0.0001$; 2000 Hz, $F_{3,18} = 309.26$, $p < 0.0001$; 4000 Hz, $F_{3,18} = 313.42$, $p < 0.0001$; and 8000 Hz, $F_{3,18} = 140.95$, $p < 0.0001$), see Figure 36. For the circumaural headphones, the Sennheiser HMEC300 NoiseGard performed significantly better than the other headphones, up to about 4000 Hz. The Bose Aviation Headset X outperformed all other headphones at frequencies greater than 4000 Hz. All headphones followed the general trend of exhibiting increasing passive insertion loss as frequency increased. Insertion loss decreased after 4000 Hz for all circumaural headphones. Again, the supra-aural Sennheiser HDC451 NoiseGard provided nearly zero passive attenuation at all frequencies up to and including 2000 Hz, achieving only about 10 dB attenuation at its most effective frequency of 8000 Hz.

Results of the Microphone-by-Frequency interaction analysis revealed that the simple main effect of Frequency was significant ($F_{6,6} = 110.11$, $p < 0.0001$) only at the highest-tested frequency of 8000 Hz, see Figure 37. The deep microphone measured significantly lower passive insertion loss (22.6 dB) than the concha microphone (26.2 dB) at 8000 Hz.

Results of the Microphone-by-Protocol interaction analysis revealed the simple main effect of Microphone was significant ($F_{1,1} = 5.95$, $p = 0.0149$) only for the deep microphone location, see Figure 38. As expected, Microphone was not significant for REAT (since microphones were not used to capture data during REAT trials). Within the MIRE protocol, however, the deep microphone measured significantly lower passive insertion loss (15.0 dB) than the concha microphone (16.0 dB).

Results of the Frequency-by-Protocol interaction analysis revealed the simple main effect of Protocol was significant ($F_{1,6} = 9.49$, $p = 0.0021$) at 125 Hz and 8000 Hz, see Figure 39. Insertion loss measured using MIRE was significantly lower than REAT at 125 Hz (1.5 dB MIRE vs. 6.4 dB REAT) and 8000 Hz (22.8 dB MIRE vs. 26.1 REAT). Graphs by individual headphone for this interaction are shown in Figures 40-43. Readily apparent is that results from both protocols track closely together for each headphone with the exception of the supra-aural Sennheiser HDC451 NoiseGard headphone, which is significantly different between protocols, up to 4000 Hz. Figure 44 shows the relationship between headphones for this interaction.

Within the circumaural headphones, the only significant variation between protocols was, as stated, at 125 Hz and 8000 Hz. This variation is relatively small across headphones, with an average difference of 5.2 dB at 125 Hz and 2.6 dB at 8000 Hz. From 500 Hz to 4000 Hz, the average difference is less than 1.4 dB. The supra-aural headphone has an average difference of 5.1 dB from 125 Hz to 2000 Hz but only a 0.3 dB average difference from 2000 Hz to 8000 Hz. Differences between headphones are likely due to the differences in electronic noise cancellation circuitry used by the different manufacturers and across differing headphone types.

Post-hoc analysis using the Tukey-Kramer test was conducted on the main effects of Headphone and Frequency (Protocol has only two levels and therefore did not require the post-hoc test). For the main effect of Headphone, the Sennheiser HMEC300 NoiseGard headphone provided the greatest level of passive insertion loss (26.4 dB) followed by the Bose Aviation Headset X (20.6 dB), Bose Quiet Comfort 2 (14.4 dB), and Sennheiser HDC451 NoiseGard (4.3 dB), respectively. All headphones were significantly different from one another, see Figure 45.

For the main effect of Microphone, significant differences were observed between REAT measurements obtained when microphones were located at the concha and deep microphone positions, see Figure 46. The deep microphone location exhibited lower IL (16.1 dB) than did the concha microphone location (16.7 dB).

For the main effect of Frequency, statistically significant differences were observed across all frequencies, see Figure 47. Levels of insertion loss increased as frequency increased (3.9 dB to 27.6 dB, respectively) across all headphones.

Significant differences were observed for the main effect of Protocol. Average passive insertion loss measured using the REAT protocol (17.3 dB) was significantly greater than average insertion loss measured using the MIRE protocol (15.5 dB), see Figure 48. As shown in the Frequency-by-Protocol interaction analysis, however, these differences occurred only at the lowest (125 Hz) and the highest (8000 Hz) frequencies tested .

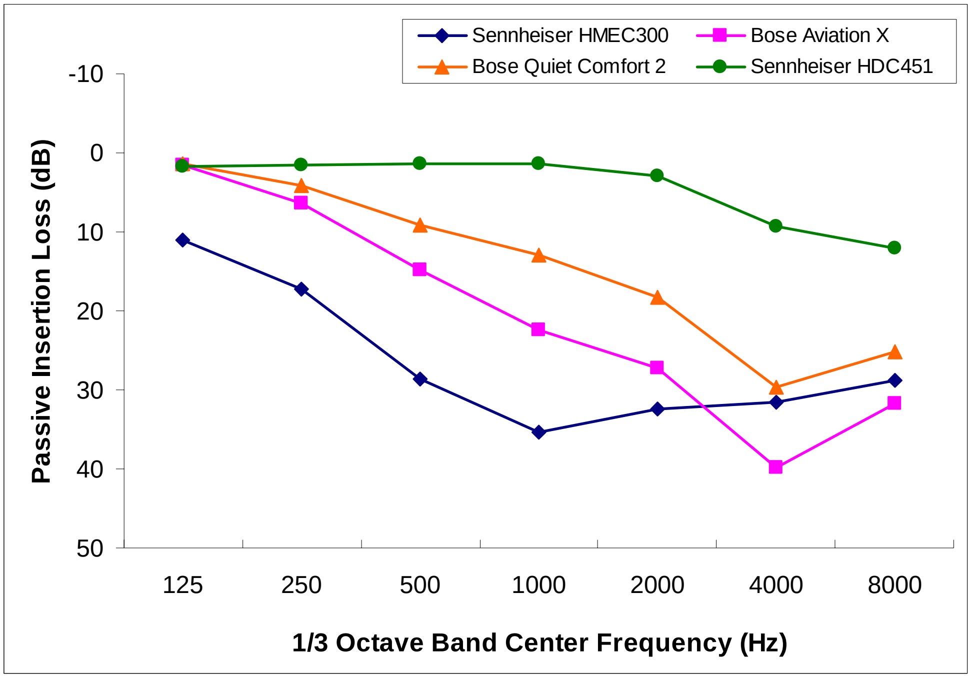

Figure 36. Headphone-by-Frequency interaction for *REAT vs. MIRE Passive Insertion Loss* dependent measure.

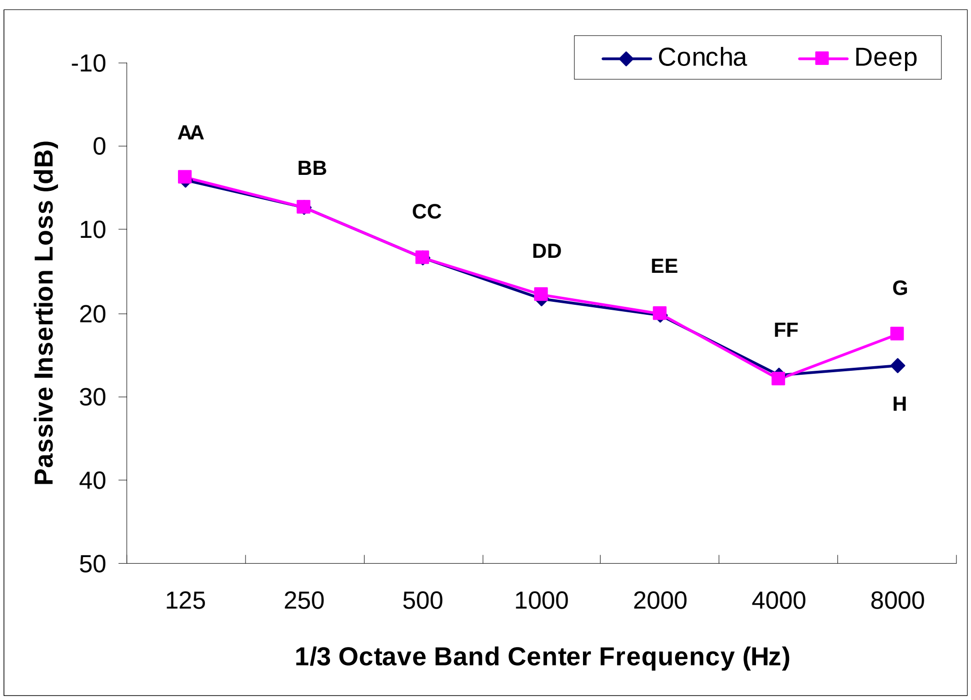

Figure 37. Microphone-by-Frequency interaction for *REAT vs. MIRE Passive Insertion Loss* dependent measure (Means with different letters are significantly different at $p \leq 0.05$).

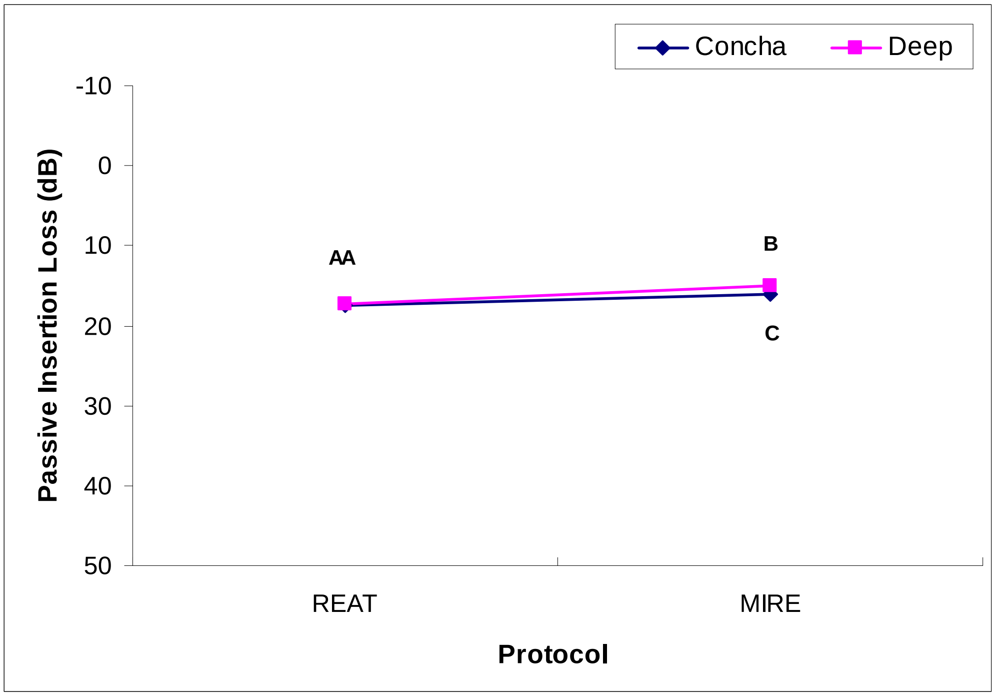

Figure 38. Microphone-by-Protocol interaction for *REAT vs. MIRE Passive Insertion Loss* dependent measure (Means with different letters are significantly different at $p \leq 0.05$).

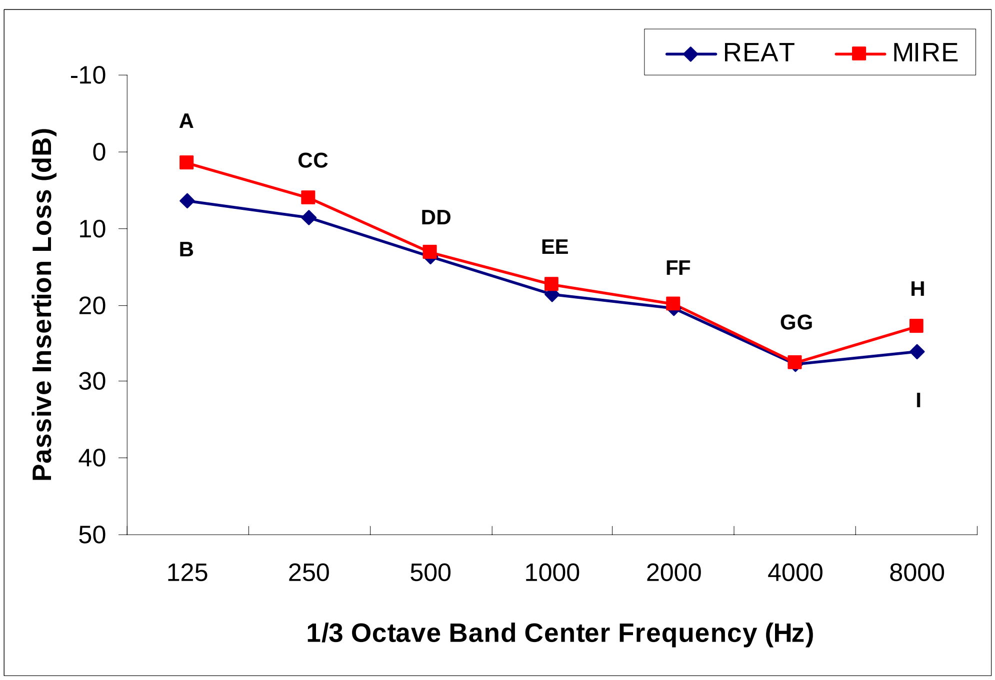

Figure 39. Frequency-by-Protocol interaction for *REAT vs. MIRE Passive Insertion Loss* dependent measure (Means with different letters are significantly different at $p \leq 0.05$).

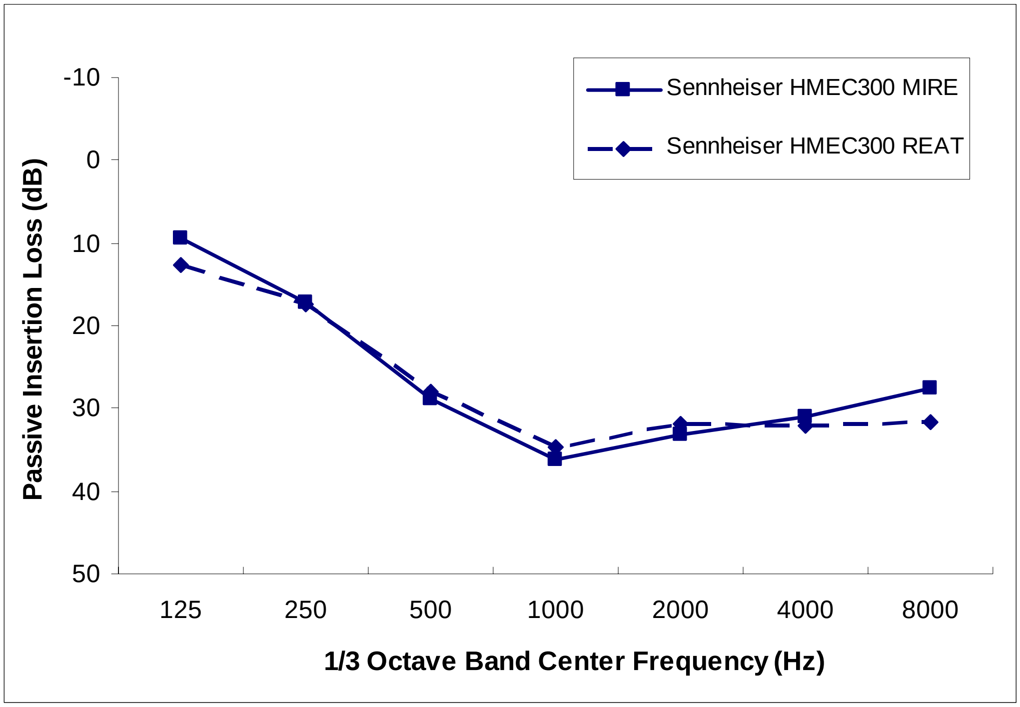

Figure 40. REAT vs. MIRE Frequency-by-Protocol Interaction for Sennheiser HMEC300.

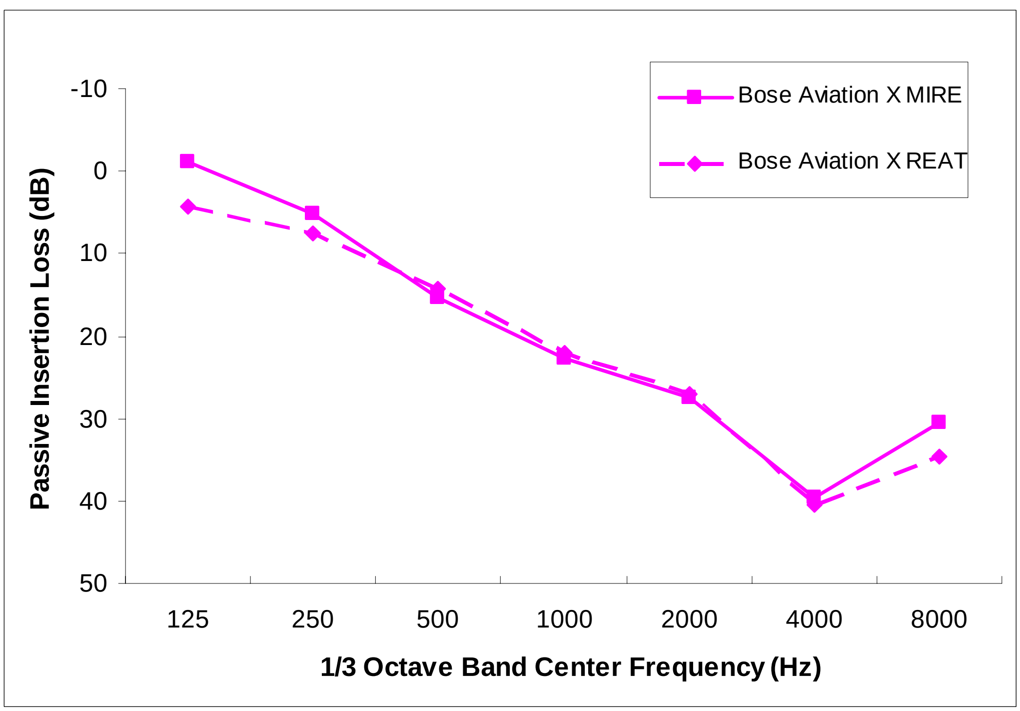

Figure 41. REAT vs. MIRE Frequency-by-Protocol Interaction for Bose Aviation X.

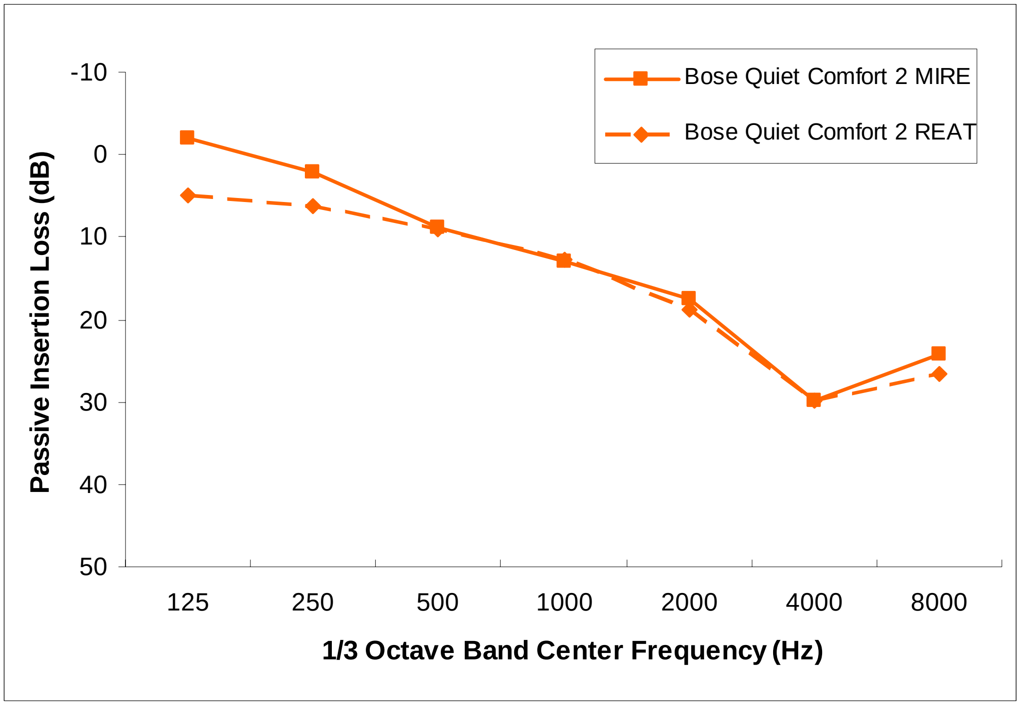

Figure 42. REAT vs. MIRE Frequency-by-Protocol Interaction for Bose Quiet Comfort 2.

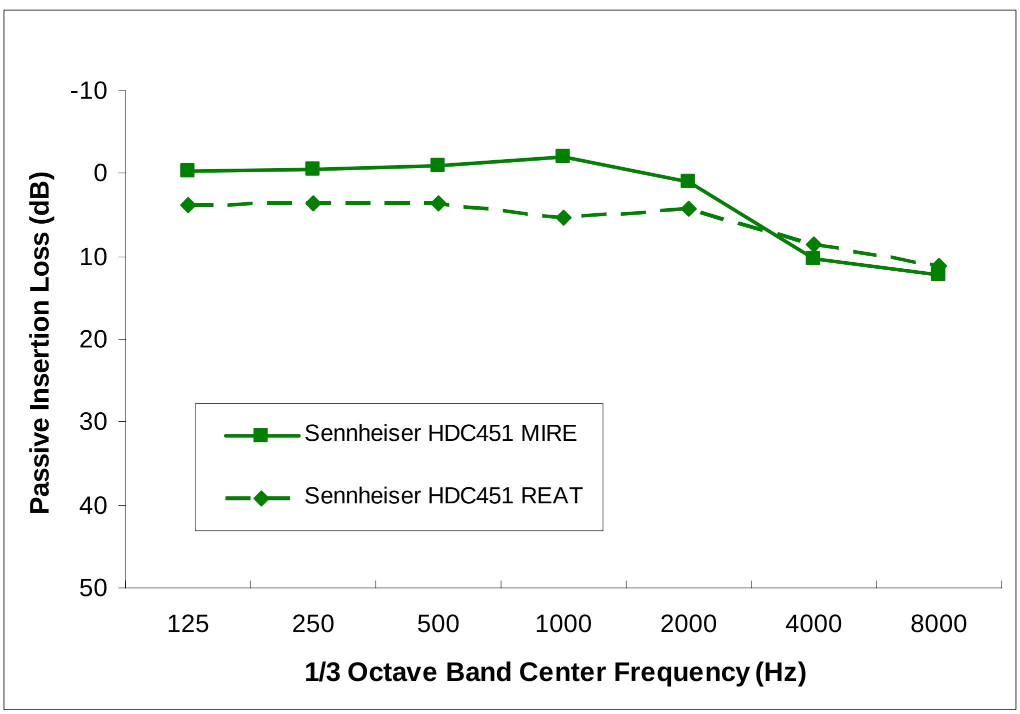

Figure 43. REAT vs. MIRE Frequency-by-Protocol Interaction for Sennheiser HDC451.

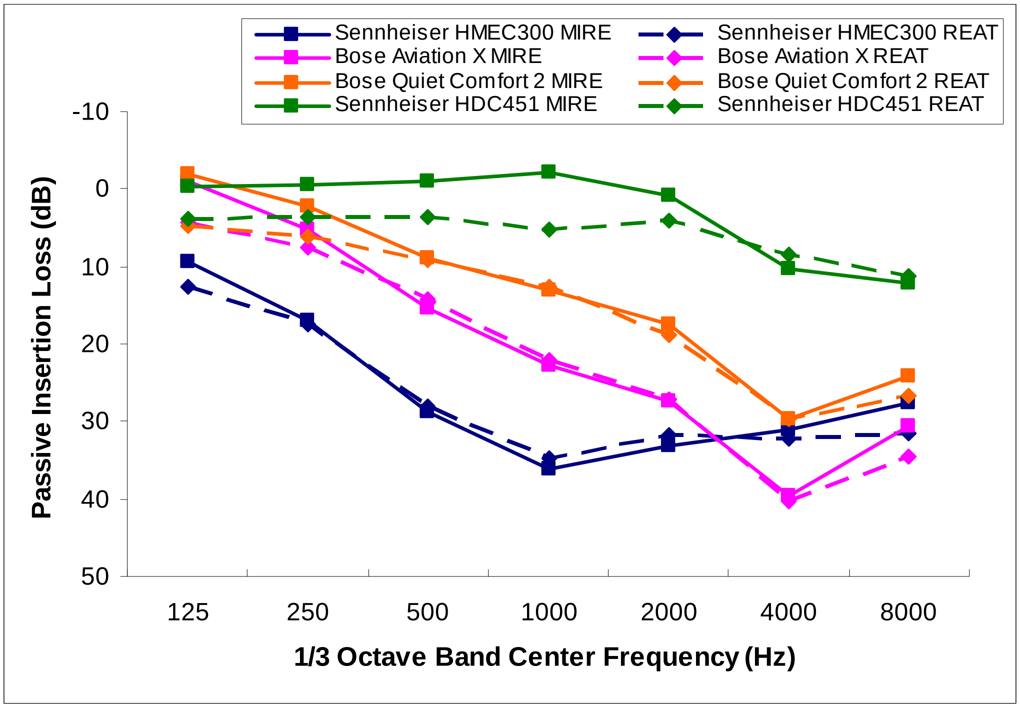

Figure 44. REAT vs. MIRE Frequency-by-Protocol Interaction breakout by headphone.

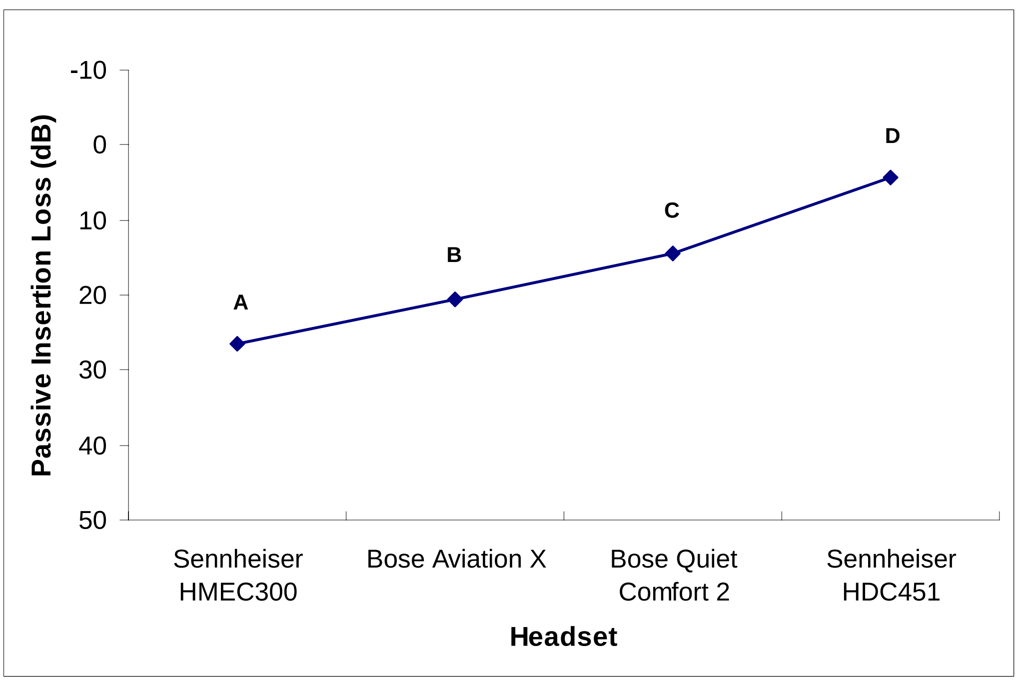

Figure 45. Headphone main effect for *REAT vs. MIRE Passive Insertion Loss* dependent measure (Means with different letters are significantly different at $p \leq 0.05$).

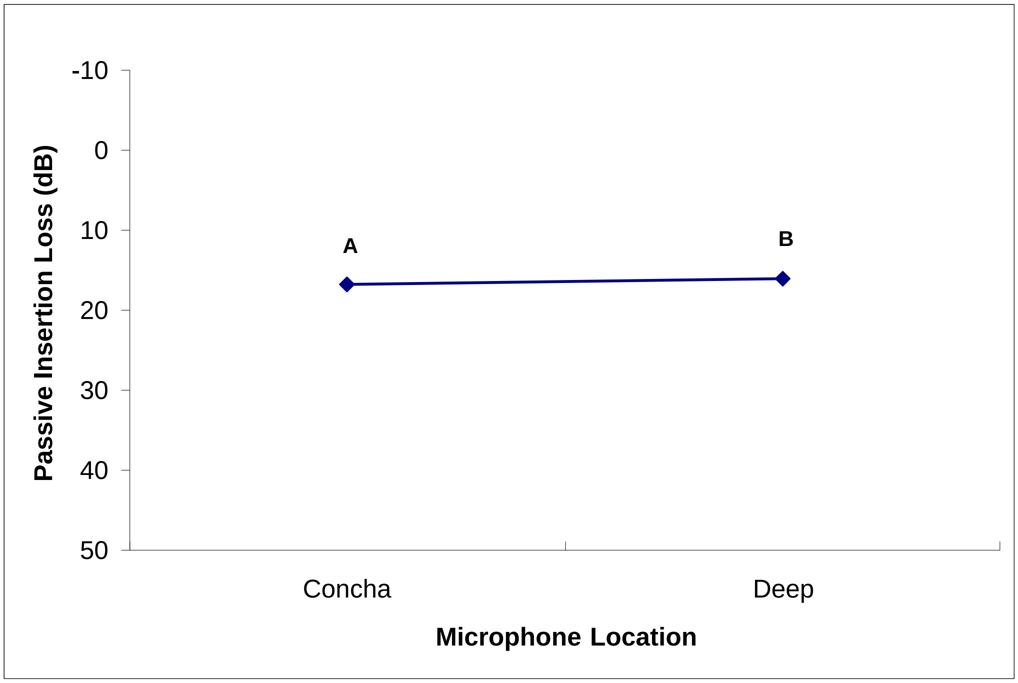

Figure 46. Microphone main effect for REAT vs. MIRE Passive Insertion Loss dependent measure (Means with different letters are significantly different at $p \leq 0.05$).

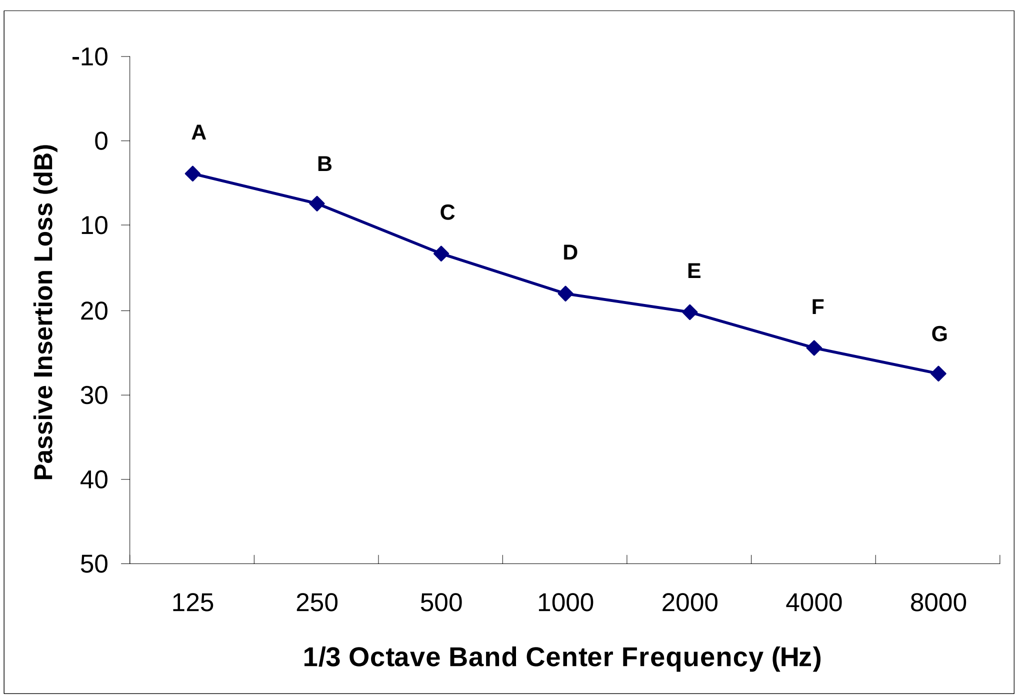

Figure 47. Frequency main effect for *REAT vs. MIRE Passive Insertion Loss* dependent measure (Means with different letters are significantly different at $p \leq 0.05$).

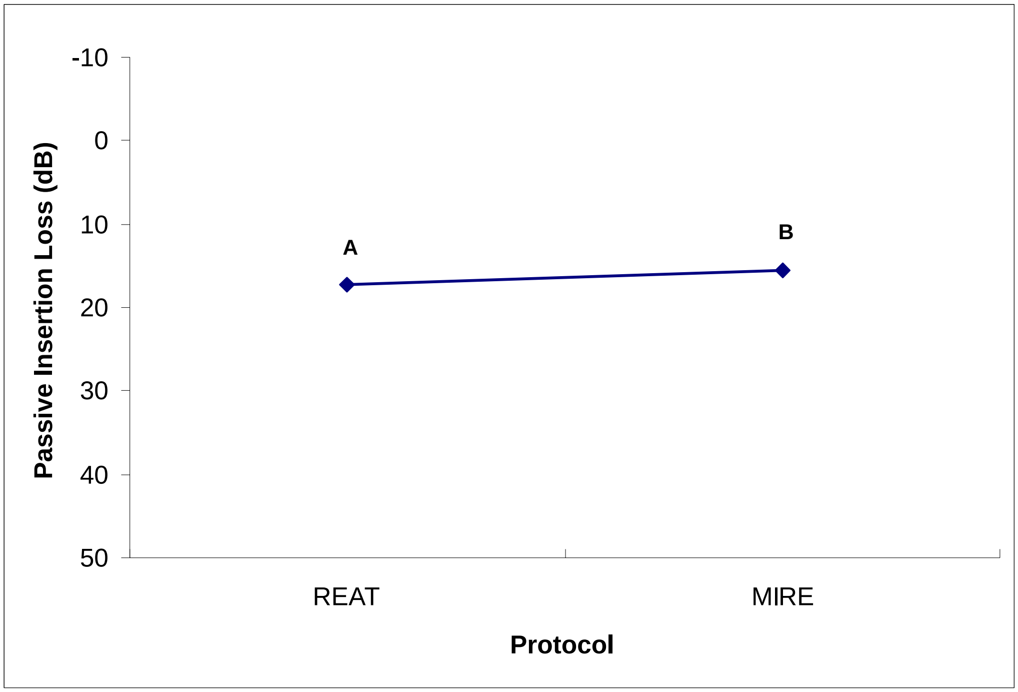

Figure 48. Protocol main effect for *REAT vs. MIRE Passive Insertion Loss* dependent measure (Means with different letters are significantly different at $p \leq 0.05$).

Comfort Index and Headband Force Results

Comfort Index data and headband force data were analyzed using a multiple linear regression model to determine the relationship between headband force and perceived levels of comfort (Table 11). The regression analysis was performed using the PC-based program SPSS, with the predictor variable *comfort index* and dependent variable *headband force*. No significant effect was observed ($r^2 = 0.22$, $p = 0.810$) between headband force and perceived levels of comfort.

TABLE 11. Regression Analysis Table

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	1.345	1	1.345	.069	.810(a)
	Residual	58.867	3	19.622		
	Total	60.212	4			

a Predictors: (Constant), CI
b Dependent Variable: HF

A one-way, nonparametric ANOVA was conducted on the Comfort Index data to determine if significant differences existed between headphones with respect to comfort. Significant differences were observed in Headphone ($F_{4,45} = 5.75$, $p = 0.0008$) for the dependent variable Comfort Index. The Bose headphones were significantly different from the others, but not from each other. The Sennheiser headphones were significantly different from the others, but not from each other. Finally, the LightSPEED Aviation Thirty 3G was significantly different from all other headphones. Specifically, the Bose Quiet Comfort 2 provided the highest level of perceived comfort (70.8), followed by the Bose Aviation Headset X (69.4), Sennheiser HDC451 NoiseGard (61.1), Sennheiser HMEC300 NoiseGard (61.0), and LightSPEED Aviation Thirty 3G (51.3), respectively, see Figure 49.

Headband force measurements were acquired in accordance with ANSI S3.19-1974, using an INSPEC earmuff headband force measurement rig. The Sennheiser HMEC300 NoiseGard headphone had the highest level of headband force (10.1 N), followed by the LightSPEED Aviation Thirty 3G (9.6 N), Bose Aviation Headset X (5.0 N), Bose Quiet Comfort 2 (3.1 N), and Sennheiser HDC451 NoiseGard (1.4 N), respectively, see Figure 50.

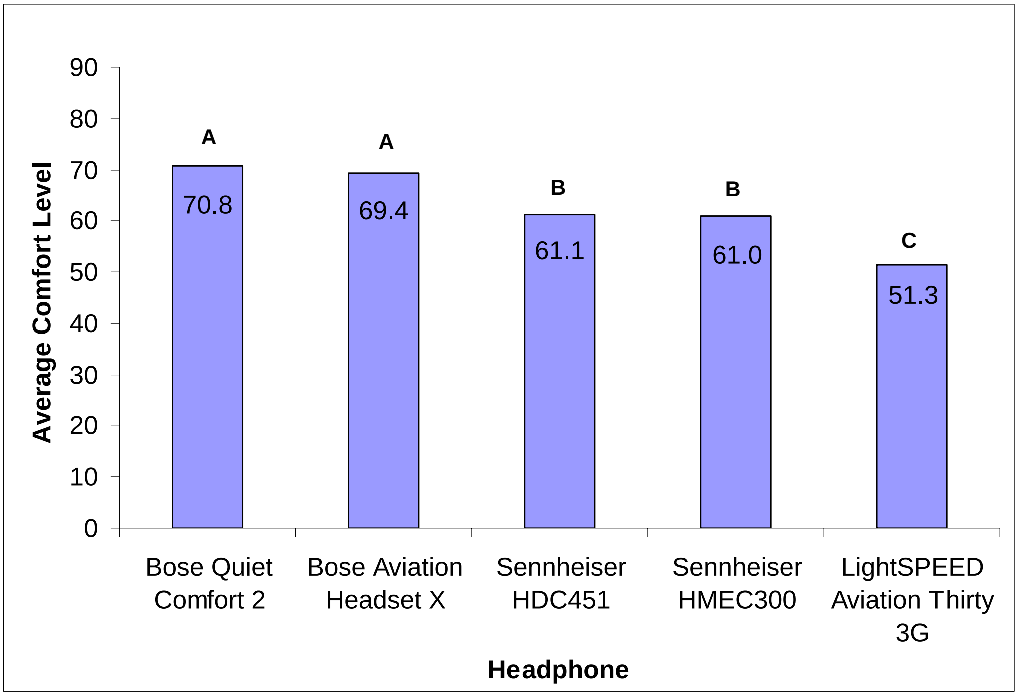

Figure 49. Comfort Index ratings by headphone (Means with different letters are significantly different at $p \leq 0.05$).

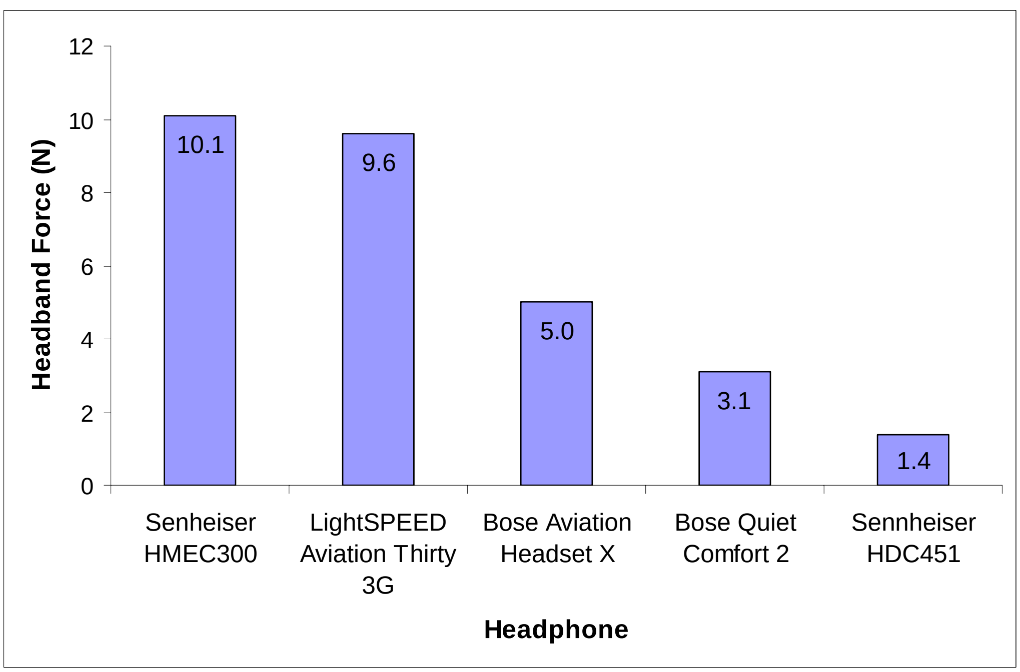

Figure 50. Headband force measurements by headphone.

DISCUSSION

The primary purpose of this research was to address a number of key issues related to ANR headphone attenuation testing such that these types of headphones may one day be tested and labeled for use as hearing protection devices. In the course of this effort, a number of goals were outlined and empirical research was designed and conducted to achieve each of these goals. What follows is a discussion of the current research results and how they relate to and address each particular research goal.

Passive attenuation values using REAT and MIRE

It has been stated that the *psychophysical* REAT protocol cannot be used to determine the active (and therefore, total) attenuation of ANR headphones. It has been hypothesized that the *physical* MIRE protocol is a possible solution to the inherent shortcomings found in the REAT protocol to accomplish this task. The results of the comparison between REAT and MIRE passive attenuation data in the current research show that the MIRE protocol does in fact closely match the REAT protocol when measuring passive attenuation of the selected headphones. However, this is not the case across all frequencies tested. Specifically, at the lowest tested frequency of 125 Hz and at the highest tested frequency of 8000 Hz, there is a significant difference between passive attenuation measured using REAT versus passive attenuation measured using MIRE.

The lower frequency results are in relative agreement with previous work conducted by Casali et al. (1995) and Gauger (1998), which state that at 125 Hz (and also at 250 Hz in Casali et al.), REAT values exceed MIRE by 7 dB. In the current study, REAT exceeded MIRE by 5.1 dB at 125 Hz. In addition, results also showed that REAT exceeded MIRE by 2.7 dB at 8000 Hz. This was not a reported outcome in the previous research. However, since there exists a significant microphone effect at 8000 Hz for these data, it is suggested the observed difference between protocols at this frequency was a factor of the microphone and not the protocol.

To support this assertion, a one-way ANOVA was conducted at the frequency in question, 8000 Hz, between the microphone locations tested. Results support initial findings that significant a microphone effect exists at 8000 Hz for the MIRE protocol ($F_{2,18} = 22.40$, $p < 0.0001$). Post-hoc evaluation indicates that the deep microphone location, again, was significantly different (lower IL) than both the concha and shallow microphone locations. The concha and shallow microphone locations were not significantly different from each other. As expected, there was no significant microphone effect for the REAT protocol at 8000 Hz ($F_{1,9} = 1.90$, $p = 0.2015$). Microphone significance is discussed further in the evaluation of microphone placement section.

Since the electronic circuitry is not active (i.e., it is turned off) during the passive testing procedure, it is not possible that the ANR circuitry is a contributing factor to the differences between protocols at the lower frequencies. REAT has been used quite extensively to determine passive attenuation of muff-type hearing protectors and a robust data set exists to support the attenuation values and ranges across the frequencies of interest for passive headphones.

As previously mentioned, however, REAT is susceptible to masking effects which do not effect MIRE testing. Physiological masking effects and bone conduction effects are a known problem with using REAT, especially in the lower frequencies. These problems do not affect MIRE measurements taken at these frequencies since masking effects are perceptual in nature and only effect REAT measurements. The differences between protocols in this study are in line with previous findings at lower frequencies and support the fact that REAT elevates insertion loss levels at this frequency (and also 250 Hz in previous studies). Since MIRE is not susceptible to these effects, it is suggested that these values are more representative of the real insertion loss values measured at this frequency.

However, one factor which could affect the attenuation values captured by MIRE is the particular measurement microphone used for the MIRE test. Perhaps the microphone is more sensitive than human hearing at the lowest and highest ranges tested. Also, the REAT test used 1/3 octave bands of noise, whereas MIRE used a 30-second duration pink noise as the stimulus from which 1/3 octave measurements were taken by the spectrum analyzer. Since REAT is perceptual in nature, and the lowest and highest frequencies are more difficult to perceive, participant response may be significantly less sensitive than the microphones at these frequencies. To determine if the microphone could have caused these differences, it is suggested that a similar test be conducted using different models of microphones (although still using microphones designed for headphone testing), with more than one sample of each. The current study used one sample of each type of microphone.

If microphone testing does not explain the differences between protocols, then perhaps a numerical spectral correction could be used to compensate for the differences. This would allow MIRE-only data to be used for the active attenuation component of

ANR devices as well as replace REAT for the passive attenuation component. This is discussed further under the next section.

Numerical Spectral Corrections for MIRE

If it is determined that the attenuation differences between protocols at the frequencies specified cannot be sufficiently reduced or eliminated, it is suggested that a numerical spectral correction be applied to the MIRE data at the frequencies in disagreement. A non-linear interpolation between the attenuation values at each of the frequencies in question would seem a logical approach, given that the differences have been shown to vary under different circumstances. However, this variation in itself may be a reason that a correction value may not be able to be determined without further evaluation. That is, in order to interpolate across headphones and conditions, a more robust data set may be required before a determination can be reached regarding choice of a constant correction value or a formulaic approach to correction.

For example, the Gauger (1998) results showed a 7 dB difference between protocols, the Casali et al. (1995) study reported a 6 dB difference, while the current research showed a difference of 5.1 dB at the same frequency (125 Hz). While these values are relatively similar, there may not be sufficient evidence for allowance of an acceptable interpolated value to use as a correction. Therefore, it is suggested that if a constant numerical value is applied to correct for the protocol difference at specific frequencies, further empirical evidence should, ideally, be presented to establish a more robust data set from which to determine such corrections. Additionally, and with a more robust data set, it may be possible to determine a correction factor within headphone groups (i.e., circumaural or supra-aural) using a regression model. Either method would require a more in-depth analysis of a much larger data set and results would of course need to be scrutinized and agreed upon by relevant standards-making committees before being incorporated into existing standards for hearing protector testing.

Another interpretation is that the MIRE values should not be adjusted at all. Instead, they could be used "as is". Since it has been shown that REAT overestimates insertion loss values in the lower frequencies (125-250 Hz) due to physiological masking effects, it is suggested that the MIRE values, which are not affected by this condition, are more representative of the true insertion loss levels at these frequencies.

Since the ultimate goal is to determine an acceptable method for testing and labeling ANR headphones, an alternative to correcting these data may be to combine the two protocols. REAT is currently required for passive headphone testing, yet it has been shown in previous studies that REAT is not appropriate to measure the active component of ANR headphones. A solution, therefore, would be to use REAT to test the passive component of ANR headphones and to use MIRE to test the active component (i.e., Total IL – Passive IL). No further data manipulation would be required and the insertion loss values could be presented as a combination of the values measured using the two different protocols. This is discussed in more detail under the recommendations for a labeling scheme.

<u>MIRE Measurement Microphone Placement</u>

Research has been mixed with regard to the potential benefits and shortcomings of placing measurement microphones inside versus outside the ear canal. In addition, comparisons between specific locations inside the ear canal (i.e., in ear canal-shallow or in ear canal-deep) have not been evaluated or reported. This research compared three locations that could possibly have a significant impact on MIRE insertion loss measurements, due to their proximity between the tympanic membrane and the point of entry for air-transmitted soundwaves. The three locations tested were 1) outside the ear canal, on the floor of the concha, 2) inside the ear canal (shallow), flush with the canal opening just behind and facing the tragus; and 3) inside the ear canal (deep), about five millimeters from the tympanic membrane. It was hypothesized that a significant difference would be observed between at least the concha and deep locations, due in part to ear canal characteristics and the decreasing gradient of the soundwave superposition as distance from the earcup increased.

Results showed no significant difference between the in-concha and in ear canal-shallow locations. That is, there was no significant effect caused by the floor of the concha, the tragus, or any resonant, reflective, and/or absorptive characteristics of the pinna or surrounding tissues before the sound waves enter the ear canal. However, the results did show a significant effect between both outer locations and the in ear canal-deep location. This significance was observed only in the Passive_IL condition and only at 8000 Hz. This effect was not present with the ANR circuitry activated.

One possible reason for this difference being observed only at the highest tested frequency of 8000 Hz could be due to the difficulties with high frequency measurement accuracy when using probe tube microphones near the tympanic membrane. These include sources of error which may vary depending upon probe tube tip location, including the magnitude of the standing wave produced in the ear canal by the reflection of sound energy from the tympanum, and acoustic impedance at the tympanum, which can determine the position of the standing wave (Gilman & Dirks, 1986; Voss & Allen, 1993; Zwislocki, 1976). It has also been shown in the literature that in ear-canal attenuation measurements can be subjected to acoustic impedance and resonance effects, particularly at high frequencies and in an open-air ear canal (Gilman & Dirks, 1986; Hawkins & Mueller, 1986). These acoustic effects and the standing wave create an amplification effect that can reduce attenuation near the tympanum.

Characteristics of the probe tube itself can also affect the measurement. Examples include tube size, which may be a problem for an ear canal that tapers sharply toward the tympanum and having the tube placed in a narrow region, and resonances generated within the tube, which may mask or emphasize other resonance effects at the tympanic membrane (Connelly & Franzoni, 1995; Gilman & Dirks, 1986). According to (Revit, 2005), sound reflecting off the tympanum can create an interference pattern called a "standing-wave null." This can cause dips in the frequency response measured in the ear canal at the probe tip – especially at high frequencies. The (Gilman & Dirks, 1986) paper illustrates that the standing wave effect is greatest at 8000 Hz (of the frequencies measured) for distances within 1.0 cm from the tympanum. Since this effect was not present during the ANR-on test, it is assumed that the ANR circuitry was responsible for canceling out significant high frequency reflections.

Probe tube position and movement can significantly effect sound pressure levels measured with the deep probe tube microphone. Since the significant effect in the current research is isolated to the extreme frequency of 8000 Hz, and considering the difference was only 0.7 dB, it is suggested that interpretation of this effect be left to the practitioner as to its practical significance.

If the best solution for testing and labeling ANR headphones is determined to be a combination of REAT and MIRE testing, then the in-concha location would likely be the best option to compete with the deep location since the in-ear canal shallow microphone, by design, occludes the ear canal. That is, of course, unless a complete REAT test is conducted with no microphone in place and then a complete MIRE test is conducted with the shallow microphone inserted into the ear canal. In this case, a shallow microphone could be used instead of the in-concha type. However, since the shallow microphone is mounted on a custom-built, shallow-fit swim plug, it is more intrusive than the in-concha microphone.

It is felt that the cost, inconvenience, fragility, and intrusive nature of the shallow microphone make it less appealing than the in-concha microphone for MIRE testing, especially considering there is no significant difference between the two locations in terms of microphone effectiveness. Furthermore, if a combination REAT and MIRE test is used, as stated, REAT would be used to test the passive component of the ANR device. Since the microphone (or its location) is not relevant during REAT, the significant microphone effect observed during the current Passive_IL test is also not relevant. Since there was no microphone effect with the ANR circuitry engaged, the MIRE test will also not be effected by the problems just described. However, given the delicate nature and difficulties associated with probe tube insertion and placement, the in-concha microphone location may be a prudent choice in terms of time, ease of use, safety, and comfort for the participant.

Another important issue to consider with regard to the in ear canal-shallow microphones, however, and one that may be of interest for further study beyond this research, is that active noise reduction headphone performance may vary nonlinearly with the test signal level introduced during insertion loss measurements. Therefore, it may be important to test ANR headphones at varying stimulus levels (e.g., 95 dB, 100 dB, 105 dB, etc.). An advantage for MIRE over REAT in this case is the fact that swim plug microphones may be used to test insertion loss in higher levels of noise because these microphones occlude the ear canal and can better protect the human participants during high levels of noise stimulus.

Headphone Comfort

Data for the calculation of CI values was collected at the end of each experimental trial. For example, at the conclusion of a particular headphone test, each participant completed the CI questionnaire while wearing the headphone they had just used during the experimental trial. These data were compiled and were used to calculate a CI value for each headphone. Average headphone CI values were used for comparisons across headphones. As described in the results section, these values were used to graphically show the relationship between each headphone with respect to comfort.

Results showed that both Bose headphones were rated as being the 'most comfortable' by all the participants, with the Bose Quiet Comfort 2 being the most comfortable and the Bose Aviation Headset X being the second most comfortable. Rating almost 10 points lower were both Sennheiser headphones, with the supra-aural HDC451 ranking third and the HMEC300 Aviation headphone ranking forth. The least comfortable headphone, again, almost 10 points away from its nearest competitor, was the LightSPEED Aviation Thirty 3G headphone.

Surprisingly, the lightest headphone, and that which maintained the lowest headband force measurement, was not rated as the most comfortable. That headphone, the supra-aural Sennheiser HDC451 NoiseGard, was rated in the middle of all the headphones. Conversely, one of the heavier and bulkier headphones, and that with the third highest headband force rating, the Bose Aviation Headset X, was rated the second-most comfortable. The two lowest-rated headphones had the highest levels of headband force. These were the more heavy and bulky Sennheiser HMEC300 NoiseGard and LightSPEED Aviation Thirty 3G headphones. As the graph in Figure 50 shows, the headband force of these two headphones was twice that of the next closest headphone (the Bose Aviation Headset X).

The CI values for each headphone were compared with each headphone's bandforce measurements using a multiple regression analysis and no significant effect was observed. A correlation analysis was also conducted in an attempt to rule out small sample size as a possible reason for non-significance, but this too resulted in no significance (Table 12). There was simply no clear distinction between headphone type, comfort rating, and headband force measurement.

TABLE 12. Correlation analysis between CI and HF values

			CI	HF
Spearman's rho	CI	Correlation Coefficient	1.000	.100
		Sig. (2-tailed)	.	.873
		N	5	5
	HF	Correlation Coefficient	.100	1.000
		Sig. (2-tailed)	.873	.
		N	5	5

However, based on the literature review and previous research conducted in real-world environments, it has been shown that comfort has a significant impact on whether or not a person will wear their hearing protector, and how long they will wear it if they are in a noisy environment, and whether or not they will wear it properly. Evidence gathered from the subjective comfort evaluations in this study may provide support for increasing headphone comfort. For example, the two highest-rated headphones, with respect to comfort (Bose Quiet Comfort 2 and Bose Aviation Headset X), provide respectable levels of attenuation (15.7 dB and 23.5 dB, respectively, with ANR on, and 15.5 dB and 21.4 dB, respectively, with ANR off), whereas the highest attenuating headphone (Sennnheiser HMEC300), with 26.6 dB ANR on and 26.9 dB ANR off, was ranked second to last in terms of comfort. If the headphone is too uncomfortable to wear, or wear properly, the higher-level attenuation properties are significantly undermined. In this case, the Bose headphones appear to strike a balance between comfort and performance by providing ‘excellent’ levels of comfort and reasonable levels of attenuation.

It is thought that a strong correlation between comfort and headband force was not observed in this study, in part, because of the short duration of use for each headphone tested. At most, participants wore each headphone for 10 minutes before removing it and replacing it with a second (identical) sample. Total time per trial with any given headphone type (with donning and doffing occurring during trials) was less than one hour. Also, participants sat motionless in a temperature-and-humidity-controlled environment. It is felt that under more real-world conditions, such as those which include physical activity, six-degree of freedom head movement, perspiration, and longer wear duration, a significant change would occur in the dynamic of each headphone's comfort and wear characteristics. This would, in turn, likely alter the perceived levels of comfort experienced by each participant, and the subsequent ratings for each headphone (Park & Casali, 1991). Higher correlation and predictability between comfort and headband force would therefore be expected.

<u>Recommendations for use of REAT vs. MIRE</u>

Based on the results of the current research and based on the previous discussions for each experimental goal, the choice of REAT versus MIRE rests on two main issues: 1) how difficult it would be to determine numerical spectral corrections that would account for variations at specific frequencies, and 2) getting the relevant acoustic testing communities and standards committees to come to an agreement on those corrections. Given that both issues may take considerable time (perhaps years), it is suggested that a combination of the REAT and MIRE protocols now be used to determine insertion loss values for ANR headphones.

This recommendation is based on a number of factors evidenced by the results of this research. First, there is a significant difference between REAT and MIRE insertion loss values. Although these differences do not occur at all frequencies tested – in fact the differences only occur at the lowest frequency – the fact that there are differences means that choices must be made regarding their resolution. Second, these choices will require further study, consensus, and standardization. ANR devices can improve hearing protection in noisy environments, especially at lower frequencies. A REAT vs. MIRE combination testing paradigm may be a viable and timely solution for allowing ANR headphones to be used in the marketplace as 'true' hearing protection devices. Waiting any longer only serves to keep this potentially useful technology from reaching those it could directly benefit.

Relevant comparisons for each headphone with respect to MIRE Passive IL, MIRE Total IL, MIRE Active IL, and REAT Passive IL are depicted in Figures 51-54. These figures provide a useful comparison between protocols for each headphone tested and clearly show the significant effect that active noise reduction has on total attenuation.

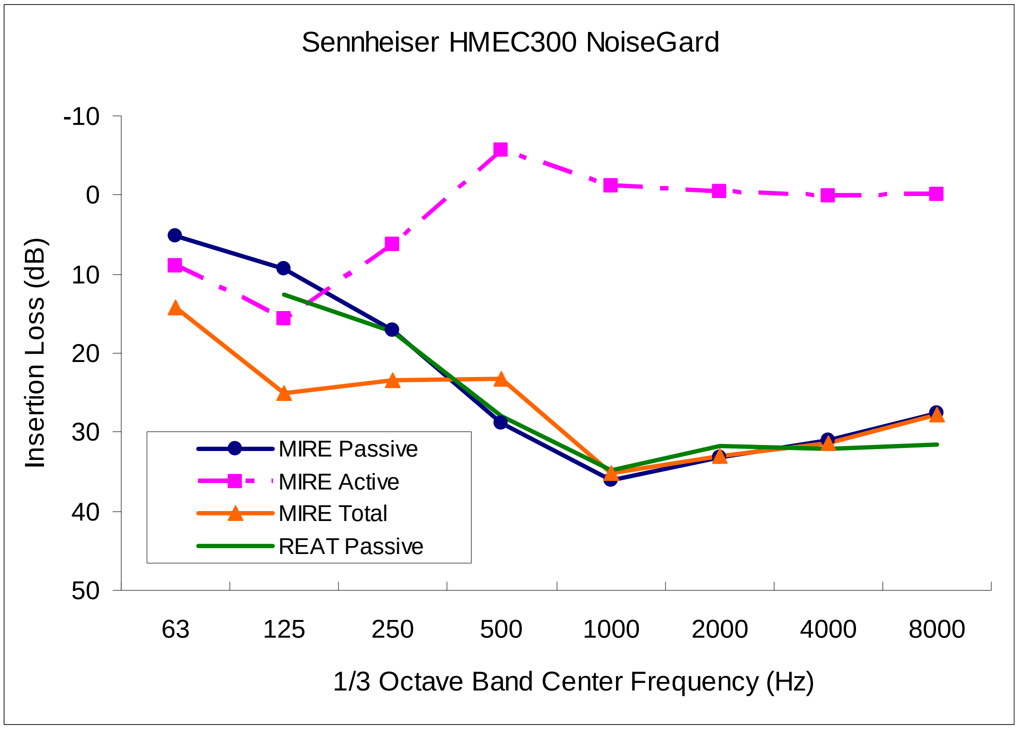

Figure 51. Insertion Loss Comparison for the Sennheiser HMEC300 NoiseGard.

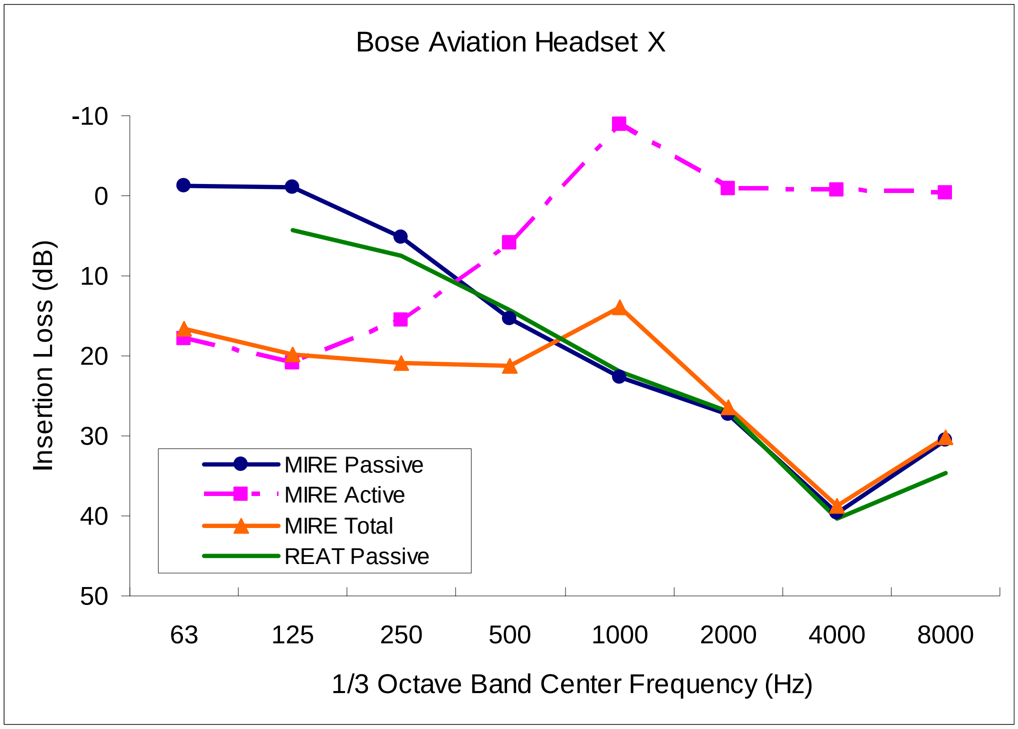

Figure 52. Insertion Loss Comparison for the Bose Aviation Headset X.

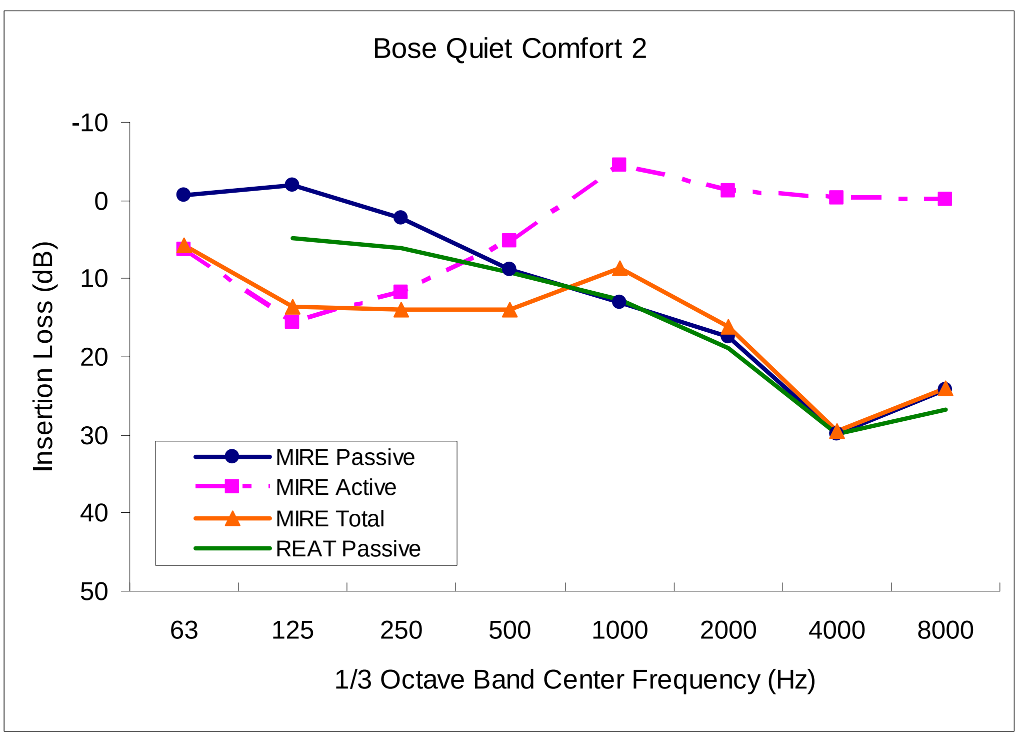

Figure 53. Insertion Loss Comparison for the Bose Quiet Comfort 2.

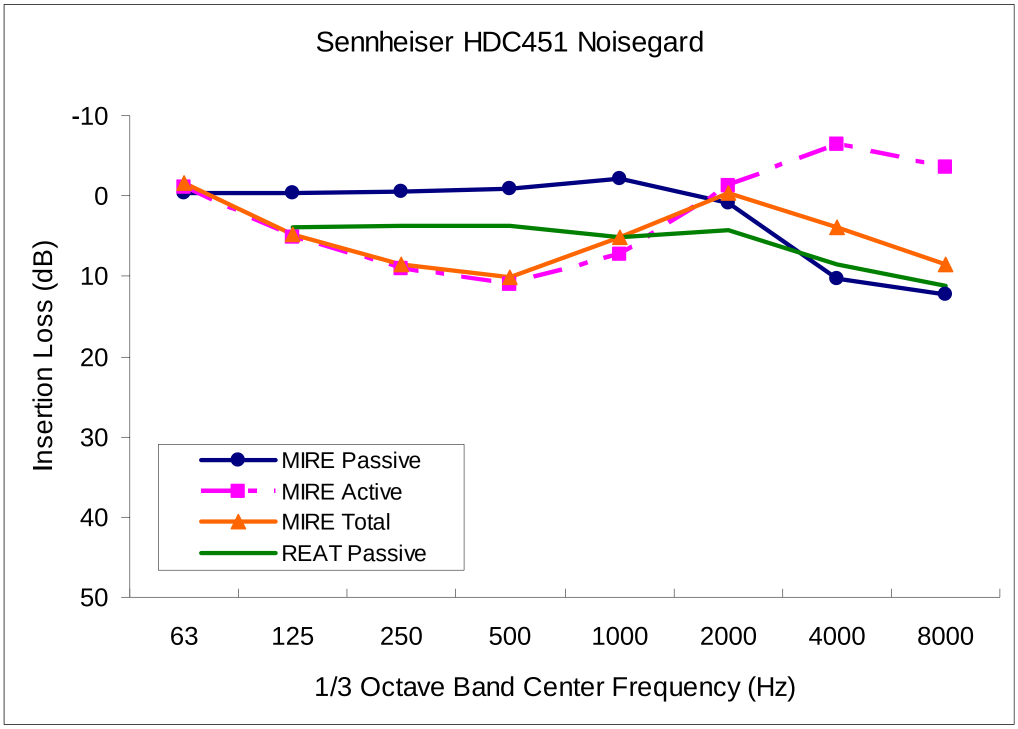

Figure 54. Insertion Loss Comparison for the Sennheiser HDC451 NoiseGard.

Headphone attenuation labeling

Whether MIRE-only or a combination of REAT (for passive component) and MIRE (for total and active components) is to be used for measuring ANR attenuation, it is recommended that a labeling scheme be used such that both passive and total attenuation are clearly delineated for the consumer. It is recommended that these data be presented similar to current EPA fuel efficiency data found on new vehicle data sheets. For example, an EPA 25/35 rating represents 25 mpg city and 35 mpg highway. On ANR-based headphones, a label with 25/35 could represent 25 dB passive attenuation and 35 dB total attenuation. These numbers should be large and clearly visible on the packaging, similar to the current NRR ratings printed on headphone packaging. In addition to these ‘at-a-glance’ attenuation values, text should be included on the label which clearly and concisely explains the meaning of these numbers.

With easy to read, at-a-glance attenuation values, and easy to understand descriptions, consumers will know that if they choose to use the headphone as a passive-only headphone, the amount of hearing protection they should expect from that device is, for example, 25 dB of attenuation. Additionally, if they choose to use the headphone with the ANR circuitry engaged, they should expect total attenuation to be the stated 35 dB. One key advantage to the availability of information regarding the two modes is that if batteries die or if for some other reason the ANR circuitry is disabled or is working at less than optimal levels, the consumer will know the least amount of attenuation they should expect to receive from the device in its “lowest protection”, or passive, mode. This information may be useful to consumers before making a determination about the correct headphone to purchase for their particular application.

CONCLUSION

The review of the literature herein has shown that the real-ear attenuation at threshold, or REAT protocol, is currently the best (and therefore, standardized) method for measuring attenuation of passive hearing protection devices. It has also been shown that this psychophysical protocol is unable to accurately measure the active attenuation component of ANR headphones due to signal masking effects caused by the electronic circuitry inherent in such devices. It is primarily for this reason that a standard for measuring the active attenuating properties of ANR headphones has not yet been established.

It has been demonstrated that the microphone in real ear, or MIRE protocol, is an acceptable method for measuring active attenuation in ANR headphones. Since this physical measurement paradigm uses microphones to measure insertion loss, proper placement of these microphones is key to obtaining the most objective measures possible. However, research has been mixed concerning microphone placement and empirical evidence has not been presented which supports or refutes any particular location.

This research has contributed both to the science as well as to practical application of hearing protector testing methodologies. Specifically, this research has addressed the issue of obtaining total attenuation values, that is, both passive and active attenuation, from ANR headphones by capturing acoustic spectral data using both REAT and MIRE protocols and by using a variety of ANR headphone designs. This research has also addressed the issue of MIRE microphone placement by investigating three distinctly different locations that might be used to obtain attenuation measurements using human test participants.

As a result of this testing, new evidence was uncovered regarding a significant decrease in insertion loss at 8000 Hz measured at the in ear canal-deep microphone location. While these results may be related to acoustic impedance or a standing wave created by resonance effects near the tympanum, it is unclear whether distance from the tympanum, probe tube characteristics, or some other factor was responsible. Further research is warranted to determine the exact cause and nature of this observed effect.

The results of this research support earlier investigations, which have shown that MIRE is able to adequately capture the active attenuation of ANR devices and that a significant difference does exist between passive attenuation captured using MIRE and passive attenuation captured using REAT. It is suggested that if MIRE is desired as the only measurement paradigm for both passive and active attenuation, that the scientific, testing, and standards communities must either agree on a suitable correction algorithm to address the differences between the two protocols, or establish a testing standard for ANR devices which incorporates both REAT and MIRE protocols. The latter suggestion would incorporate the inherent strengths of both protocols for their respective measurements (i.e., REAT for passive IL and MIRE for active IL). Attenuation labeling suggestions were made with emphasis given to separation of passive and total attenuation (similar to EPA fuel-economy ratings), whether these values are provided by one or both protocols.

Additionally, this research has provided a standards-based, empirical data set for specific microphone placement when using the MIRE protocol. Specifically, it was shown that there is no statistically significant difference between the three microphone locations tested (i.e., in-concha, in ear canal-shallow, and in ear canal-deep) – with the exception of the deep microphone placement at 8000 Hz, which was addressed in the discussion section. This information may help support decisions by future researchers who may wish to use one particular microphone placement versus another (i.e., for reasons of cost, time, or intrusiveness), by providing empirical support for neutrality across locations tested in this research.

Hearing protectors can be as effective as their attenuation values state only when they are worn and worn properly throughout the duration of exposure in a noise environment. This study looked at the relationship between comfort and headphone headband force. Although for reasons previously stated, a significant correlation was not observed, information collected for each headphone with respect to comfort and headband force may be useful to headphone manufacturers for future design considerations. Results from subjective comfort ratings and objective headband force measurements provide comparative values between headphones from each manufacturer, as well as values across headphones provided by other manufacturers.

The data, results, and discussion provided by this research have answered specific questions regarding hearing protector testing and attenuation measurement methods, measurement microphone placement, and headphone design characteristics as they relate to comfort between and across leading manufacturers. It is hoped this information is deemed useful to the scientific and testing communities, given the recent debates over testing protocols, the upcoming EPA regulation changes to standards for ANR headphone testing and labeling as hearing protection devices, and the desire to integrate high attenuation with comfortable design for increased consumer usability.

RECOMMENDATIONS FOR FURTHER RESEARCH

As previously suggested, further research regarding numerical spectral corrections of passive attenuation data measured with the MIRE protocol may be warranted. While results between REAT and MIRE were similar to previous research, the values were different enough to suggest that a constant correction factor may not be a suitable solution to the differences between protocols. As mentioned, a non-linear interpolation between the protocols at the frequencies of disparity (specifically, 125 Hz, but also 250 Hz based on previous research) should be further investigated for suitability as a correction method. If test data could be obtained that show such a correction is possible and repeatable, perhaps the use of a single testing protocol, i.e., MIRE, could be used to obtain total attenuation values for ANR headphones.

Although the difference observed at 8000 Hz between the deep microphone location and the outer-ear locations (in-concha and in ear canal-shallow) was categorized as anomalous and specific to the measurement microphone type and location (which may have created a standing null wave and significantly reduced attenuation levels at that frequency), it is suggested that further investigation be conducted in this area to isolate the reason for the 8000 Hz effect. Specifically, it may be of import to evaluate different microphone types, probe tube material and hole diameter, and distances from the tympanum.

Finally, as previously mentioned, further study is required to determine if ANR headphones require testing at different stimulus levels other than 90 dBA, since ANR headphone performance may vary nonlinearly with test signal level.

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APPENDIX A – ANR Headphone Design Specifications

Bose Aviation Headset X

An innovative aviation communication headset designed for the unique challenges pilots of all types of aircraft encounter. Delivers an unmatched combination of full-spectrum noise reduction, comfortable fit and clearer sound. Enjoy full-spectrum noise reduction, comfortable fit and clearer sound when you fly with the Bose® Aviation Headset X. Thanks to unique Bose acoustic technologies, this unmatched combination of benefits is available in one lightweight headset. And with our AdaptiSense™ headset technology, you can enjoy the performance of the Aviation Headset X for at least 40 hours from just two AA alkaline batteries.

Breadth: 4.8 to 6.3 inches • Height: 4.5 to 5.7 inches • Weight: 12 oz (340 g)

TriPort® headset structure
Proprietary Bose technology enables a smaller, lighter, more comfortable headset with less clamping force.

Acoustic Noise Cancelling® headset technology
Only from Bose, this patented technology electronically identifies and reduces unwanted noise, allowing improved intelligibility of radio and intercom audio. The continuous roar of flying is reduced, so your concentration is improved.

AdaptiSense™ headset technology
Sophisticated electronics monitor power demand and instantaneously adjust the voltage to maintain maximum battery life. Smart shutoff detects when you've stopped using the headset and automatically turns off all electronics to preserve battery life.

Active equalization
Electronically tunes the frequency response, enabling outstanding audio performance for improved speech intelligibility.

Magnesium alloy headband
Provides exceptionally strong, durable frame that's remarkably lightweight and comfortable.

Center torsion spring
Enjoy a consistent, comfortable fit for any size head with half the clamping force of conventional active headsets.

Adjustable headband sliders
Experience a comfortable fit with up to 3 inches of adjustment in headband length.

Sheepskin headband cushion
Plush, soft headband cushion eliminates hot spots and provides comfortable, even distribution of the headset weight.

Earcup rotation
Earcups rotate 10 degrees vertically and horizontally to maintains uniform pressure around the ears for superb noise reduction performance and comfort.

Boom microphone
Enables smoother, more precise adjustment so you can put the microphone right where you want it—and keep it there.

5-year transferable limited warranty
Complete limited warranty coverage for parts, labor and second-day return shipping expenses for any non-abuse and acts of nature malfunction.

Carry bag headset
Provides an easy way to bring your headset wherever you go.

Integrated system design
This system is designed so every element—media center, speakers and Acoustimass module—works in harmony, enhancing performance and ease of operation.

Portable Control Module

AdaptiSense™ headset technology
You get only the power you need at any given time-up to 40 hours on 2 AA batteries.

Smart shutoff
Guards against battery drain by detecting when you have stopped using the headset and shuts off automatically.

Ergonomic portable control module design
Enjoy a more comfortable fit in your hand with all controls within easy reach.
30% smaller than the previous version.

Boom microphone
Enables smoother, more precise adjustment so you can put the microphone right where you want it-and keep it there.

Battery life status indicator
Take the guesswork out of battery replacement with a convenient LED that reflects three status indications for remaining battery power.

Installed Control Module

Single connector for installed configuration
Eliminates the need for battery power and provides all signal connections through one dime-sized connector.

Ergonomic installed control module design
Fits comfortably in your hand and puts all controls within easy reach.

6-foot pre-wired harness and connector receptacle
Integrates into the aircraft for a convenient single point connection to the headset.

Bose QuietComfort® 2

Experience the innovative combination of our best noise reduction technology and our best headphone audio performance with the QuietComfort® 2 Acoustic Noise Cancelling® headphones. Our premium headphones dramatically reduce unwanted noise, and advances in Bose® technology make what you want to hear sound even better. Their ergonomic design allows for a comfortable fit and the fold-flat feature makes storage of these lightweight headphones even easier. Our premium headphones offer our best combination of noise reduction technology and headphone audio performance. Innovative design for easy storage, lightweight and comfortable.

Overall headphone dimensions: 7 3/4"H x 6 1/2"W
Ear cushion outside dimensions: 3 4/5"H x 3"W
Weight with cables: 6.9 oz.

Patented Acoustic Noise Cancelling® headphone technology
Electronically identifies and reduces noise while faithfully preserving the music, speech or silence that you desire.

Acoustic Structure of the TriPort® headphone system
Enjoy deeper, richer lows from a small headphone design. Proprietary Bose® technology utilizes three small ports in the earcups to produce a richness of audio performance remarkable for headphones this small.

Active equalization
Electronically tunes the frequency response, enabling outstanding audio performance.

Single earcup audio cable
Connect to your audio sources with greater convenience and ease than provided by standard dual cable designs.

Detachable audio cable with built-in Hi/Lo switch
Remove the audio cable from the earcup; you'll still enjoy the benefits of noise reduction. A simple integrated control allows adjustment depending on the audio source you're listening to: Lo for in-flight entertainment and A/C-powered sources, such as a stereo; Hi for battery-powered sources, such as a portable CD player.

Right earcup rotation
The earcup rotates downward for easy access to the battery door.

QuietComfort® ear cushions
Proprietary cushion design establishes a critical acoustical seal between the headphones and your head, enhancing noise reduction and helping to maximize sound quality.

Adjustable headband

Comfortable settings for a wide variety of head sizes give you up to three inches of adjustment in headband length.

Low battery life indicator
Flashing light gives ample notification of remaining battery power, letting you know when remaining battery life is approximately five hours.

Dual plug adapter
Single headphone plug converts to dual jacks to connect to a variety of airline audio sources.

1/4-inch stereo phone adapter
Convert headphone plug to the jacks used on home stereo equipment.

5-foot extension cord
An additional five-foot cable allows freedom of movement and increased accessibility to audio sources.

Portable carry case
This sleek, compact case allows you to protect your headphones and store your accessories easily and safely.

LightSPEED Aviation Thirty 3G

Building on the success of the LightSPEED "XL" series of Active Noise Reduction headsets, the third generation or "3G" Series is comparable or improved in almost every feature area, keeping LightSPEED a step ahead of the competition.

The "Twenty 3G" and "Thirty 3G" replace the 20XL and 25XL, the most popular models in LightSPEED's second generation "XL" series.

Thanks to the ANR power and long-battery life, combined with an ultra-competitive price, the 20XL was [sitename]'s most popular ANR headset ever.

How does the 3G compare to the XL Series in other areas of headset performance?
The ANR performance is better than its XL counterpart in portions of the noise spectrum…deeper and broader quieting. A nominal improvement in passive attenuation comes from a new leather ear seal system.

- Thirty 3G offers 28-30dB active noise reduction.
- Twenty 3G offers 24-26dB active noise reduction.

The new battery box still delivers exceptional battery life of at least 50 hours) from two AA-sized batteries with a green-to-red blinking indicator for low battery condition. Auto shut-off, dual volume controls, stereo/mono capability, and a three year warranty combine to make this <16 oz. headset a nice improvement over our popular XL series.

New features built into the 3G series that will provide exciting benefits for a broad range of pilots:

- Adjustable side tone equalization...adjusts the way the audio sounds best to you by boosting the treble or bass signal. Key advantages: (1) Clear/obvious improvement in intelligibility for those with a hearing loss. (2) Improved bass response for those listening to music.

- Personal audio interface...allowing multiple auxiliary sources with the 3G Series. A single interface to support either a cell phone or music source. Key advantages: (1) Pilot can plug in and operate his cell phone while wearing his headset (note: cell phones must ONLY be used on the ground). (2) Pilots, and/or their passengers can plug in their own stereo music source (CD or tape) and enjoy music while flying.
- User switch to control either mute/non-muting of the auxiliary audio signal.
- Cables included with 3G Series for both interfaces:
  --3.5mm to 3.5mm for stereo interface
  --2.5mm to 3.5mm for cell phone (note: not all cell phones use this plug and not all cell phones will work with this interface)

Applying advanced ergonomic research with the latest active noise cancellation technology, the 3G headsets continue to have LightSPEED's standard quality features:

- Triangular shaped domes (just like your ears).
- Left and right domes for optimal fit.
- 1-1/2" thick FoamSeals conform around each ear with minimal side pressure.
- Headband with extra-large surface area and 1" foam cushioning to distribute the 16 oz. (.45 Kg) headset weight evenly.
- Adjusts small enough to fit most women and children.
- 3-year parts and labor warranty from manufacturer.

General Data

- **Connector:** .250" stereo plug, .206 stereo microphone plug
- **Power Supply:** Small In-Line with Left and Right Ear Level Control, Stereo/Mono Switch, Powered by Two AA Batteries
- **Battery Fuel Gauge:** Three color LED for High/Medium/Low Battery Status
- **Operating Time:** Over 50 hours
- **Weight:** 15 oz.

Headphone Data

- **Transducer:** Dynamic, Selective Frequency Amplified for Enhanced Speech Intelligibility
- **Frequency Response:** 20-30,000 Hz
- **Nominal Impedance:** 120 ohms Stereo, 60 ohms Mono

Microphone Data

- **Transducer Principle:** Noise canceling electret
- **Frequency Response:** 200-5000 Hz
- **Maximum SPL:** 114 dB
- **Terminating Impedance:** 470 ohms
- **Operating Voltage:** 8-16V DC Appx 5-12mA

Sennheiser HDC 451 NoiseGard™

The HDC 451-1 NoiseGard™ mobile are open stereo headphones with active noise compensation for mobile applications.
Features
 Reduction of ambient noise by up to 10 dB
 Protects the hearing and reduces stress
 Lightweight and comfortable to wear
 Considerably improves audio reproduction quality in noisy environments
 Powered via 2 AA size alkaline batteries or environmentally friendly NiCd rechargeable batteries
 Delivery includes: 1 HDC 451 NoiseGard™ mobile
 2-year guarantee
Delivery Includes
 1 HDC 451-1 NoiseGard™ mobile
 1 adaptor to ¼" (6.3 mm) stereo jack plug
 1 adaptor 2xmono

Technical Data
 Transducer principle dynamic, open
 Ear coupling supraaural
 Nominal impedance 250 Ohm
 Input voltage range 387 mV (1 Pa, 94 dB)
 Max. Sound pressure level (aktiv) 100 dB linear
 Operating voltage (mains) 2 x 1,5 V
 Contact pressure ca. 1,6 N

Weight w/o cable ca. 110 g
Connection cable 2 m
Jack plug 3,5 mm stereo
Power supply 2 x 1,5 V (AA) Alkali- Mangan-Batterien oder 2 x 1,2 V Akkus Mignon (AA) 600 mAh
Operating time ca. 80 h (Batterie) ; ca. 20 h (Akku)
Noise compensation (active) 10 dB ± 3 dB
Frequency response (headphones) 20.....18000 Hz
THD, total harmonic distortion < 1 %

Sennheiser HMEC 300 NoiseGard™

Featuring NoiseGard active noise compensation and excellent passive attenuation, the HMEC 300 pilot's headset is an ideal choice for helicopters, propeller and turboprop aircraft.

Features

Constant attenuation of up to 40 dB throughout the entire audio range
Advanced transducer design ensures excellent speech intelligibility
Electronics fully integrated into headphone capsules
Can be used as conventional headphones when supply voltage is switched off
Noise-compensated boom microphone for superior speech transmission

Delivery Includes

1 HMEC 300 NoiseGard™
1 x 3-pin input socket for aircraft's internal power supply
1 carrying case for headset and accessories
1 MZQ 2002-1 cable clip
1 MZW 45 windshield

Technical Data

Transducer principle (Headphones) dynamic
Ear coupling circumaural
Nominal impedance (active/passive) 300/150 Ohm-mono, 600/300 Ohm-stereo
Attenuation (active + passive) > 25 - 40 dB
Contact pressure ca. 10 N
Weight w/o cable 370 g
Transducer principle (Microphone) Electret - MKE 45-1
Max. Sound pressure level (aktiv) 120 dB

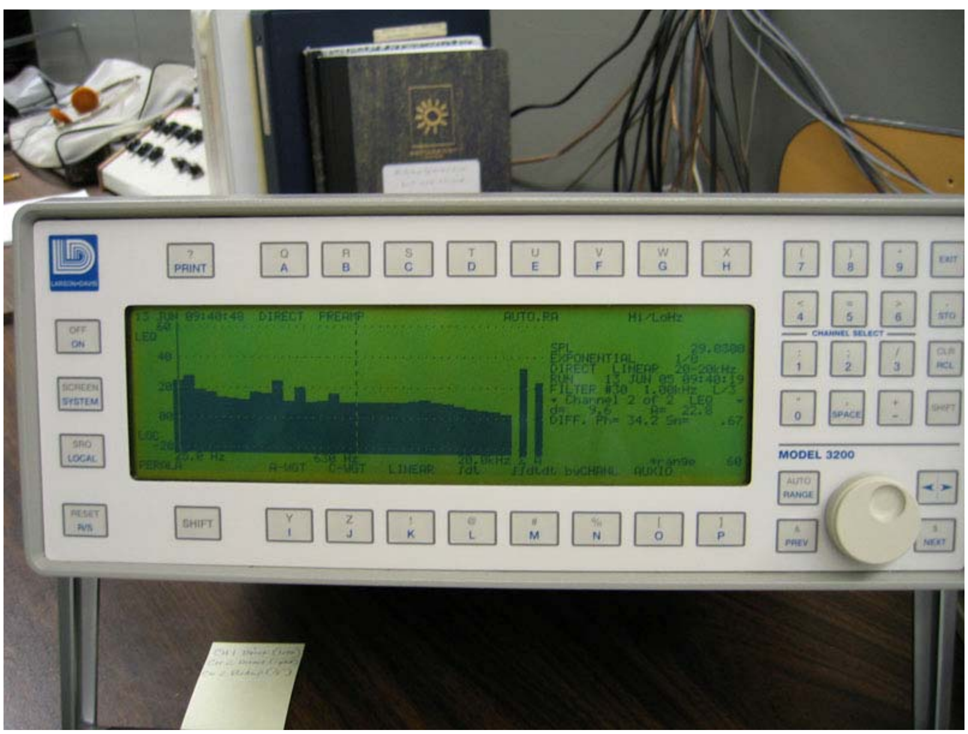
Output voltage 400 mV +/- 3 dB / 114 dB/SPL
Operating voltage (stand alone) typ. 16 VDC (8-16 VDC, 8-25 mA)
Operating temperature -10 °C...+55 °C
Storage temperature -55 °C...+55 °C
NoiseGard-Supply 12 - 35 VDC, ca. 27 mA, max. 80 mA
Specials NoiseGard on/off & mono/stereo switch
Connection cable 1.5 m
Connector 6.3 mm stereo-headphones, PJ-068-microphone, XLR-3 NoiseGard power, volume control for headphones
Frequency response (headphones) 45.....15000 Hz
Frequency response (microphone)

APPENDIX B – Comfort and Acceptability Rating Scale

For actual questionnaire, please refer to (Casali, Lam, & Epps, 1987)

APPENDIX C – Photographs of Experimental Environment and Apparatus

Experimenter's Station with NE828 (under table), LD3200, and IBM PC.

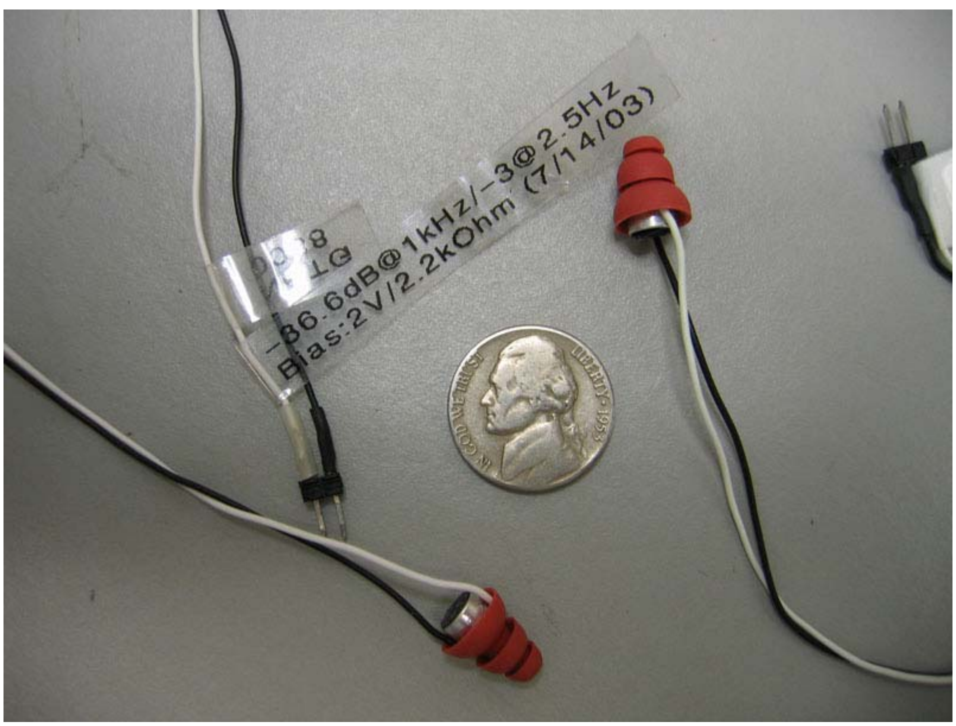


Front view of the LD3200 Real-Time Spectrum Analyzer used for MIRE testing.

Adding pin-connectors to the miniature microphone wires.

Deep probe tube microphone with probe tube attached and extra probe tubes.

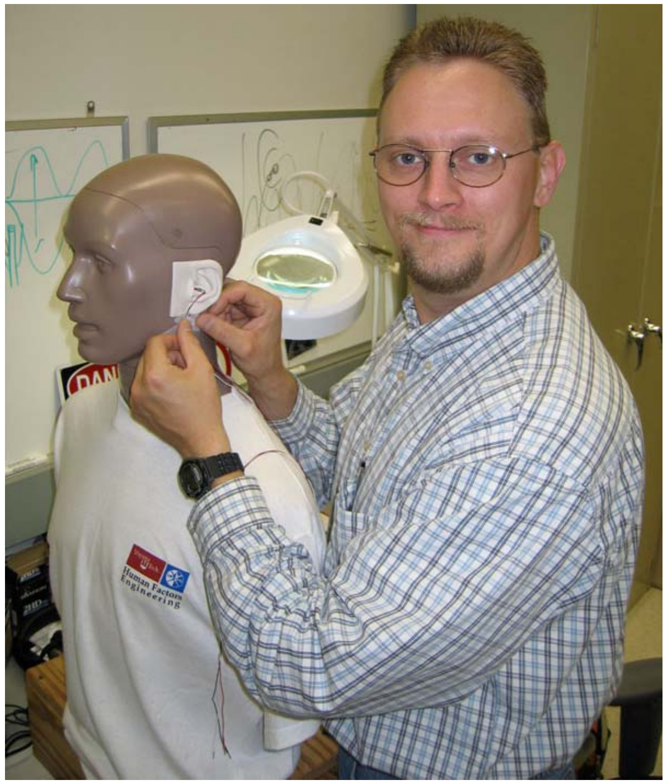
VT-ASL Electronics workbench.



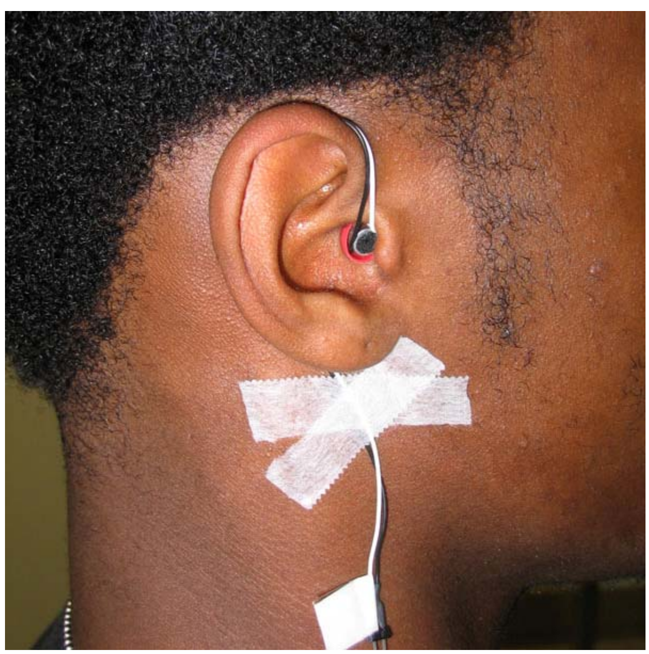
In ear canal-shallow microphones mounted on AEARO Ultrafit™ swim earplugs.

Pre-testing in-concha microphone (left) and shallow microphones (right) with and without sample headset on ATF manikin.

View of ATF manikin on video monitor and inside reverberant chamber.

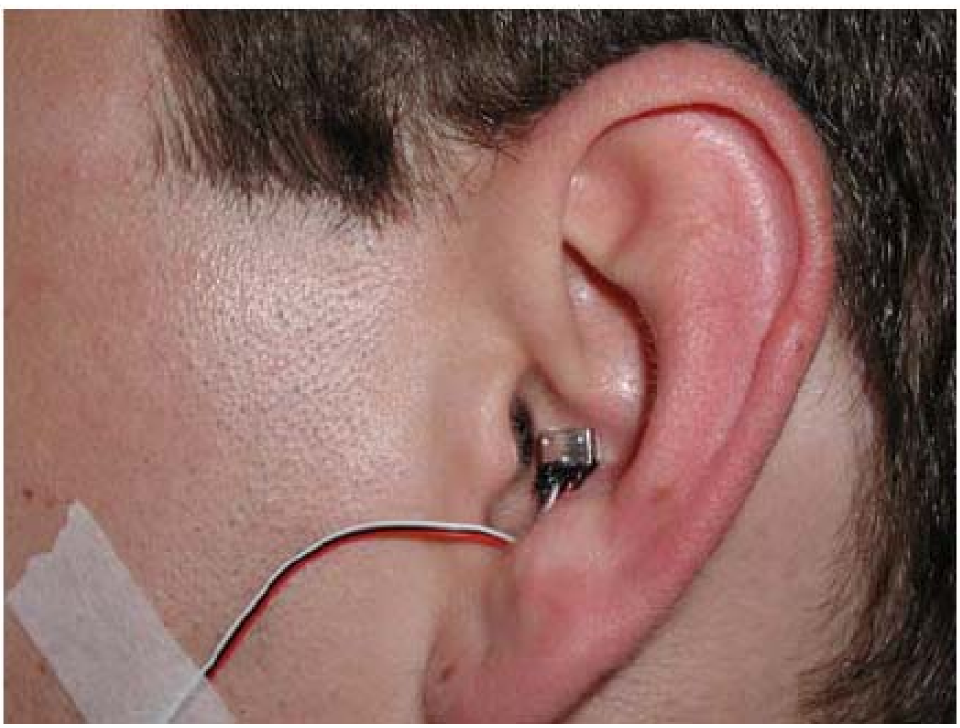


Pre-testing microphone fit and function using artificial test fixture (ATF) manikin.



Shallow microphone (right ear) in proper testing configuration. Left ear microphone configured the same.

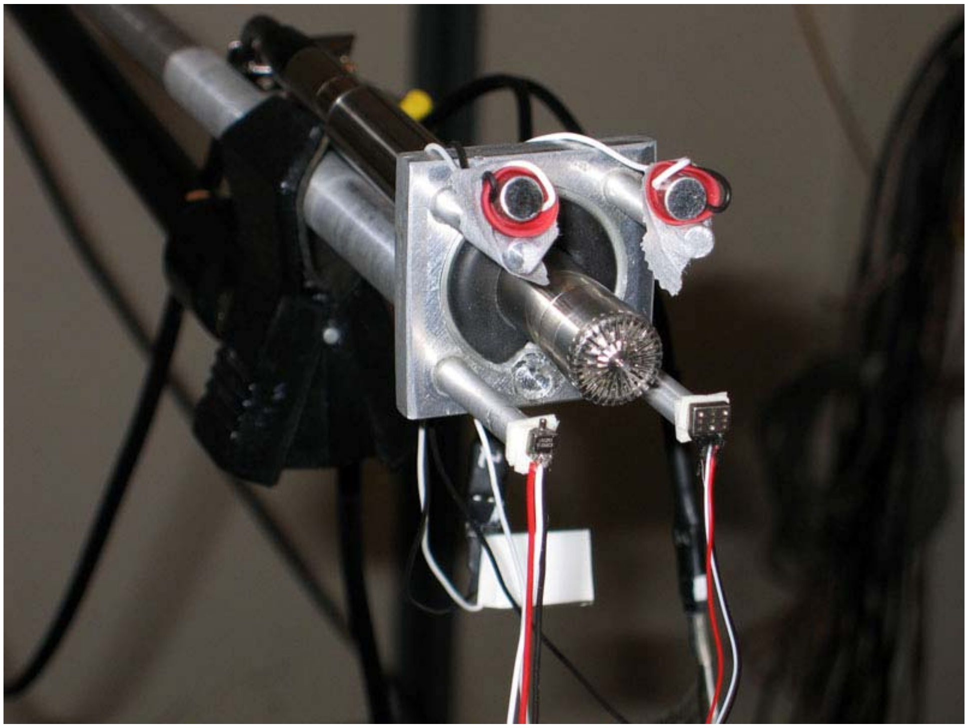
Deep microphone (left ear only) in proper testing configuration.



Concha microphone (left ear only) in proper testing configuration.

INSPEC earmuff headband force measurement apparatus.

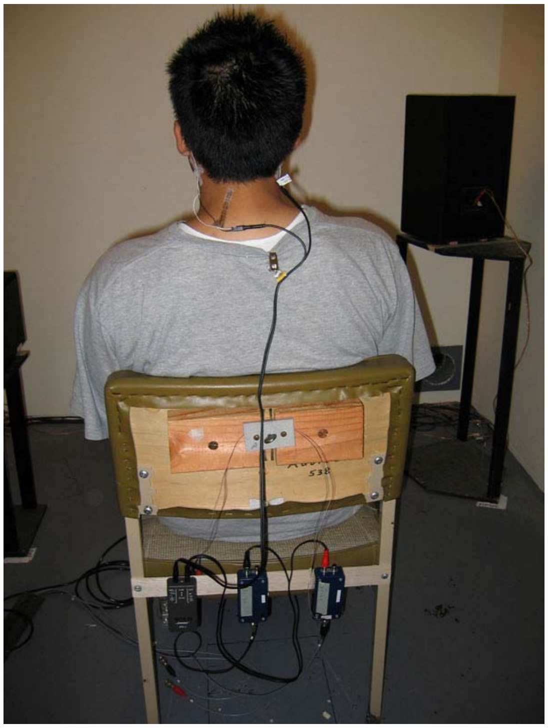
Setting up miniature microphone calibration test fixture centered inside reverberant chamber.



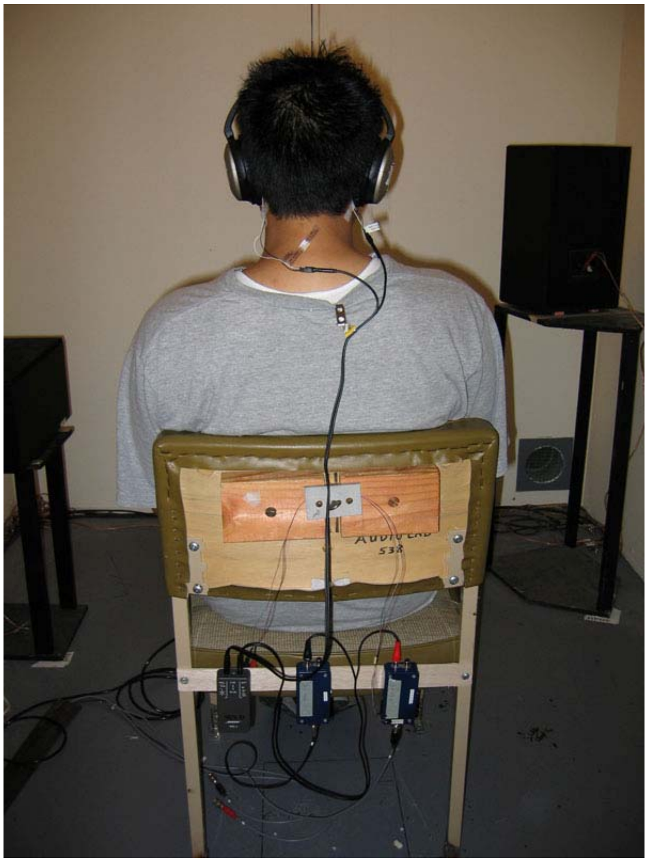
Close-up of miniature microphone calibration test fixture.

Screenshot of NE828 Headphone testing system during REAT test.

Performing an audiometric evaluation (hearing threshold test) during participant screening phase.



Participant fitted with shallow microphones sitting in reverberant chamber.



Participant fitted with shallow microphones and sample headphone sitting in reverberant chamber.

APPENDIX D – IRB Request for Approval of Research Proposal

PROTOCOL DESCRIPTION
Evaluation of the Attenuation Afforded by Passive and Active Hearing Protection Devices Using Procedures Standardized by ANSI S3.19-1974, ANSI S12.6-1984/1997, ANSI S12.42-1995, ISO 4869-1: 1990, and MIL-STD-912

Submitted by:

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The purpose of the hearing protector tests described herein is to evaluate the passive and/or active noise reduction (i.e., protective capability) afforded by hearing protection devices (HPDs). Although it is possible to test the attenuation characteristics of headphones using acoustical test fixtures, such measurements do not account for the fitting differences among humans, the compliance of human flesh, human variability, and to some extent, acoustical properties of the human head. Therefore, standardized procedures have been developed to test headphones using human subjects. These Standards include: ANSI S3.19-1974, *American National Standard Method for the Measurement of Real-Ear Protection of Hearing Protectors and Physical Protection of Earmuffs*, ANSI S12.6-1997, *Methods for Measuring the Real-Ear Attenuation of Hearing Protectors*, ISO 4869-1: 1990, *Acoustics–Hearing Protectors–Part 1: Subjective Method for the Measurement of Sound Attenuation*, MIL-STD-912, *Physical Ear Noise Attenuation Testing*, and ANSI S12.42-1995, *Microphone-in-Real-Ear and Acoustic Test Fixture Methods for the Measurement of Insertion Loss of Circumaural Hearing Protection Devices*. There is also a Canadian standard, Z94.2-02 (July 2002), *Hearing Protection Devices—Performance, Selection, Care, and Use*, and that standard relies on the use of either ANSI S3.19-1974 or ANSI S12.6-1997 (ANSI, 1997).

The noise reduction characteristics of *passive* hearing protectors and the *passive* performance of active noise reduction (ANR) devices can be measured using real-ear attenuation at threshold (REAT) techniques such as those outlined in ANSI S3.19 or S12.6. [ANSI S3.19 is required by the EPA (1990) for use in obtaining attenuation data for product labeling purposes.] These methods take into account the psycho-physiological factors that influence passive hearing protector attenuation, including the bone and tissue conduction of sound that acts as a flanking path around the headphone. These procedures are equally applicable to all types of hearing protection devices including earplugs (custom-molded, user-molded, and premolded), semi-aural canal caps, circumaural earmuffs, and helmet or cap-mounted devices.

There are currently no ISO or ANSI consensus attenuation testing Standards which specifically address the testing of ANR-based hearing protectors. Dr. Casali has been active in the Standards Working Groups which have attacked this problem, and has also been asked by the EPA to provide input to the testing/labeling needs, but a testing standard has not been finalized. However, existing standard procedures can be adapted to evaluate the performance of such devices.

As mentioned above, the passive attenuation of an ANR device, measured with the ANR circuitry turned off, can be evaluated using REAT procedures. However, as detailed in Casali and Robinson, *NCEJ* (1994), REAT methods are contaminated by and are inaccurate for measuring the *active* component of attenuation and therefore, the total attenuation. To properly characterize the full attenuation properties of ANR devices, objective techniques, using microphone/analyzer measurements, are also needed. For the active and total attenuation measurements, the most defensible method is to use the human head as a fixture (rather than as a listener), with miniature microphones mounted in each pinna to measure the attenuation provided by the headphone. These techniques have been used extensively in the Auditory Systems Laboratory by Casali, Mauney, and Burks (1993) and Casali and Robinson (1994). This is referred to as "physical ear" or "microphone in real-ear" (MIRE) testing. ANSI S12.42-1995 details the procedure for this MIRE method, and although it is not specifically directed toward ANR device assessment, it is the most appropriate Standard now in existence. These MIRE measurements obtained under this standard entail the total (active + passive) attenuation and the passive attenuation. The difference between these two MIRE measurements constitutes the active attenuation component of the ANR device. Furthermore, in some applications, MIRE measurements are useful for measuring the attenuation of passive, conventional headphones as well as ANR electronic devices, and the protocol described herein supports that usage.

Screening Requirements and Procedures

A typical test will require from 10 to 20 participants (depending on the specific standard in use), recruited from the general population of the Virginia Tech/Blacksburg communities using flyers and word-of-mouth. A gender mix of at least 7/3 is typically required for all tests. Participants must be at least 18 years of age, have no obvious injury or infection of the ears, and have hearing thresholds no greater than 25 dBHL from 125 to 8000 Hz. (Specific hearing level requirements will vary depending upon the requirements of each test standard and the purpose of the particular research project.) Participants must also demonstrate the ability to track their open-ear auditory threshold at the 1/3 octave-bands (OB) centered at 125 to 8000 Hz over a minimum of 5 trials with a trial-to-trial variability on the last three trials of no more than 5-6 dB (dependent upon the test standard being followed). Finally, prospective subjects for whom a visually apparent quality fit of the device being tested cannot be achieved or who have hair length that is incompatible with the device will be dismissed.

Each test will require participants to attend a screening session that will last approximately 1 to 1-1/2 hours and one or more experimental sessions lasting approximately one hour each. All screening and experimental sessions will be conducted in the Auditory Systems Laboratory, Room 538 Whittemore Hall on the Virginia Tech campus. Participants will be paid at least at a rate of $8 per hour for the time spent in the laboratory. (This rate may be increased as labor rates increase.)

At the beginning of the screening session, the prospective participant will be given a verbal description of the experiment and a copy of the attached Informed Consent Form. This consent form gives a detailed explanation of the procedures to be used in the experiment. If the participant chooses to take part in the study, the experimenter will determine if the participant's physical auditory health is sufficient to participate in the experiment by asking the participant the questions shown in the Self Report Data section on the second page of the attached Screening Form. The experimenter will also perform a visual examination of the participant's external ear and ear canal using an otoscope (a light source with an attached magnifier) and record his/her observations in the Otoscopic Data section of the Screening Form.

The experimenter will then administer a pure-tone audiogram using a Beltone clinical pure-tone audiometer to determine if the participant meets the hearing level requirements of the standard being used for testing. The results of the audiogram will be recorded on the first page of the Screening Form. The participant may examine the data if he/she wishes. In conducting the audiogram, the experimenter will fit a set of headphones on the participant and then present very quiet pulsed pure tones to the participant through the headphones to determine the participant's auditory threshold. The participant will indicate that he/she hears the tones by pressing a silent push button on a hand-held response switch. The tones presented to the participant during the audiogram are at or below the participant's auditory threshold and pose no risk to the participant's hearing.

Occasionally, it may also be necessary to conduct a bone-conduction audiogram in addition to the air-conduction audiogram described above. The procedures are identical in both cases with the exception that instead of headphones, a vibration transducer is placed against either the mastoid bone behind the ear or on the forehead. The participant will still hear a tone just like that presented in the air-conduction test. Again, the tones presented to the participant during the bone-conduction audiogram are at or below the participant's auditory threshold and pose no risk to the participant's hearing.

The participant will be in a sound-isolated test booth while the audiogram is being obtained. The experimenter will be sitting outside the booth. The door to the test booth will be closed, but not locked. For the participant's safety, the door can be easily opened from the inside. The test booth is also instrumented with a closed-circuit television system that allows the experimenter to visually monitor the participant at all times. A two-way intercom system is also present that allows the participant to speak to the experimenter at any time without the necessity of pressing a switch. The participant is made aware of these features in the Informed Consent Form. Participants who do not meet the hearing level requirements will be thanked for their time and released without compensation.

Those participants that do qualify and choose to continue will be asked to re-enter the test booth for further testing. In this second screening test, the variability of the participant's threshold-tracking ability will be tested. Instead of presenting pure-tones to the participant through a pair of earphones, third-octave bands of noise are presented to the participant via loudspeakers located in the test booth. Again, the participant will indicate that he/she hears the test signal by pressing a silent pushbutton on a hand-held response switch. Between 5 and 10 thresholds will be obtained in this manner. Again, the test signals will be at or below the participant's auditory threshold and pose no risk to the participant's hearing. Those participants that meet the threshold variability requirements (typically no more than a 5 or 6 dB range at any frequency across the last three trials) will be accepted into the study, paid at a rate of at least $8.00 per hour for their time and scheduled for their first experimental session. Those individuals who do not meet the variability requirements will be thanked for their time and compensated at the same minimum $8.00 per hour rate as the other participants.

Real-Ear at Threshold Protocol

REAT trials are very much like the last part of the screening session described above in that third-octave bands of noise will be presented to the participant through the loudspeakers located in the test booth. A total of four to six trials will be conducted, depending upon the specific test standard being followed. Half of the trials will be conducted with the participant wearing the headphone (the occluded condition) and half of trials will be conducted while the participant is not wearing the headphone (the unoccluded condition). The participant will indicate that he/she hears the test signal by pressing a silent pushbutton on a hand-held response switch. As before, the test signals will be at or below the participant's auditory threshold and will pose no harm to the participant's hearing. These experimental sessions will last approximately one hour.

Protocol for Obtaining Ear Impressions for Custom-Molded Earplugs

Occasionally, the need arises to obtain ear impressions of volunteer participants for the purposes of making and testing custom-molded earplugs. Unlike standard headphones, which are designed to fit a wide range of the user population, custom-molded earplugs are made specifically to fit one individual. When testing such devices, it is necessary to obtain impressions of the participants' ears so that the devices can be manufactured prior to testing. The materials used to obtain these impressions are non-toxic, silicone-based compounds approved by the FDA for use on human skin. Although many materials are available for such purposes, the two compounds with which the Auditory Systems Laboratory has experience are Ply-O-Life, manufactured by Pink House Studios, and Equa-Sil, manufactured by Emtech Laboratories, Inc. Product descriptions and material safety data sheets for these two products are attached. These and similar materials are routinely used by audiologists and hearing-aid manufacturers to obtain impressions of patients' ears preparatory to the manufacture of custom-molded hearing aids and earplugs. IRB approval, at the not more than minimal risk level, has previously been received for use of the Ply-O-Life compound and the procedures described below (ref. IRB 93-104, Ear Data Gathering Experiment). Typical procedures used in obtaining impressions are as follows.

Before making the ear impressions, the subject's sensitivity to the material used will be ascertained by placing a small amount of the material on the palmar side of the subject's wrist. If a reaction is evident, the subject will be paid for his/her time and dismissed. If no reaction is evident, the subject is asked to lay his/her head on a foam pad or pillow placed on a table so that his/her head is roughly horizontal. A small piece of foam or cotton, with a string attached, is then inserted into the subject's ear canal about half the distance from the ear canal's outer opening to the eardrum with the string extending out of the ear. This foam dam will prevent any of the material used to form the impression from reaching the subject's eardrum. After the eardam has been inserted, the non-toxic, two-part, silicone-based impression material is mixed and used to fill the subject's outer ear canal and concha. The material is injected into the ear with a large syringe. After the material has hardened sufficiently, the participant is allowed to lift his/her head from the table. After allowing sufficient time for the molding compound to cure completely, the impression is carefully removed from the ear. The procedure is then repeated for the other ear**.**

Microphone-in-Real-Ear Protocol

MIRE sessions involve the direct measurement of the noise levels reaching the participant's outer ears using miniature microphones. For MIRE measurements, there are three techniques for positioning and placement of a miniature microphone: 1) in the concha (hereafter, “concha”), 2) at the entrance of the ear canal, (hereafter, “canal entrance”) and 3) in the ear canal using probe tube microphone (hereafter, “canal probe”). For *concha* microphone positioning and placement, the experimenter will first fit a foam or other soft earplug in the participant's ear canals and then secure a miniature microphone (e.g., Knowles EK-3132) to the floor of the concha using double-sided foam tape. For the *canal entrance* position and placement, the experimenter will insert a small soft earplug, which has a miniature microphone within its exterior plane (as an integral part of its structure), into the ear canal and approximately flush with its entrance. For the *canal probe* position and placement, the experimenter will connect a miniature microphone (e.g., Knowles FG-3652) to a length of soft, flexible, hearing aid tubing, the end of which will be placed into the ear canal but not touching the tympanic membrane (eardrum). The insertion of the probe tube in this method is akin to deeply fitting an earplug into the ear, and does not pose a known risk to the subject. The microphone of the probe tube is located at the outer end of the tube (i.e., outside the ear canal), and only the hearing aid tubing is in the ear canal. For all three MIRE positions, after microphone placement, a small piece of paper first-aid tape will be used to secure the thin (28/30-gauge) wire leads of the microphone to the participant's cheeks and shoulders. This will prevent normal head and body movement from loosening the microphone during the course of the experiment. After the participant enters the test booth, the experimenter will attach the microphone leads to the appropriate cables. In all 3 MIRE techniques, the subject’s skin is not in contact with any bare wires or terminals, as these are insulated with plastic sheathing.

The procedures for the MIRE part of the experiment differ from the REAT procedures described earlier in that the participant is not required to respond to any signals. Since the microphones directly measure the sound levels reaching the outer ear, the participant need only be as still and quiet as possible while sitting in the test booth. Up to nine noise-level measurements will be made during a typical session. Three of these measurements will be made while the ANR headphone is not worn (the unoccluded condition); the other six measurements will be made while the ANR headphone is worn (the occluded conditions). Of the six occluded measurements, three will be made with the ANR electronics turned off (the passive state) and three will be made with the ANR electronics turned on (the active state). The test signal for these measurements will be a broadband pink noise (flat by octaves) or white noise (flat by Hz) presented at a level no greater than 100 dBA. Each of the nine measurements will take no more than 60 seconds.

Although the 100 dBA level used in MIRE tests is loud, it is necessary to determine the active noise reduction characteristics of some ANR headphones which are in need of testing. Furthermore, it may be needed for testing particularly effective passive headphones or headphones worn in combination, such as an earmuff over an earplug. The Occupational Safety and Health Administration (OSHA) allows industrial workers in the U.S. to be exposed to continuous 100 dBA noise for two hours every day without wearing hearing protectors. The maximum total exposure time to the noise in this experiment will be less than 10 minutes (i.e., less than 9% of the exposure time allowed per day by OSHA). IRB approval at the *"not more than minimal risk level"* has previously been received for the majority of the procedures described above (ref. IRB 96-024, Evaluation of the Active and Passive Modes of Operation of a Circumaural, Active Noise Reduction headphone Using ANSI S12.42-1995 MIRE and ANSI S3.19-1974 REAT Methods), and the passages which are underlined herein represent the protocol changes from those prior IRB applications.

Each experimental participant will be paid at a minimum rate of $8.00 per hour for the time spent in the laboratory.

The hearing tests described herein are believed to pose no risk to the participant's health or well-being. However, since all hearing protectors are intended to provide a snug fit so that noise will be blocked, the test participants may experience some minor discomfort as a result of the tight fit, but the protectors will not harm them in any way. Furthermore, in the MIRE conditions which do not use an earplug to hold the microphone, the pink or white noise may seem loud to the subject; however, as mentioned above, the actual noise exposure time at this level is less than 10% of the time allowed by OSHA in industry. These issues are brought to the attention of potential subjects in the Informed Consent Form attached herewith.

Experimental participants will be identified by name only on their screening and Informed Consent forms. These forms will be kept in the Auditory Systems Laboratory and only authorized Laboratory personnel will have access to this information. Experimental data will identify subjects only by number (1 through 10), age and gender. No record linking a particular subject to his or her data will be kept after the tests have been completed.

APPENDIX E – Informed Consent for Participants of Investigative Projects

VIRGINIA POLYTECHNIC INSTITUTE AND STATE UNIVERSITY
DEPARTMENT OF INDUSTRIAL AND SYSTEMS ENGINEERING (ISE)
AUDITORY SYSTEMS LABORATORY

Informed Consent for Participants of Investigative Projects

Title of Project: Hearing Protector Attenuation Test

Principal Investigators: Chuck H. Perala, Research Experimenter, ISE
Dr. J. G. Casali, Grado Professor, ISE
Dr. J. A. Lancaster, Research Assistant Professor, ISE

Faculty Advisor: Same as above.

I. THE PURPOSE OF THIS RESEARCH

You are invited to participate in a research study aimed at determining the noise reduction characteristics of a hearing protection device (HPD). In order to measure the passive performance of the device, it will be necessary to measure your hearing ability (auditory threshold) in two conditions: 1) while wearing the headphone, and 2) while your ears are uncovered. If the device being tested is an active noise reduction (ANR) design, an additional session will be required in which miniature microphones will be placed in your ears to directly measure the sound levels reaching your ears in the same two conditions (while wearing the device and while your ears are uncovered). A total of 10 to 20 individuals (both males and females) are being recruited for this study with separate experimental sessions scheduled for each participant.

II. PROCEDURES

The procedures to be used in this research are as follows. If you wish to become a participant after reading the description of the study, then sign this form. First, you will be screened to determine if you qualify for the experiment. Screening will consist of a hearing test and several assessment tests. To begin with, you will be asked several questions to assess the general health and condition of your ears. Then you will be given an examination in which the experimenter will look into your ears using an otoscope to determine the condition of your ears. Next, your right and left ear hearing will be tested with very quiet tones played through a set of headphones. You will have to be very attentive and listen carefully for these tones. **Depress the button on the hand-held switch and hold it down whenever you hear the pulsed-tones and release it when you do not hear the tones.** The tones will be very faint and you will have to listen carefully to hear them. No loud or harmful sounds will be presented over the headphones.

It may also be necessary to obtain a bone-conduction threshold in addition to the air-conduction threshold described above. The procedures and your responses will be identical to those described above. The only difference between the two tests are that instead of wearing headphones, you will be wearing a small vibration transducer placed against the mastoid bone behind your ear or against your forehead. You will hear the same tones you heard during the air-conduction audiogram and you are asked to respond in exactly the same manner. Again, the tones will be very faint and you will have to listen carefully to hear them; no loud or harmful sounds will be presented during this test.

Next, the variability of your open-ear threshold will be determined. For this test, the test signals will be third-octave bands of noise rather than tones and they will be presented over loudspeakers located in the test booth instead of over headphones. Again, you will have to be very attentive and listen carefully for the test signals. **Depress the button on the hand-held switch and hold it down whenever you hear the pulsed test signals and release it when you do not hear the signals.** The test signals will be very faint and you will have to listen carefully to hear them. No loud or harmful sounds will be presented. As many as 10 trials may be conducted with each trial taking from three to five minutes. You may request a break at any time between trials.

If you qualify and choose to continue, you will be asked to participate in one or more experimental sessions. If the device to be tested is of the passive variety, the procedures for the experimental sessions will be similar to those used in the second part of the screening session. You will be asked to listen for the pulsing sounds presented over the loudspeakers located in the test booth. However, in these sessions, half of the threshold measurements will be made while you are wearing the headphone. Remember, you will have to be very attentive and listen carefully for the test signals. **Depress the button on the hand-held switch and hold it down whenever you hear the pulsed test signals and release it when you do not hear the signals.** The test signals will be very faint and you will have to listen carefully to hear them. No loud or harmful sounds will be presented. As before, you will have the opportunity to take rest breaks between trials.

The purpose of this experiment is to test the noise reduction capabilities of hearing protection devices (HPDs). You will be fit with a headphone in one of the following manners:

[ ] The headphones will be fit and adjusted by the experimenter.

[ ] You will be asked to fit the device yourself, but the experimenter will provide instruction and guidance (both verbal and physical) in properly fitting the device.

[ ] You will be asked to fit the device yourself following the written instructions provided by the device manufacturer, but the experimenter cannot provide you with any assistance.

<u>If the test method is one using miniature microphones for measurement, then we will be testing either a headphone of the electronic active noise reduction (ANR) variety, or perhaps just a standard passive headphone. For these tests, the protocol will be as follows. The first session will be conducted exactly as described above. For this session, the device's ANR electronics will be turned off so that its passive attenuation characteristics can be determined (or in the case of a passive headphone, the passive attenuation test will be done as described above). The second experimental session will involve direct measurement of the noise levels reaching your ears using miniature microphones. For MIRE measurements, there are three techniques for positioning and placement of a miniature microphone: 1) in the concha (hereafter, "concha"), 2) at the entrance of the ear canal, (hereafter, "canal entrance") and 3) in the ear canal using probe tube microphone (hereafter, "canal probe"). For *concha* microphone positioning and</u>

placement, the experimenter will first fit a foam or other soft earplug in your ear canals and then secure a miniature microphone) to the floor of the concha using double-sided foam tape. For the *canal entrance* position and placement, the experimenter will insert a small soft earplug, which holds a miniature microphone, into the outer portion of your ear canals. For the *canal probe* position and placement, the experimenter will connect a miniature microphone to a length of soft, flexible, hearing aid tubing, the end of which will be placed into your ear canal but not touching the tympanic membrane (eardrum). The insertion of the probe tube in this method is similar to deeply fitting an earplug into your ear, and does not pose a known risk to you. The microphone of the probe tube is located at the outer end of the tube (i.e., outside your ear canal), and only the hearing aid tubing will be in your ear canal. For all three MIRE positions, after microphone placement, a small piece of paper first-aid tape will be used to secure the thin wire leads of the microphone to your cheeks and/or shoulders. This will prevent normal head and body movement from loosening the microphone during the course of the experiment. After you enter the test booth, the experimenter will attach the microphone leads to the appropriate cables. In all 3 MIRE techniques, your skin will not be in contact with any bare wires or terminals, as these are insulated with plastic sheathing.

The procedures for this part of the experiment differ from those in the previous session in that you are not required to respond to any signals. Since the microphones will directly measure the sound levels reaching your outer ears, you need only be as still and as quiet as possible while sitting in the test booth. Nine noise level measurements will be made during this session. In the case of testing an ANR headphone, three of these measurements will be made while the ANR headphone is not worn (the unoccluded condition); the other six measurements will be made while the ANR headphone is worn (the occluded conditions). Of the six occluded measurements, three will be made with the ANR electronics turned off (the passive state) and three will be made with the ANR electronics turned on (the active state). The test signal for these measurements will be a broadband pink or white noise at a level of 100 dBA. Each of the nine measurements will take no more than 60 seconds. As before, you will be able to take rest breaks between measurements.

Occasionally, the need arises to test custom-molded earplugs. Unlike standard headphones, which are designed to fit a wide range of people, custom-molded earplugs are made to fit one specific individual. Therefore, when testing such devices it is necessary to obtain an impression of each of your ears so that the devices can be manufactured prior to testing. The materials used to obtain these ear impressions are non-toxic and approved by the FDA for use on human skin. A description of the product and the material safety data sheets are available for your inspection if so desired. The materials will not harm you in any way. The general procedures used in obtaining these impressions are as follows.

Before making the ear impressions, your sensitivity to the molding material will be ascertained by placing a small amount of the material on your wrist. If a reaction is evident, you will be paid for your time and no earmold will be made. If no reaction is evident, you will be asked to lay your head on the foam pad or pillow on the table so that your head is roughly horizontal. A small piece of foam or cotton, with a string attached, will then be inserted into your ear canal with the string extending out of the ear. This foam dam will prevent any of the material used to form the impression from reaching your eardrum. After the eardam has been inserted, the molding compound will be mixed and injected into your outer ear canal and concha using a large syringe. Once the material has hardened sufficiently, you will be asked to lift your head from the table. After allowing sufficient time for the molding compound to cure completely, the impression will be carefully removed from your ear by the experimenter. The procedure is then repeated for the other ear. These procedures will not harm you in any way. Similar materials and procedures are routinely used by audiologists and hearing-aid manufacturers to obtain impressions of patients' ears preparatory to the manufacture of custom-molded hearing aids and earplugs.

III. RISKS

The Occupational Safety and Health Administration (OSHA) allows industrial workers in the U.S. to be exposed to continuous 100 dBA noise for two hours every day without wearing hearing protectors. The maximum total exposure time to the noise in this experiment without hearing protectors will be less than 10 minutes (that is, less than 10% of the exposure time allowed per day by OSHA), and 100 dBA is the maximum noise level that will be used.

All of the tests described above will be conducted in a soundproof booth with the experimenter sitting outside. The door to the booth will be shut but not locked; either you may open it from the inside or the experimenter may open it from the outside. There is also an intercom system through which you may communicate with the experimenter by simply talking. (There are no buttons to push.)

There is no known risk to your well-being posed by the hearing tests involved in this research or health assessments. Also, realize that they are not designed to assess or diagnose any physiological or anatomical hearing disorders. The assessments and tests will only be used to determine your ability to participate in the experiment.

The purpose of this experiment is to test the noise reduction capabilities of hearing protection devices (HPDs). Unless the experiment calls for a subject-fit condition, the headphones will be fit by the experimenter. If you are asked to fit the device yourself, the experimenter will provide instruction and guidance in properly fitting the device. headphones are intended to provide a snug fit so that noise will be blocked. Therefore, they may seem tight in or around your ears. Some minor discomfort may result from the tight fit, but the protectors will not harm you in any way. If earmolds are obtained for the manufacture of custom-molded devices, your ears may feel "full" and the material may feel "rubbery", but the material will not harm your ears or hearing.

Several physical measurements may also be obtained as part of the study. These will include dimensional measurements such as ear and head width, obtained with simple rulers, calipers and an ear gauge. None of the previously mentioned health tests and measurements pose any risk to your well-being or cause any pain. (You should also know that the instruments are sanitized prior to each new participant.) You may ask to see and examine these instruments, the test system, or the safety literature for the molding material at this time if you wish.

IV. BENEFITS OF THIS RESEARCH

Your participation in this experiment will provide information that will be used to develop a rating of how well noise is blocked by the particular hearing protection device tested.

No guarantee of benefits has been made to encourage you to participate. You may also receive a summary of the results of this research when completed. Please leave or send a self-addressed envelope if you are interested in the summary. To avoid biasing other potential participants, you are requested not to discuss the study with anyone until six months from now.

V. EXTENT OF ANONYMITY AND CONFIDENTIALITY

The results of this study will be kept strictly confidential. At no time will the researchers release the results of the study to anyone other than the individuals working on the project without your written consent. The information you provide will have your name removed and only a participant number will identify you during analyses and any written reports of the research.

VI. COMPENSATION

For participation in this experiment, you will receive a minimum of $8.00 for each hour that you participate.

VII. FREEDOM TO WITHDRAW

You are free to withdraw from this study at any time without penalty. If you choose to withdraw, you will be compensated for the portion of time you have spent in the study. There may also be certain circumstances under which the investigator may determine that you should not continue as a participant of this project. These include, but are not limited to, unforeseen health-related difficulties, inability to perform the task, and unforeseen danger to the participant, experimenter, or equipment.

VIII. APPROVAL OF RESEARCH

This research project has been approved, as required, by the Institutional Review Board for projects involving human participants at Virginia Polytechnic Institute and State University, and by the Department of Industrial and Systems Engineering.

IX. PARTICIPANT’S RESPONSIBILITIES

I know of no reason why I cannot participate in this study. I have the following responsibilities:

- To listen attentively to the sounds during the hearing tests and to press and release the button with relative accuracy and to follow instructions to the best of my ability.

- To notify the experimenter at any time about discomfort or desire to discontinue participation.

____
Signature of Participant

X. PARTICIPANT'S PERMISSION

Before you sign the signature page of this form, please make sure that you understand, to your complete satisfaction, the nature of the study and your rights as a participant. If you have any questions, please ask the experimenter at this time. Then if you decide to participate, please sign your name on this page and the following pages.

I have read a description of this study and understand the nature of the research and my rights as a participant. I hereby consent to participate, with the understanding that I may discontinue participation at any time if I choose to do so, being paid only for the portion of the time that I spend in the study.

Signature ________________________________
Printed Name ________________________________
Date ________________________________

The research team for this experiment includes Dr. John G. Casali, Director of the Auditory Systems Laboratory and Dr. Jeff A. Lancaster, Research Assistant Professor. They may be contacted at the following address and phone numbers:

Auditory Systems Laboratory
Room 538 Whittemore Hall
Virginia Tech
Blacksburg, VA 24061

Dr. Casali: (540) 231-5073
Dr. Lancaster: (540) 231-2680

In addition, if you have detailed questions regarding your rights as a participant in University research, you may contact the following individual:

Dr. David Moore
CVM Phase II (0442)
Virginia Tech
Blacksburg, VA 24061
(540) 231-4991

APPENDIX F – Participant Screening Forms

SCREENING FORM
Pure-Tone Audiometric Tests for Normal Hearing

Participant: ________________________________ Age:_____ Sex:_____

Phone:____________________ Screening Date:_________ Qualify?____

Right Ear

Frequency Hz	t-1	t-2	t-3	t-4	t-5	t-6	final threshold
125	_____	_____	_____	_____	_____	_____	_____
250	_____	_____	_____	_____	_____	_____	_____
500	_____	_____	_____	_____	_____	_____	_____
1000	_____	_____	_____	_____	_____	_____	_____
2000	_____	_____	_____	_____	_____	_____	_____
3000	_____	_____	_____	_____	_____	_____	_____
4000	_____	_____	_____	_____	_____	_____	_____
6000	_____	_____	_____	_____	_____	_____	_____
8000	_____	_____	_____	_____	_____	_____	_____

Left Ear

Frequency Hz	t-1	t-2	t-3	t-4	t-5	t-6	final threshold
125	_____	_____	_____	_____	_____	_____	_____
250	_____	_____	_____	_____	_____	_____	_____
500	_____	_____	_____	_____	_____	_____	_____
1000	_____	_____	_____	_____	_____	_____	_____
2000	_____	_____	_____	_____	_____	_____	_____
3000	_____	_____	_____	_____	_____	_____	_____
4000	_____	_____	_____	_____	_____	_____	_____
6000	_____	_____	_____	_____	_____	_____	_____
8000	_____	_____	_____	_____	_____	_____	_____

SCREENING FORM
Anthropometric Data

Ear canal size:	(R) _______	(L) _______
Bitragus breadth:	in _______	cm _______
Head height:	in _______	cm _______
Pinna height (R):	in _______	cm _______
Pinna height (L):	in _______	cm _______
Pinna width (R):	in _______	cm _______
Pinna width (L):	in _______	cm _______

Otoscopic Data

Occluding wax?: ____________________________________

Ear canal irritation?: ____________________________________

Unusual canal characteristics: ____________________________________

Eardrum perforations?: ____________________________________

Eardrum scar tissue? ____________________________________

Foreign matter?: ____________________________________

Tympanogram: ____________________________________

Self-Report Data

Tinnitus or head noises: ____________________________________

Otopathological history: ____________________________________

Occupation: ____________________________________

Noisy hobbies: ____________________________________

Headphone experience: ____________________________________

Other: ____________________________________

EXPERIENCE FORM

Experience with Hearing Protection
Screening Version

a. Have you *ever* received one-on-one personal instruction in the fitting of hearing protectors?	Yes No
b. (1) Within the last two years, have you attended a lecture about how to fit hearing protectors?	Yes No
(2) Within the last two years, have you watched videotaped or computer-based instruction about how to fit hearing protectors?	Yes No
c. Within the last two years, have you participated in an experiment designed to measure hearing protector noise reduction?	Yes No
d. Please complete the chart below to describe your use of hearing protection during the last two years.	

Have you worn hearing protectors (HP) because you were exposed to noise as a part of:		If yes, please fill in below (HP use in the last two years)	
		Type of Hearing Protection	Days used
(1) your occupation	Yes No		
(2) military duty	Yes No		
(3) other activity (describe)	Yes No		
Have you worn earplugs while			
(1) sleeping	Yes No	Earplugs	
(2) swimming	Yes No	Earplugs	

EXPERIENCE FORM

Experience with Hearing Protection
Test Version

a. Have you *ever* received one-on-one personal instruction in the fitting of hearing protectors?	Yes No
b.(1) Within the last two years, have you attended a lecture about how to fit hearing protectors?	Yes No
b.(2) Within the last two years, have you watched videotaped or computer-based instruction about how to fit hearing protectors?	Yes No
c. Please complete the chart below to describe your use of hearing protection during the last two years.	

Have you worn hearing protectors (HP) because you were exposed to noise as a part of:		If yes, please fill in below (HP use in the last two years)	
		Type of Hearing Protection	Days used
(1) your occupation	Yes No		
(2) military duty	Yes No		
(3) other activity (describe)	Yes No		
Have you worn earplugs while			
(1) sleeping	Yes No	Earplugs	
(2) swimming	Yes No	Earplugs	

Special Instructions for S12.6 Subject-Fit Test

Screening

The experimenter will tell the participant,

"Because I do not want to influence the choices you will be making in the hearing protector evaluations, I cannot tell you any of your test results as long as you are a participant in this laboratory. After you complete your work as a participant on our subject-fit test panel, I will be pleased to share with you any of your results."

When performing anthropometric measurements, the experimenter will not tell the participant that his or her ear canals are being sized and will not tell him/her the results until s/he is no longer involved in the hearing protection tests. The following communication is recommended: "I am going to inspect your ears and measure your head using standard evaluation devices."

Fitting Instructions – prior to Threshold Testing

Experimenter will tell the participant,

"The purpose of this test is to estimate the noise reduction that you would be likely to attain while wearing this hearing protector in a noisy environment. Please read the instructions, and fit and adjust the hearing protector to the best of your ability. <u>I am not allowed to assist you in that process</u>."

The experimenter will hand the participant the hearing protector(s) to be used for the test, along with the manufacturer's written fitting instructions that would normally accompany the hearing protector(s). The participant will have 5 minutes to fit both ears and adjust the fit. Once comfortable with the fit, the participant will remove the hearing protectors until occluded testing.

Final Fitting - prior to Occluded Testing

The experimenter will tell the participant,

"After I leave the chamber, please put on the hearing protector in the way you have just practiced. Refer to the manufacturer's instructions as needed. Once you indicate that you have completed fitting the protector, the test will begin, and you may not touch or adjust the protector until you are asked to remove it at the end of the test. If the device falls out of your ear during the test, please signal me. Throughout the test I will be able to observe you through the window [or, using the TV camera]."

The experimenter will leave the chamber and will not remain for the final fitting. He or she will not provide any assistance or explanations. The participant will have 5 minutes to fit the hearing protector.

If the hearing protector falls out of the participant's ear, the test will be stopped. The experimenter will enter the test room, hand the hearing protector to the participant and tell him/her to reinsert the device for a retest. If the hearing protector falls out twice in one trial, the participant will be excused from the experiment.

Testing

If the participant requests information about his/her results, the experimenter tell him/her:

"Because I do not want to influence the choices you will be making in the hearing protector evaluations, I cannot tell you any of your test results as long as you are a participant in this laboratory. After you complete your work as a participant on our subject-fit test panel, I will be pleased to share with you any of your results."

APPENDIX G – Data Tables

REAT MS Excel Data Table Sample

SENNHEISER HMEC 300								
		FREQUENCY (Hz)						
Subject	**Trial**	**125**	**250**	**500**	**1000**	**2000**	**4000**	**8000**
1	Shallow unoccluded w/o mic	-6.5	-2.4	-1.1	4.5	6.6	-0.2	0.1
1	Deep 1 unocc w/mic	-6.0	-5.6	-1.6	1.1	1.4	-2.1	-2.5
1	Deep 1 occluded	-4.6	2.0	16.8	31.4	34.0	27.6	30.5
1	Deep 2 occluded	0.3	7.3	25.0	34.1	30.4	29.1	26.0
1	Deep 2 unocc w/mic	-4.7	-1.0	0.3	2.9	1.0	-3.1	-6.4
1	Concha 2 occluded	5.6	13.0	30.5	38.1	32.3	27.4	30.6
1	Concha 2 unocc w/o mic	-5.9	-1.0	0.5	2.5	0.1	-4.6	-2.6
1	Attenuation Deep 1	1.4	7.6	18.4	30.3	32.6	29.7	33.0
1	Attenuation Deep 2	5.0	8.3	24.7	31.2	29.4	32.2	32.4
1	Attenuation Concha 2	11.5	14.0	30.0	35.6	32.2	32.0	33.2
1	TTS	0.6	1.4	1.6	2.0	6.5	4.4	2.7
2	Shallow unoccluded w/o mic	-10.1	-9.1	-5.9	1.9	-5.5	-0.5	-4.6
2	Deep 1 unocc w/mic	-10.4	-11.8	-7.2	-1.0	-7.7	-0.4	-4.7
2	Deep 1 occluded	6.1	12.0	24.1	37.9	29.4	31.5	28.9
2	Deep 2 occluded	5.1	15.0	23.8	36.5	28.4	30.6	30.9
2	Deep 2 unocc w/mic	-9.3	-9.6	-8.2	0.6	-5.9	-2.2	-6.0
2	Concha 2 occluded	7.3	13.4	22.0	41.1	28.5	36.0	31.8
2	Concha 2 unocc w/o mic	-10.1	-9.3	-8.7	1.8	-3.7	-0.9	-5.6
2	Attenuation Deep 1	16.5	23.8	31.3	38.9	37.1	31.9	33.6
2	Attenuation Deep 2	14.4	24.6	32.0	35.9	34.3	32.8	36.9
2	Attenuation Concha 2	17.4	22.7	30.7	39.3	32.2	36.9	37.4
2	TTS	0.0	0.2	2.8	0.1	1.8	0.4	1.0

BOSE AVIATION HEADSET X								
		FREQUENCY (Hz)						
Subject	**Trial**	**125**	**250**	**500**	**1000**	**2000**	**4000**	**8000**
1	Shallow unoccluded w/o mic	-7.1	-3.4	-4.1	4.5	5.0	0.5	-0.1
1	Deep 1 unocc w/mic	-6.4	-4.6	-2.5	0.4	3.0	-2.0	-4.0
1	Deep 1 occluded	-3.1	5.5	15.8	24.9	31.4	37.3	28.0
1	Deep 2 occluded	-4.4	5.1	15.3	25.6	28.5	37.6	32.8
1	Deep 2 unocc w/mic	-7.1	-1.9	0.0	0.3	2.0	-5.6	-6.0
1	Concha 2 occluded	-2.7	3.5	14.9	22.9	28.1	34.1	30.6
1	Concha 2 unocc w/o mic	-6.9	-3.5	-1.9	-1.4	-0.2	-6.5	-4.2
1	Attenuation Deep 1	3.3	10.1	18.3	24.5	28.4	39.3	32.0
1	Attenuation Deep 2	2.7	7.0	15.3	25.3	26.5	43.2	38.8
1	Attenuation Concha 2	4.2	7.0	16.8	24.3	28.3	40.6	34.8
1	TTS	0.2	0.1	2.2	5.9	5.2	7.0	4.1
2	Shallow unoccluded w/o mic	-9.6	-8.8	-9.2	1.6	-3.9	0.5	-4.1
2	Deep 1 unocc w/mic	-9.6	-10.6	-7.0	-0.5	-4.6	1.8	-3.2
2	Deep 1 occluded	-3.7	2.4	13.9	25.0	27.4	41.5	34.3
2	Deep 2 occluded	-5.5	-2.5	7.0	22.1	23.4	43.3	36.8
2	Deep 2 unocc w/mic	-10.5	-9.6	-7.2	-0.9	-6.1	-1.1	-5.7
2	Concha 2 occluded	-7.1	-2.9	8.8	25.8	21.8	42.8	37.3
2	Concha 2 unocc w/o mic	-10.2	-9.7	-7.0	1.0	-2.9	-0.7	-5.4
2	Attenuation Deep 1	5.9	13.0	20.9	25.5	32.0	39.7	37.5
2	Attenuation Deep 2	5.0	7.1	14.2	23.0	29.5	44.4	42.5
2	Attenuation Concha 2	3.1	6.8	15.8	24.8	24.7	43.5	42.7
2	TTS	0.6	0.9	2.2	0.6	1.0	1.2	1.3

BOSE QUIET COMFORT 2								
		FREQUENCY (Hz)						
Subject	Trial	125	250	500	1000	2000	4000	8000
1	Shallow unoccluded w/o mic	-9.2	-2.2	-5.1	1.4	2.0	-2.2	-0.7
1	Deep 1 unocc w/mic	-8.9	-5.5	-2.1	1.8	3.1	-3.5	-4.5
1	Deep 1 occluded	-4.7	3.6	6.6	10.1	18.1	24.8	23.5
1	Deep 2 occluded	1.4	3.4	9.4	15.1	19.8	29.4	25.9
1	Deep 2 unocc w/mic	-6.5	-2.9	-1.0	0.5	-4.7	-4.6	-5.6
1	Concha 2 occluded	-0.4	5.0	8.1	11.1	18.4	22.5	29.4
1	Concha 2 unocc w/o mic	-7.7	-2.2	-5.1	-1.1	-4.2	-6.2	-5.4
1	Attenuation Deep 1	4.2	9.1	8.7	8.3	15.0	28.3	28.0
1	Attenuation Deep 2	7.9	6.3	10.4	14.6	24.5	34.0	31.5
1	Attenuation Concha 2	7.3	7.2	13.2	12.2	22.6	28.7	34.8
1	TTS	1.5	0.0	0.0	2.5	6.2	4.0	4.7
2	Shallow unoccluded w/o mic	-9.1	-9.2	-6.1	-1.2	-4.9	1.9	-5.1
2	Deep 1 unocc w/mic	-9.6	-8.5	-7.0	-1.5	-1.7	1.4	-3.4
2	Deep 1 occluded	-5.0	-2.4	4.4	11.5	12.6	31.5	18.5
2	Deep 2 occluded	-7.6	-4.1	2.1	11.3	12.8	31.6	16.8
2	Deep 2 unocc w/mic	-10.5	-9.4	-6.2	0.1	-3.6	-1.7	-5.0
2	Concha 2 occluded	-6.5	-2.6	4.1	14.0	12.6	33.4	25.0
2	Concha 2 unocc w/o mic	-10.6	-6.4	-5.7	1.3	-3.5	-0.9	-4.7
2	Attenuation Deep 1	4.6	6.1	11.4	13.0	14.3	30.1	21.9
2	Attenuation Deep 2	2.9	5.3	8.3	11.2	16.4	33.3	21.8
2	Attenuation Concha 2	4.1	3.8	9.8	12.7	16.1	34.3	29.7
2	TTS	1.5	2.8	0.4	2.5	1.4	2.8	0.4

SENNHEISER HDC451								
		FREQUENCY (Hz)						
Subject	Trial	125	250	500	1000	2000	4000	8000
1	Shallow unoccluded w/o mic	-12.1	-4.5	-7.5	0.6	1.6	-3.9	-2.2
1	Deep 1 unocc w/mic	-9.9	-5.8	-5.5	-2.0	-2.4	-7.7	-4.9
1	Deep 1 occluded	-8.8	2.1	-11.8	2.0	-1.6	-2.2	6.0
1	Deep 2 occluded	-5.4	-9.6	-13.2	-13.2	-12.4	-12.6	-0.9
1	Deep 2 unocc w/mic	-12.9	-6.5	-10.9	-6.7	-11.8	-12.7	-10.7
1	Concha 2 occluded	-11.4	-10.7	-13.9	-12.8	-9.4	-12.9	-12.5
1	Concha 2 unocc w/o mic	-13.1	-10.4	-12.1	-9.1	-11.7	-12.2	-12.6
1	Attenuation Deep 1	1.1	7.9	6.3	4.0	0.8	5.5	10.9
1	Attenuation Deep 2	7.5	3.1	2.3	6.5	0.6	0.1	9.8
1	Attenuation Concha 2	1.7	0.3	1.8	3.7	2.3	0.7	0.1
1	TTS	1.0	5.9	4.6	9.7	13.3	8.3	10.4
2	Shallow unoccluded w/o mic	-10.6	-7.2	-5.1	0.9	-5.5	-2.2	-5.4
2	Deep 1 unocc w/mic	-10.3	-7.9	-5.4	-1.5	-4.0	1.5	-3.7
2	Deep 1 occluded	-7.5	-9.3	-2.1	5.1	3.1	6.4	4.8
2	Deep 2 occluded	-7.4	-8.1	1.8	6.1	7.0	10.5	6.3
2	Deep 2 unocc w/mic	-7.1	-7.5	-4.5	2.9	-1.9	0.0	-4.2
2	Concha 2 occluded	-4.7	-7.5	1.8	7.6	3.8	10.1	7.0
2	Concha 2 unocc w/o mic	-8.3	-7.4	-3.4	0.5	-1.1	1.6	-5.0
2	Attenuation Deep 1	2.8	1.4	3.3	6.6	7.1	4.9	8.5
2	Attenuation Deep 2	0.3	0.6	6.3	3.2	8.9	10.5	10.5
2	Attenuation Concha 2	3.6	0.1	5.2	7.1	4.9	8.5	12.0
2	TTS	2.3	0.2	1.7	0.4	4.4	3.8	0.4

MIRE MS Excel Data Table Sample

SENNHEISER HMEC300										
Left Ear -- Channel 1										
Subj.	Trial	Measurement	63	125	250	500	1000	2000	4000	8000
1		amb	18.1	21.2	7.0	11.5	11.3	12.2	15.5	17.3
1										
1	1	Unocc	60.1	74.2	73.2	77.2	77.4	77.2	83.0	82.1
1	1	Occ. Pass.	55.5	66.1	57.9	50.4	42.7	47.3	53.1	54.1
1	1	Occ. Act+Pass	44.2	48.2	50.4	53.3	43.1	46.5	51.2	52.5
1	1	Pass. IL	4.6	8.1	15.3	26.8	34.7	29.9	29.9	28.0
1	1	Total IL	15.9	26.0	22.8	23.9	34.3	30.7	31.8	29.6
1	1	Act. IL	11.3	17.9	7.5	-2.9	-0.4	0.8	1.9	1.6
1	1	Headroom	26.1	27.0	43.4	38.9	31.4	34.3	35.7	35.2
1										
1	2	Unocc	59.5	74.4	73.4	77.1	77.0	76.5	82.7	81.6
1	2	Occ. Pass.	54.3	65.3	55.6	48.3	41.5	43.2	51.6	50.9
1	2	Occ. Act+Pass	46.9	49.3	50.1	54.7	43.3	44.3	51.6	51.2
1	2	Pass. IL	5.2	9.1	17.8	28.8	35.5	33.3	31.1	30.7
1	2	Total IL	12.6	25.1	23.3	22.4	33.7	32.2	31.1	30.4
1	2	Act. IL	7.4	16.0	5.5	-6.4	-1.8	-1.1	0.0	-0.3
1	2	Headroom	28.8	28.1	43.1	36.8	30.2	31.0	36.1	33.6
		AVERAGE PASSIVE IL	4.9	8.6	16.6	27.8	35.1	31.6	30.5	29.4
		AVERAGE TOTAL IL	14.3	25.6	23.1	23.2	34.0	31.5	31.5	30.0
		AVERAGE ACTIVE IL	9.4	17.0	6.5	-4.7	-1.1	-0.1	0.9	0.6
2		amb	19.0	20.6	7.3	12.6	11.4	11.9	15.5	17.5
2										
2	1	Unocc	61.7	74.4	74.9	78.0	78.0	78.8	83.5	75.6
2	1	Occ. Pass.	52.1	61.4	50.3	42.3	35.7	42.3	48.1	39.3
2	1	Occ. Act+Pass	39.5	44.8	45.1	48.8	36.4	41.8	48.0	39.4
2	1	Pass. IL	9.6	13.0	24.6	35.7	42.3	36.5	35.4	36.3
2	1	Total IL	22.2	29.6	29.8	29.2	41.6	37.0	35.5	36.2
2	1	Act. IL	12.6	16.6	5.2	-6.5	-0.7	0.5	0.1	-0.1
2	1	Headroom	20.5	24.2	37.8	29.7	24.3	29.9	32.5	21.8
2										
2	2	Unocc	61.8	74.2	74.4	78.2	78.2	79.0	83.1	75.9
2	2	Occ. Pass.	51.7	60.3	52.3	42.7	35.3	41.1	49.4	41.7
2	2	Occ. Act+Pass	40.0	44.0	46.9	49.3	36.2	41.6	49.4	42.3
2	2	Pass. IL	10.1	13.9	22.1	35.5	42.9	37.9	33.7	34.2
2	2	Total IL	21.8	30.2	27.5	28.9	42.0	37.4	33.7	33.6
2	2	Act. IL	11.7	16.3	5.4	-6.6	-0.9	-0.5	0.0	-0.6
2	2	Headroom	21.0	23.4	39.6	30.1	23.9	29.2	33.9	24.2
		AVERAGE PASSIVE IL	9.9	13.5	23.4	35.6	42.6	37.2	34.6	35.3
		AVERAGE TOTAL IL	22.0	29.9	28.7	29.1	41.8	37.2	34.6	34.9
		AVERAGE ACTIVE IL	12.2	16.5	5.3	-6.6	-0.8	0.0	0.1	-0.3

BOSE AVIATION HEADSET X

Left Ear -- Channel 1

Subj.	Trial	Measurement	63	125	250	500	1000	2000	4000	8000
1		amb	18.1	20.4	6.6	5.3	5.8	7.4	9.5	12.3
1										
1	1	Unocc	60.1	74.5	73.8	77.5	76.7	76.3	82.3	80.2
1	1	Occ. Pass.	60.8	74.2	66.2	60.9	54.7	48.9	41.9	43.0
1	1	Occ. Act+Pass	40.8	53.0	51.3	55.2	62.0	49.1	42.5	42.8
1	1	Pass. IL	-0.7	0.3	7.6	16.6	22.0	27.4	40.4	37.2
1	1	Total IL	19.3	21.5	22.5	22.3	14.7	27.2	39.8	37.4
1	1	Act. IL	20.0	21.2	14.9	5.7	-7.3	-0.2	-0.6	0.2
1	1	Headroom	22.7	32.6	44.7	49.9	48.9	41.5	32.4	30.5
1										
1	2	Unocc	59.8	74.2	74.3	77.4	77.0	75.8	82.3	80.2
1	2	Occ. Pass.	60.6	75.3	68.0	62.4	54.6	49.8	43.3	43.3
1	2	Occ. Act+Pass	42.6	52.8	52.7	56.9	61.3	50.5	44.4	43.1
1	2	Pass. IL	-0.8	-1.1	6.3	15.0	22.4	26.0	39.0	36.9
1	2	Total IL	17.2	21.4	21.6	20.5	15.7	25.3	37.9	37.1
1	2	Act. IL	18.0	22.5	15.3	5.5	-6.7	-0.7	-1.1	0.2
1	2	Headroom	24.5	32.4	46.1	51.6	48.8	42.4	33.8	30.8
		AVERAGE PASSIVE IL	-0.8	-0.4	7.0	15.8	22.2	26.7	39.7	37.1
		AVERAGE TOTAL IL	18.3	21.5	22.1	21.4	15.2	26.3	38.9	37.3
		AVERAGE ACTIVE IL	19.0	21.9	15.1	5.6	-7.0	-0.5	-0.9	0.2
2		amb	18.7	21.1	7.1	11.1	11.5	11.9	15.7	17.5
2										
2	1	Unocc	61.9	74.4	74.4	77.6	78.3	78.2	84.2	75.1
2	1	Occ. Pass.	62.6	76.0	67.9	59.6	54.3	48.9	39.5	36.4
2	1	Occ. Act+Pass	41.6	53.8	52.4	54.4	59.8	50.1	40.1	36.0
2	1	Pass. IL	-0.7	-1.6	6.5	18.0	24.0	29.3	44.7	38.7
2	1	Total IL	20.3	20.6	22.0	23.2	18.5	28.1	44.1	39.1
2	1	Act. IL	21.0	22.2	15.5	5.2	-5.5	-1.2	-0.6	0.4
2	1	Headroom	22.9	32.7	45.3	43.3	42.8	37.0	23.8	18.5
2										
2	2	Unocc	61.9	74.5	74.4	77.8	78.2	78.2	84.3	74.9
2	2	Occ. Pass.	62.9	74.0	69.4	61.0	54.3	50.4	42.1	34.2
2	2	Occ. Act+Pass	42.9	51.9	53.8	56.2	58.6	52.8	42.7	35.0
2	2	Pass. IL	-1.0	0.5	5.0	16.8	23.9	27.8	42.2	40.7
2	2	Total IL	19.0	22.6	20.6	21.6	19.6	25.4	41.6	39.9
2	2	Act. IL	20.0	22.1	15.6	4.8	-4.3	-2.4	-0.6	-0.8
2	2	Headroom	24.2	30.8	46.7	45.1	42.8	38.5	26.4	16.7
		AVERAGE PASSIVE IL	-0.9	-0.5	5.8	17.4	24.0	28.6	43.5	39.7
		AVERAGE TOTAL IL	19.7	21.6	21.3	22.4	19.1	26.8	42.9	39.5
		AVERAGE ACTIVE IL	20.5	22.2	15.6	5.0	-4.9	-1.8	-0.6	-0.2

BOSE QUIET COMFORT 2										
Left Ear -- Channel 1										
Subj.	Trial	Measurement	63	125	250	500	1000	2000	4000	8000
1		amb	19.3	21.2	7.1	11.1	11.9	12.3	15.9	17.5
1										
1	1	Unocc	59.9	74.9	73.9	76.9	76.9	76.4	82.2	79.8
1	1	Occ. Pass.	60.8	75.4	68.7	66.6	63.5	58.4	50.0	46.5
1	1	Occ. Act+Pass	52.3	57.5	57.7	61.6	67.2	59.1	49.4	46.5
1	1	Pass. IL	-0.9	-0.5	5.2	10.3	13.4	18.0	32.2	33.3
1	1	Total IL	7.6	17.4	16.2	15.3	9.7	17.3	32.8	33.3
1	1	Act. IL	8.5	17.9	11.0	5.0	-3.7	-0.7	0.6	0.0
1	1	Headroom	33.0	36.3	50.6	50.5	51.6	46.1	33.5	29.0
1										
1	2	Unocc	60.5	74.4	73.9	77.1	77.1	76.3	82.7	80.5
1	2	Occ. Pass.	60.7	75.9	68.9	66.4	63.1	55.2	51.5	47.4
1	2	Occ. Act+Pass	54.3	57.0	56.5	63.1	68.9	56.3	52.7	48.2
1	2	Pass. IL	-0.2	-1.5	5.0	10.7	14.0	21.1	31.2	33.1
1	2	Total IL	6.2	17.4	17.4	14.0	8.2	20.0	30.0	32.3
1	2	Act. IL	6.4	18.9	12.4	3.3	-5.8	-1.1	-1.2	-0.8
1	2	Headroom	35.0	35.8	49.4	52.0	51.2	42.9	35.6	29.9
		AVERAGE PASSIVE IL	-0.6	-1.0	5.1	10.5	13.7	19.6	31.7	33.2
		AVERAGE TOTAL IL	6.9	17.4	16.8	14.7	9.0	18.7	31.4	32.8
		AVERAGE ACTIVE IL	7.5	18.4	11.7	4.2	-4.8	-0.9	-0.3	-0.4
2		amb	25.3	20.0	7.0	5.6	5.8	7.3	9.5	12.3
2										
2	1	Unocc	61.7	74.2	74.4	77.8	78.2	79.4	83.8	76.3
2	1	Occ. Pass.	62.4	77.4	74.5	67.6	63.8	62.0	58.8	54.5
2	1	Occ. Act+Pass	56.6	62.0	61.8	62.2	67.5	62.8	59.1	55.1
2	1	Pass. IL	-0.7	-3.2	-0.1	10.2	14.4	17.4	25.0	21.8
2	1	Total IL	5.1	12.2	12.6	15.6	10.7	16.6	24.7	21.2
2	1	Act. IL	5.8	15.4	12.7	5.4	-3.7	-0.8	-0.3	-0.6
2	1	Headroom	31.3	42.0	54.8	56.6	58.0	54.7	49.3	42.2
2										
2	2	Unocc	61.7	74.7	74.6	77.8	78.0	79.5	83.4	75.9
2	2	Occ. Pass.	63.0	76.9	72.7	66.4	62.1	59.3	53.6	52.2
2	2	Occ. Act+Pass	54.9	60.0	58.9	62.5	66.8	60.8	53.9	51.4
2	2	Pass. IL	-1.3	-2.2	1.9	11.4	15.9	20.2	29.8	23.7
2	2	Total IL	6.8	14.7	15.7	15.3	11.2	18.7	29.5	24.5
2	2	Act. IL	8.1	16.9	13.8	3.9	-4.7	-1.5	-0.3	0.8
2	2	Headroom	29.6	40.0	51.9	56.9	56.3	52.0	44.1	39.1
		AVERAGE PASSIVE IL	-1.0	-2.7	0.9	10.8	15.2	18.8	27.4	22.8
		AVERAGE TOTAL IL	6.0	13.5	14.2	15.5	11.0	17.7	27.1	22.9
		AVERAGE ACTIVE IL	7.0	16.2	13.3	4.7	-4.2	-1.2	-0.3	0.1

SENNHEISER HDC451

Left Ear -- Channel 1

Subj.	Trial	Measurement	63	125	250	500	1000	2000	4000	8000
1		amb	20.7	22.8	7.2	11.4	11.4	11.9	15.6	17.7
1										
1	1	Unocc	60.5	74.7	73.9	77.4	77.4	75.8	82.0	79.1
1	1	Occ. Pass.	60.2	74.2	74.3	78.2	78.9	77.4	71.2	66.5
1	1	Occ. Act+Pass	63.4	70.5	67.5	70.8	75.0	80.6	81.0	73.9
1	1	Pass. IL	0.3	0.5	-0.4	-0.8	-1.5	-1.6	10.8	12.6
1	1	Total IL	-2.9	4.2	6.4	6.6	2.4	-4.8	1.0	5.2
1	1	Act. IL	-3.2	3.7	6.8	7.4	3.9	-3.2	-9.8	-7.4
1	1	Headroom	39.5	47.7	60.3	59.4	63.6	63.9	55.6	48.8
1										
1	2	Unocc	60.9	74.6	74.0	76.9	77.4	76.2	82.1	79.3
1	2	Occ. Pass.	60.1	74.8	74.3	77.7	78.8	77.4	72.1	67.0
1	2	Occ. Act+Pass	62.7	70.3	66.8	69.9	72.1	79.1	79.1	72.6
1	2	Pass. IL	0.8	-0.2	-0.3	-0.8	-1.4	-1.2	10.0	12.3
1	2	Total IL	-1.8	4.3	7.2	7.0	5.3	-2.9	3.0	6.7
1	2	Act. IL	-2.6	4.5	7.5	7.8	6.7	-1.7	-7.0	-5.6
1	2	Headroom	39.4	47.5	59.6	58.5	60.7	64.3	56.5	49.3
		AVERAGE PASSIVE IL	0.5	0.1	-0.3	-0.8	-1.5	-1.4	10.4	12.5
		AVERAGE TOTAL IL	-2.4	4.3	6.8	6.8	3.9	-3.8	2.0	6.0
		AVERAGE ACTIVE IL	-2.9	4.1	7.2	7.6	5.3	-2.4	-8.4	-6.5
2		amb	24.7	21.1	7.1	11.2	11.2	11.8	15.1	17.1
2										
2	1	Unocc	61.5	74.3	74.0	77.5	78.0	78.3	83.3	73.4
2	1	Occ. Pass.	62.1	73.9	74.6	78.5	79.8	74.7	73.4	63.6
2	1	Occ. Act+Pass	63.1	69.6	66.2	66.9	73.6	76.7	79.1	65.1
2	1	Pass. IL	-0.6	0.4	-0.6	-1.0	-1.8	3.6	9.9	9.8
2	1	Total IL	-1.6	4.7	7.8	10.6	4.4	1.6	4.2	8.3
2	1	Act. IL	-1.0	4.3	8.4	11.6	6.2	-2.0	-5.7	-1.5
2	1	Headroom	36.8	48.5	59.1	55.7	62.4	62.9	58.3	46.5
2										
2	2	Unocc	61.3	74.6	74.2	77.4	77.8	78.3	83.5	73.4
2	2	Occ. Pass.	61.7	74.2	74.6	78.3	79.8	75.5	74.7	64.0
2	2	Occ. Act+Pass	61.9	69.4	65.2	64.9	70.6	76.5	79.1	65.4
2	2	Pass. IL	-0.4	0.4	-0.4	-0.9	-2.0	2.8	8.8	9.4
2	2	Total IL	-0.6	5.2	9.0	12.5	7.2	1.8	4.4	8.0
2	2	Act. IL	-0.2	4.8	9.4	13.4	9.2	-1.0	-4.4	-1.4
2	2	Headroom	36.6	48.3	58.1	53.7	59.4	63.7	59.6	46.9
		AVERAGE PASSIVE IL	-0.5	0.4	-0.5	-0.9	-1.9	3.2	9.3	9.6
		AVERAGE TOTAL IL	-1.1	5.0	8.4	11.6	5.8	1.7	4.3	8.2
		AVERAGE ACTIVE IL	-0.6	4.6	8.9	12.5	7.7	-1.5	-5.0	-1.5

Headband Force Data Table

	Headband Force (N)				
	Senheiser HMEC300	LightSPEED Aviation Thirty 3G	Bose Aviation Headset X	Bose Quiet Comfort 2	Sennheiser HDC451
Sample 1	10.1	9.5	5.2	3.7	1.6
Sample 2	10.1	9.7	4.8	2.5	1.2
Average	10.1	9.6	5.0	3.1	1.4
StdDev	0.0	0.1	0.3	0.8	0.3

Comfort Index Rating Scale Data Table

	Comfort Index (range 12-84)				
Subject	Bose Quiet Comfort 2	Bose Aviation Headset X	Sennheiser HDC451	Sennheiser HMEC300	LightSPEED Aviation Thirty 3G
1	75	71	71	61	38
2	67	69	64	54	49
3	82	73	66	63	64
4	77	74	79	61	43
5	58	57	37	54	55
6	63	66	45	64	69
7	66	69	62	59	24
8	70	68	63	65	57
9	78	78	73	78	71
10	72	69	51	51	43
Average	70.8	69.4	61.1	61.0	51.3
StdDev	7.4	5.6	13.1	7.6	14.8

ANOVA Tables for Higher-Order Interaction Analyses

MIRE Passive IL:

Headphone x Microphone x Frequency

Type 3 Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Headphone	3	864	1239.78	<.0001
Mic	2	864	5.81	0.0031
Freq	7	864	793.16	<.0001
Headphone*Mic	6	864	0.76	0.6031
Headphone*Freq	21	864	78.10	<.0001
Mic*Freq	14	864	3.76	<.0001
Headphone*Mic*Freq	42	864	0.74	0.8832

MIRE Total IL:

Headphone x Microphone x Frequency

Type 3 Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Headphone	3	864	1185.05	<.0001
Mic	2	864	4.06	0.0176
Freq	7	864	163.33	<.0001
Headphone*Mic	6	864	0.87	0.5189
Headphone*Freq	21	864	44.26	<.0001
Mic*Freq	14	864	2.89	0.0003
Headphone*Mic*Freq	42	864	0.53	0.9945

REAT vs. MIRE Passive IL:

Headphone x Microphone x Frequency

Type 3 Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Headphone	3	1064	1174.13	<.0001
Mic	1	1064	4.04	0.0447
Freq	6	1064	566.96	<.0001
Headphone*Mic	3	1064	0.48	0.6997
Headphone*Freq	18	1064	60.86	<.0001
Mic*Freq	6	1064	3.57	0.0017
Headphone*Mic*Freq	18	1064	0.64	0.8666

Headphone x Microphone x Protocol

Type 3 Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Headphone	3	1104	234.30	<.0001
Mic	1	1104	0.81	0.3695
Protocol	1	1104	9.65	0.0019
Headphone*Mic	3	1104	0.09	0.9629
Headphone*Protocol	3	1104	0.48	0.6957
Mic*Protocol	1	1104	0.61	0.4349
Headphone*Mic*Protocol	3	1104	0.22	0.8814

Microphone x Frequency x Protocol

Type 3 Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Mic	1	1092	0.79	0.3749
Freq	6	1092	110.60	<.0001
Protocol	1	1092	9.43	0.0022
Mic*Freq	6	1092	0.70	0.6525
Mic*Protocol	1	1092	0.60	0.4401
Freq*Protocol	6	1092	1.13	0.3449
Mic*Freq*Protocol	6	1092	0.36	0.9051

Headphone x Microphone x Frequency x Protocol

Type 3 Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Headphone	3	1008	1328.79	<.0001
Mic	1	1008	4.57	0.0328
Freq	6	1008	641.65	<.0001
Protocol	1	1008	54.72	<.0001
Headphone*Freq	18	1008	68.88	<.0001
Headphone*Mic	3	1008	0.54	0.6566
Headphone*Protocol	3	1008	2.73	0.0430
Freq*Mic	6	1008	4.04	0.0005
Freq*Protocol	6	1008	6.53	<.0001
Mic*Protocol	1	1008	3.46	0.0632
Headphone*Freq*Protocol	18	1008	3.77	<.0001
Headphone*Mic*Protocol	3	1008	1.26	0.2880
Headphone*Freq*Mic	18	1008	0.73	0.7837
Headphone*Freq*Mic*Protoco	24	1008	0.79	0.7487

Headphone x Frequency x Protocol

Type 3 Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Headphone	3	1064	1311.77	<.0001
Freq	6	1064	633.43	<.0001
Protocol	1	1064	54.02	<.0001
Headphone*Freq	18	1064	67.99	<.0001
Headphone*Protocol	3	1064	2.69	0.0450
Freq*Protocol	6	1064	6.45	<.0001
Headphone*Freq*Protocol	18	1064	3.72	<.0001*

* This interaction was found to be significant and was further decomposed in the analysis of *simple effects* tables below.

Analysis of Simple Effects Data Tables

Matrix of sums for analysis of Simple A x B at C1 (REAT) Interaction

n	10
a	4
b	7
c	2

	Headphone1 (A1)	Headphone2 (A2)	Headphone3 (A3)	Headphone4 (A4)	**Sum**	SS (B)
125 (B1)	12.6	4.3	4.8	3.9	**25.6**	652.80
250 (B2)	17.4	7.5	6.2	3.7	**34.7**	1204.78
500 (B3)	28.0	14.2	9.1	3.7	**55.0**	3027.20
1000 (B4)	34.7	22.0	12.7	5.2	**74.6**	5568.89
2000 (B5)	31.8	27.1	18.9	4.2	**81.9**	6700.24
4000 (B6)	32.2	40.4	29.8	8.5	**110.9**	12295.48
8000 (B7)	31.6	34.6	26.7	11.2	**104.2**	10856.60
SUM	**188.2**	**150.0**	**108.2**	**40.4**	**486.8**	237013.19 SS (T)
SS (AB)	5493.49	4318.82	2263.55	285.93		
SS (A)	35421.12	22503.00	11711.57	1632.56		

SS AxB at C1 = Sum(AB)^2/n - Sum(A)^2/bn - Sum(B)^2/an + T^2/abn

1236.18 1018.12 1007.65 846.48

SS AxB at C1 = 56.89

df AxB at C1 = df num. = (a-1)(b-1) = (4-1)(7-1)

df num. = 18

MS AxB at C1 = SS AxB at C1 / df AxB at C1 = 56.89/18

MS AxB at C1 = 3.16

MS S/ABC SS= 846.37 (from initial ANOVA table)

MS S/ABC MS= 5.22 (Error Term from initial ANOVA table for Headphone*Prot*Freq(Subject))

df denom.= 162 (from initial ANOVA table)

F = MS AxB at C1 / MS S/ABC = 3.16/5.22

F = 0.61

Pr > F = 1.56 Not Significant

*A table for the A x B at C2 (MIRE) interaction was also completed but not shown.

Matrix of sums for analysis of Simple B x C at A1 (Headphone1) Interaction

	REAT (C1)	MIRE (C2)	Sum	SS (B)	
125 (B1)	12.6	9.5	**22.1**	486.53	
250 (B2)	17.4	17.3	**34.6**	1199.06	
500 (B3)	28.0	29.1	**57.1**	3256.98	
1000 (B4)	34.7	36.1	**70.8**	5019.37	
2000 (B5)	31.8	33.0	**64.8**	4199.69	
4000 (B6)	32.2	31.1	**63.2**	3998.03	
8000 (B7)	31.6	26.0	**57.6**	3317.76	
SUM	**188.2**	**182.0**	**370.2**	137075.81	SS (T)
SS (BC)	5493.49	5269.09			
SS (C)	35421.12	33135.83			

n	10
a	4
b	7
c	2

SS BxC at A1 = Sum(BC)^2/n - Sum(C)^2/cn - Sum(B)^2/bn + T^2/bcn

1076.26 979.39 1073.87 979.11

SS BxC at A1 = 2.11

df BxC at A1 = df num. = (b-1)(c-1) = (7-1)(2-1)

df num. = 6

MS BxC at A1 = SS BxC at A1 / df BxC at A1 = 2.11/6

MS BxC at A1 = 0.35

MS S/ABC SS= 846.37 (from initial ANOVA table)

MS S/ABC MS= 5.22 (Error Term from initial ANOVA table for Headphone*Prot*Freq(Subject))

df denom.= 162 (from initial ANOVA table)

F = MS BxC at A1 / MS S/ABC = 0.35/5.22

F = 0.07

Pr > F = 2.14 **Not Significant**

*Tables for the B x C at A2 (Headphone2), A3 (Headphone3), and A4 (Headphone4) interactions were also completed but not shown.

Matrix of sums for analysis of Simple A x C at B1 (125 Hz) Interaction

	Headphone1 (A1)	Headphone2 (A2)	Headphone3 (A3)	Headphone4 (A4)	Sum				
								n	10
	Headphone1 (A1)	Headphone2 (A2)	Headphone3 (A3)	Headphone4 (A4)	**Sum**	SS (C)		***a***	4
REAT (C1)	12.6	4.3	4.8	3.9	**25.6**	652.80		***b***	7
MIRE (C2)	9.5	-1.2	-0.6	-0.5	**7.2**	52.13		***c***	2
SUM	**22.1**	**3.1**	**4.3**	**3.3**	**32.8**	1073.87	SS (T)		
SS (AC)	247.96	19.92	23.78	15.08					
SS (A)	486.53	9.50	18.38	11.17					

SS AxC at B1 = Sum(AC)^2/n - Sum(A)^2/cn - Sum(C)^2/an + T^2/acn

30.67   26.28   17.62   13.42

SS AxC at B1 = 0.19

df AxC at B1 = df num. = (a-1)(c-1) = (4-1)(2-1)

df num. = 3

MS AxC at B1 = SS AxC at B1 / df AxC at B1 = 0.19/3

MS AxC at B1 = 0.06

MS S/ABC SS= 846.37 (from initial ANOVA table)

MS S/ABC MS= 5.22 (Error Term from initial ANOVA table for Headphone*Prot*Freq(Subject))

df denom.= 162 (from initial ANOVA table)

F = MS AxC at B1 / MS S/ABC = 0.06/5.22

F = 0.01

Pr > F = 2.14 Not Significant

*Tables for the A x C at B2 (250 Hz), B3 (500 Hz), B4 (1000 Hz), B5 (2000 Hz), B6 (4000 Hz), and B7 (8000 Hz) interactions were also completed but not shown.

APPENDIX H – Glossary of Terms

Active noise reduction: The process of superimposing two sound pressure waves of equal amplitudes, but with a 180° out-of-phase relationship, resulting in destructive wave cancellation.

Attenuation: The decrease in amplitude of an electrical signal. Attenuation is the opposite of amplification. For example a volume control on an audio system may be referred to as an attenuator.

Acoustic impedance: For a given frequency, the complex quotient obtained when the sound pressure averaged over the surface is divided by the volume velocity through the surface. The real and imaginary components are called, respectively, acoustic resistance and acoustic reactance.

Anechoic chamber: A room designed to suppress internal sound reflections. Used for acoustical measurements.

Average sound pressure level: Of several related sound pressure levels measured at different positions or different times, or both, in a specified frequency band, ten times the common logarithm of the arithmetic mean of the squared pressure ratios from which the individual level were derived.

Critical band: In human hearing, only those frequency components within a narrow band, called the critical band, will mask a given tone. Critical bandwidth varies with frequency but is usually between 1/6 and 1/3 octaves.

DB (A): A sound-level meter reading with an A-weighting network simulating the human-ear response at a loudness level of 40 phons.

Decibel, dB: The term used to identify ten times the common logarithm of the ratio of two like quantities proportional to power or energy. (See level, sound transmission loss.) Thus, one decibel corresponds to a power ratio of 100.1.

Diffuse field: An environment in which the sound pressure level is the same at all locations and the flow of sound energy is equally probable in all directions.

Equalization: The process of adjusting the frequency response of a device or system to achieve a flat or other desired response.

Free field: An environment in which a sound wave may propagate in all directions without obstructions or reflections. Anechoic rooms can produce such an environment under controlled conditions.

Frequency: The measure of the rapidity of alterations of a periodic signal, expressed in cycles per second or Hz.

Frequency response: The changes in the sensitivity of a circuit, device, or room with frequency.

Headphones: Also known as earphones, earbuds, stereophones, headset. A pair of transducers that receive an electrical signal from a media player or receiver and use speakers placed in close proximity to the ears (hence the name earphone) to convert the signal into audible sound waves.

Headroom: The ability of an amp to go beyond its rated power for short durations in order to reproduce musical peaks without distortion. This capability is often dependent on the power supply used in the design.

Hearing Protection Devices (Headphone): Personal protective equipment that is designed to be worn in the ear canal or over the ear to reduce the sound level reaching the ear drum. Examples include ear muffs or plugs.

Hertz (Hz): A unit of measurement of frequency, expressed as cycles per second.

Impedance: The opposition to the flow of electric or acoustic energy measured in ohms.

Insertion loss (IL): Of a silencer or other sound-reducing element, in a specified frequency band, the decrease in sound power level, measured at the location of the receiver, when a sound insulator or a sound attenuator is inserted in the transmission path between the source and the receiver.

Masking: The amount (or the process) by which the threshold of audibility for one sound is raised by the presence of another (masking) sound.

MIRE: Microphone-in-real-ear. A *physical* hearing protector testing standard involving use of the human head as the “test fixture”, with miniature microphones placed inside the ears (at or near the opening of the ear canal, or sometimes within the canal itself) and insertion loss measurements are performed using relatively high levels of a broadband noise stimulus. This methodology is standardized in ANSI S12.42-1995.

Noise: Interference of an electrical or acoustical nature. Random noise is a desirable signal used in acoustical measurements. Pink noise is random noise whose spectrum falls at 3 dB per octave: it is useful for use with sound analyzers with constant percentage bandwidths. Unwanted, bothersome, or distracting sound.

Noise reduction (NR): The difference in sound pressure level between any two points along the path of sound propagation. As an example, noise reduction is the term used to describe the difference in sound pressure levels between the inside and outside of an enclosure.

Noise Reduction Rating (NRR): The Noise Reduction Rating of hearing protection devices (Headphone) indicates the theoretical amount of reduction of noise levels that can be achieved if the Headphone is worn correctly. This rating is shown on the Headphone packaging.

Octave: An octave is a doubling or halving of frequency. 20Hz-40Hz is often considered the bottom octave. Each octave you add on the bottom requires that your speakers move four times as much air!

Octave bands: Frequency ranges in which the upper limit of each band is twice the lower limit. Octave bands are identified by their geometric mean frequency, or center frequency.

One-third octave bands: Frequency ranges where each octave is divided into one-third octaves with the upper frequency limit being 2* (1.26) times the lower frequency. Identified by the geometric mean frequency of each band.

Phase: Phase is the measure of progression of a periodic wave. Phase identifies the position at any instant which a periodic wave occupies in its cycle. It can also be described as the time relationship between two signals.

Pure tone: A tone with no harmonics. All energy is concentrated at a single frequency.

REAT: Real-ear attenuation at threshold. A *psychophysical* hearing protector testing standard involving real-ear, sensation-based responses from human subjects. As implemented in the current Headphone test standards of the American National Standards Institute (ANSI S3.19-1974 and ANSI S12.6-1997[R2002]), participants track their hearing thresholds for 1/3-octave bands of noise at center frequencies of 125, 250, 500, 1000, 2000, 3150, 4000, 6300, and 8000 Hz with (occluded) and without (unoccluded) a hearing protector in place to obtain insertion loss measurements.

Resonance: A natural periodicity, or the reinforcement associated with this periodicity.

Resonant frequency: Any system has a resonance at some particular frequency. At that frequency, even a slight amount of energy can cause the system to vibrate. A stretched piano string, when plucked, will vibrate for a while at a certain fundamental frequency. Plucked again, it will again vibrate at that same frequency. This is its natural or resonant frequency. While this is the basis of musical instruments, it is undesirable in music-reproducing instruments like audio equipment.

Reverberant sound field: The sound in an enclosed or partially enclosed space that has been reflected repeatedly or continuously from the boundaries.
Reverberation: The persistence of sound in an enclosed or partially enclosed space after the source of sound has stopped; by extension, in some contexts, the sound that so persists.

Reverberation room: A room so designed that the reverberant sound field closely approximates a diffuse sound field, both in the steady state when the sound source is on, and during the decay after the source of sound has stopped.

Sound: Sound is vibrational disturbance, exciting hearing mechanisms, transmitted in a predictable manner determined by the medium through which it propagates. To be audible the disturbance must fall within the frequency range 20Hz to 20,000Hz.

Sound attenuation: The reduction of the intensity of sound as it travels from the source to a receiving location. Sound absorption is often involved as, for instance, in a lined duct. Spherical spreading and scattering are other attenuation mechanisms.

Sound level: Of airborne sound, a sound pressure level obtained using a signal to which a standard frequency-weighting has been applied.

Sound pressure level (SPL): Given in decibels (dB) is an expression of loudness or volume. A 10 dB increase in SPL represents a doubling in volume. Live orchestral music reaches brief peaks in the 105 dB range and live rock easily goes over 120 dB.

Sound waves: Sound waves can be thought of like the waves in water. Frequency determines the length of the waves; amplitude or volume determines the height of the waves. At 20Hz, the wavelength is 56 feet long! These long waves give bass its penetrating ability, (why you can hear car boomers blocks away).

Spectrum analyzer: An instrument for measuring, and usually recording, the spectrum of a signal.

Standing wave: A resonance condition in an enclosed space in which sound waves traveling in one direction interact with those traveling in the opposite direction, resulting in a stable condition.

Superposition: Many sound waves may transverse the same point in space, the air molecules responding to the vector sum of the demands of the different waves.

Threshold of hearing: The lowest level sound that can be perceived by the human auditory system. This is close to the standard reference level of sound pressure, 20uPA.

Tympanic membrane: The thin, semitransparent, oval membrane separating the middle and external ear.

Tympanum: The eardrum.

APPENDIX I – Curriculum Vitae

Publications

Sterling, B. S. and Perala, C. H. (2006). *Shared mental model and team behavior as a function of interface modality*. ARL Technical Report (ARL-TR-3735), U. S. Army Research Laboratory Human Research and Engineering Directorate, Fort Knox Field Element, Fort Knox, Kentucky.

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