Evaluation Of A Test Method For Assessing Horizontal Localization And Auditory Learning With Electronic Pass-Through Hearing Protection

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ABSTRACT

A warfighter's situation awareness is vital to their survival and lethality on the battlefield. Situation awareness, achieved through audition, allows the warfighter to quickly and accurately locate the position of fellow warfighters and potential threats. However, hearing loss, acoustic trauma, or the use of hearing protection can diminish this vital ability to locate sounds in the environment accurately. The introduction of electronically modulated hearing protection and enhancement devices (HPED) is an attempt to improve auditory situation awareness for the warfighter. Currently, however, there are no auditory fitness-for-duty measures that allow an warfighter, commander, or medical personnel to assess localization performance in the open-ear or with hearing protection. Such an assessment is important for pre-placement of a warfighter into a hearing critical job and also as a readiness metric prior-to and during a deployment. The ability to measure performance with a hearing protector will also assist warfighters in selecting protection that will afford maximum performance.

This study examined a set of auditory fitness for duty (AFFD) test/stimulus combinations designed to quantify horizontal localization performance. Three listening conditions were used throughout the study; they included an open-ear condition as well as in-the-ear HPED and over-the-ear HPED. The Peltor Com-Tac II^{TM} was used as the over-the-ear HPED and the Etymotic EB15 BlastPLG^{TM} was used as the in-the-ear HPED.

Stimuli consisted of filtered pink-noise that differed in both duration and frequency. Frequencies ranged from 500-1000 Hz (low) and 3000-6000 Hz (high) and durations included 300 ms (short) and 3 seconds (long). Stimuli were presented at 60 and 70 dB SPL.

AFFD measures were specifically designed to measure current performance or to predict performance after training. Measures of current performance include an accuracy test measured in four quadrants (Left-Front, Right-Front, Left-Rear, and Right-Rear) and a front-back confusion test (FBCT). Accuracy within each quadrant was reduced to a mean absolute error, in degrees, for stimuli presented at 30° and 60° from the medial plane. FBCT consisted of a percent correct for stimuli presented at 0° and 180°. Measures of post-training performance include an inter-aural cues test and a front-back difference test FBDT. The IACT and FBDT required participants to identify if two sequential stimuli were presented from the same or different locations. The IACT was tested in the left-front and right-front quadrants (for stimuli at 30° and 60°) and the FBCT was tested with stimuli at 0° and 180°. These tests also provided a percent.

Results show that the high-frequency long-duration (H-Long) stimuli predicted current localization performance well, for all listening conditions. Other AFFD test/stimulus combinations were also found to predict performance for a given listening condition, but not for all conditions. AFFD measures designed to predict post-training performance did not show any AFFD test/stimuli combinations that worked for all listening conditions. There were some combinations that worked for a given listening condition but not all conditions. A further analysis of the data showed that the limited number and types of HPEDs used may have confounded these results.

Passive hearing protectors as well as HPEDs are known to disturb the spectral and temporal auditory cues that allow for accurate localization. While these cues are disturbed they are often still present in the signal heard by the listener. With training/use of a hearing protector, auditory learning may occur that allows these cues to be used again to accurately locate a sound source. Auditory learning was assessed by providing HPED training/use to novice hearing protection users. Pre and post-training testing was performed with the open-ear, in-the-ear HPED, and over-the-ear HPED. Training was provided for only one type of HPED.

Results indicate that auditory learning occurred for the training HPED only. There was no crossover of auditory learning to the non-training protector. Other measures of auditory learning included a subjective confidence rating of the HPED and a measure of response time for the localization task. Results showed that confidence increased for the HPED that was used in training. However, no changes in response time were found for any listening condition.

Based on the results of this study, it is recommended that AFFD measures continue to be developed for implementation as pre-placement, HPED selection, return-to-duty, and readiness metrics for U.S. military personnel. It is also recommended that objective and subjective measures of hearing protection performance consider the effect of auditory learning. The rating or ranking of HPEDs by novice users of such a device, without adequate training/use to allow for auditory learning, should be weighed carefully.

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Acronyms and Abbreviations

Abeam	At a right angle to the fore-aft line.
AFFD	Auditory fitness for duty.
ANOVA	Analysis of variance.
ANR	Active noise reduction.
Binaural	Having or relating to two ears.
Broadband	Noise with components over a wide range of frequencies.
CPU	Central Processing Unit
dB	Decibel: a logarithmic ratio of a measured sound pressure to a reference (.0002 dynes/cm^2). dB without a suffix letter (such as dBA) implies a frequency linear measurement.
dBHL	Decibel hearing level: a decibel scale used in measuring human hearing thresholds. A correction factor is applied to dB SPL that allows 0 dBHL to indicate the softest sound that a human (with normal hearing) can hear .
Dichotic	Presentation of different auditory signals to each ear.
Diotic	Presentation of the same auditory signal to both ears.
DL	Difference limen: the smallest detectable sensation.
Doppler effect	A change in the pitch of a sound when the linear distance between a listener and the sound source is changing. When the linear distance is decreasing the pitch sounds higher than normal, and when the linear distance is increasing the pitch appears lower than normal.
FBCT	Front-back confusion test.
FBDT	Front-back difference test.
Free field	A region where sound can propagate without encountering any obstructions or reflections from boundaries.
Hertz	A unit of frequency used to indicate the number of cycles per second of a periodic signal.
HL	Hearing level: A level based on the threshold of normal hearing.
HPD	Hearing protection device.
HPED	Hearing protection and enhancement device.
Hz	Hertz: the unit of measurement for frequency (cycles per second).
IACT	Interaural cues test.
IBM	International Business Machines Corporation

IID	Interaural intensity difference: the difference in intensity, of a single sound source, when measured/heard at both ears of a listener. IID and ILD are often used interchangeably.
ILD	Interaural level difference: the difference in level, of a single sound source, when measured/heard at both ears of a listener. ILD and IID are often used interchangeably.
IPD	Interaural phase difference: the difference in phase, of a single sound source, when measured/heard at both ears of listener at a given instance. IPD and ITD are often used interchangeably.
ITD	Interaural time difference: the difference in time, of a single sound source, as it arrives (in the same phase) at the ears of a listener. ITD and IPD are often used interchangeably.
ITE	In the ear.
JND	Just noticeable difference: The smallest difference that can be detected at least half of the time.
kHz	1,000 Hertz or 1,000 cycles per second.
MAA	Minimum audible angle: The smallest angle at which a change in the relative position of a sound can be detected. The sound is usually heard once at each location.
MAMA	Minimum audible movement angle: The smallest angle at which movement of a sound source can be detected.
Median	The central number/value of a sequential list of numbers. If there is no one single central number (e.g., a list with an even number of values) then the arithmetic mean of the two central numbers is used.
Midline	Found on the sagittal plane when the plane bisects the center of the head.
Monotic	Presentation of an auditory signal to only one ear.
MPANL	Maximum permissible ambient noise level.
MUX	Multiplexer.
OTE	Over-the-ear.
Phons	A unit of the perceived loudness of sounds.
RT60	The time required for reflections of a direct sound to decay 60 dB below the level of the direct sound.
S.D.	Standard deviation.
SL	Sensation level: A level based on an individual’s threshold.
SLM	Sound Level Meter.
SNR	Signal to noise ratio: a number used to describe the difference in level between a signal and a competing noise. A positive number indicates

	that the signal is higher in level than the noise. A negative number indicates that the signal is lower in level than the noise. A SNR of 0 indicates that the signal and noise have the same level.
SNR	Speech to noise ratio: the same as signal to noise ratio with a speech signal.
SPL	Sound pressure level: a type of decibel (dB) defined as 20 $\log_{10} P_1/P_2$ where P_1 is the measured sound pressure and P_2 is a reference pressure (0.0002 dynes/cm2).
SPSS	Statistical Package for the Social Sciences.
TCAPS	Tactical communications and protective system: a type of HPED that allows the user to have two-way radio communication with another person.
Unity gain	The gain setting on a HPED at which ambient sounds are heard at the same level as they would without the HPED.
USB	Universal Serial Bus.
USB-6009	A National Instruments multi-function data acquisition system that connects to a computer via a USB port.
Veridical	Agrees with reality.

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INTRODUCTION

Sound localization abilities are critical to the safety and performance of many occupations. For the military warfighter, sound localization is vital for survival and mission success. However, because of hazardous noise levels experienced in combat operations, the use of hearing protection is also required to prevent permanent hearing loss. While many Soldiers recognize the importance of protecting their hearing, they will often lay aside their hearing protection because it degrades their auditory situation awareness and ability to communicate. Auditory situation awareness is the ability to detect, recognize, discriminate and localize a sound in space (Casali, Keady, Killion, & Talcott, 2011; Hajicek, Myrent, Li, Barker, & Coyne, 2010), and its loss can have devastating results on combat operations. Endsley (Endsley, 1995) has outlined a more general definition of situation awareness that covers three distinct levels (perception, comprehension, and projection). The first and most basic level is perception of the environment. Perception allows for a comprehension, and together can be used to project a future state. The auditory situation awareness is more focused on the first two levels of situation awareness.

The recent development and use of hearing protection and enhancement devices (HPED) has provided the Soldier with various electronic and passive devices that are designed to enhance communication while still providing protection from hazardous noise. The acceptance of these devices is mixed, as many Soldiers still report difficulty localizing a sound source. Soldiers make a conscious decision to remove their hearing protection and risk permanent hearing loss to ensure physical survival on the battlefield.

Current research demonstrates that modern HPEDs continue to degrade the sound localization performance of the user. However, these studies fail to account for the adaptation process that can occur when these devices are worn day after day, as is common for military operations.

Auditory (sensory) adaptation is the ability of the mind to adjust to an altered auditory input and regain a veridical perception of the environment. Adaptation in adults has been demonstrated for both subtle and gross sensory perturbations in auditory stimuli. Studies have also demonstrated that adaptation can improve localization abilities in both the vertical (elevation) and horizontal (azimuth) plane. It is reasonable to expect that adaptation to HPEDs can restore, or significantly improve, auditory localization in the horizontal plane. While it is expected that adaptation may take several weeks or even months, and that adaptation may not be complete due to the non-permanent nature of device usage, the potential benefits of adaptation (increased survival, mission success, and preserved hearing) are expected to outweigh the alternative negative impact of permanent hearing loss from not using the device.

The military currently uses specific standards to assess individual fitness for duty (Department of the Army, 2010). These standards include general auditory criteria to enter the military, and criteria specific to some occupational specialties, e.g., aviation. These standards are based on audiometric thresholds for pure tone stimuli. Interestingly, entrance standards do not assess speech in noise abilities, localization abilities, or other factors that affect situation awareness. The only speech in noise criteria in current use is employed to determine if an individual can remain in the military, or in a noise hazardous occupational specialty, after they have suffered severe and permanent hearing loss. The standard is designed to protect an individual from a noise hazardous environment, i.e., to protect them from further hearing loss, rather than address initial situation awareness and job performance requirements (Donahue & Ohlin, 1993). Recently, the military has moved to develop an auditory fitness for duty (AFFD) standard that will assess various situation awareness factors for both initial assignment into a occupational specialty, as well as return to duty standards for individuals with an auditory injury (Department of Defense, 2012).

This study will explore the validity of an AFFD test method that will assess horizontal localization abilities of individuals both with and without the use of an HPED. Further, it will attempt to determine if auditory adaptation to a specific HPED is possible for an individual, and will test the level of auditory adaptation achieved. Upon successful completion of this study, a recommendation will be made for a test method and stimuli to assess horizontal localization for open-ear and HPED listening conditions.

BACKGROUND

Auditory Requirements in a Military Environment

Military unique operations require an individual to have good situation awareness and communication abilities. Whether on a combat patrol or working a radio in a tactical operations center, good situation awareness and the ability to communicate are critical. Some operational environments, such as a combat patrol, are less forgiving for failures to maintain situation awareness or communication. These operations are more difficult when conducted in the dark, in high ambient noise, with equipment (e.g. HPED) that hinder auditory performance, or with individual hearing loss.

Situation Awareness

The military has long understood the benefits of good hearing as a combat multiplier (Donahue & Ohlin, 1993; Peters & Garinther, 1990; Price & Hodge, 1976). Educational material provided by the military has highlighted the need for good hearing to locate, identify, describe, and understand the meaning of various combat related sounds (Donahue & Ohlin, 1993). Figure 1 shows the relationship of various auditory tasks within auditory situation awareness. Past experience has shown that soldiers can locate snipers, other patrol members, and vehicles by the sounds they make (Donahue & Ohlin, 1993). Soldiers can also identify types of weapons, booby traps, and the quantity and types of enemy vehicles (Donahue & Ohlin, 1993). Hearing is even used to navigate during night-time patrols (Donahue & Ohlin, 1993). All of these actions require not only good hearing thresholds, but also good situation awareness. However, not everyone has good hearing, or is capable of auditory situation awareness. The ability to detect, identify, localize, understand, and react appropriately to sound is a critical component of situation awareness.

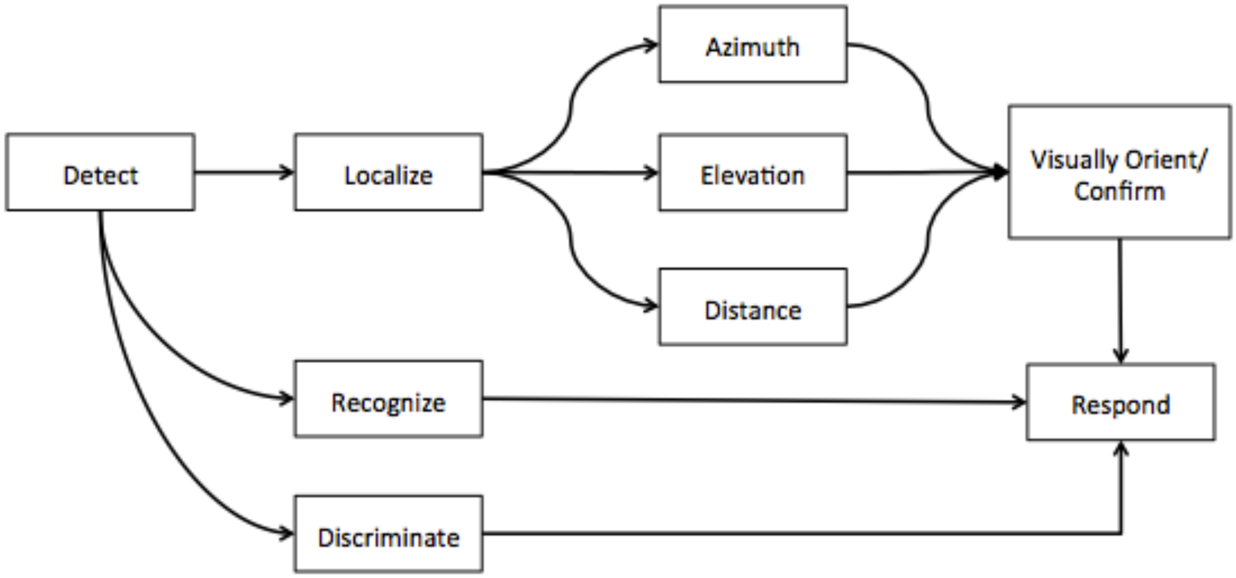


Figure 1. Auditory situation awareness sequential tasks (adapted from Casali et al., 2011)

Communication

Communication is a key element of the modern and historic battlefield (Department of the Army, 2009). Every soldier is familiar with the phrase “shoot, move, and communicate.” It is one of the most basic directives found in the military, and applies to all levels of combat. Communication can take many forms, from visual signals and text based messages to radio or face-to-face speech. In the historic book about World War II, *Men Against Fire*, Brigadier General Samuel Marshall (AKA S.L.A. Marshall or “Slam”) said:

“When you prepare to fight, you must prepare to talk. You must learn that speech will help save your situation. You must be alert at all times to let others know what is happening to you. You must use your brain and your voice any time that any word of yours will help you or others…It is when you talk to others and they join with you that your action becomes important” (Marshall, 1947, p. 137).

Modern and future battlefields are no different. The communication medium may vary, but the fundamental concept is still the same. Communication is best achieved through vision or hearing. In a battlefield where vision is required to scan for non-auditory threats, hearing becomes a primary means for communication. Soldiers rely on their hearing to “detect the enemy and to perform other communication requirements of the mission” (Donahue & Ohlin, 1993, p. 208). Communication can take place face-to-face, within speaking/shouting distance, or with the aid of radio equipment. Regardless of the medium, communication methods must overcome, or be compatible with, the ambient environment (noise), other equipment worn or used by individual soldiers, and the constraints of the mission. A soldier using a handheld radio cannot easily return fire. A soldier using headphones that mask ambient noise may not hear critical information around them. Poor communication systems or poor hearing can also affect communication abilities. Peters and Garinther (1990) studied armor crew performance at various levels of speech intelligibility among the crew. The mission was to engage and kill a target. Armor crews used standardized phrases to limit communication time and improve overall performance. Their findings indicate that degraded speech intelligibility resulted in a significant decline in target identification, targets killed, targets killed with one shot, time to complete mission, and crew survivability.

Noise

Noise, both hazardous and nuisance, is a problem on the battlefield. Exposure to hazardous noise is one of the leading problems facing soldiers in peacetime (Donahue & Ohlin, 1993) and combat operations. In 2010, the Department of Veterans Affairs (VA) reported that over 672,000 veterans received compensation for hearing loss (Department of Veterans Affairs, 2010). This is a four-fold increase since 2001. The total number of Veterans receiving compensation in 2010 for an “Impairment of Auditory Acuity” (which includes hearing loss, tinnitus, and middle ear dysfunction) was 1,525,066 (Department of Veterans Affairs, 2010). The annual number of veterans receiving compensation continues to increase at an alarming rate. The number of veterans receiving compensation for the first time in 2010 was 63,583 for hearing loss, and 92,260 for tinnitus (Department of Veterans Affairs, 2010). While these data are staggering, they only account for service members who have left the service and are eligible for VA compensation. Many service members who suffer hearing loss, from either combat or training, continue to serve in the military. Because of their decreased hearing ability, the risk of errors during critical combat conditions is magnified, and consequences of these errors can be life threatening. It is expected that the number of veterans receiving compensation will continue to rise as more combat experienced service members exit the military.

Hazardous and non-hazardous, i.e. nuisance, noise can also degrade situation awareness and verbal communication. As ambient noise levels increase, sound detection and localization become more difficult, if not impossible. Localization is affected first in distance estimation (making sounds appear closer than they are), followed by errors in elevation (for high frequency sounds) and azimuth (horizontal angle) (Robinson & Casali, 2000). Ambient noise also affects speech communication for both the speaker and listener. Ambient noise causes the speaker to raise their voice, which results in distorted vowel/consonant level ratios. Not only is this difficult for the speaker to sustain for long periods of time, but it can also make speech understanding more difficult (Robinson & Casali, 2000). Listeners will begin to have difficulty understanding speech when noise is masking parts of the speech signal. High frequency speech sounds (near 2000Hz) are the most critical to understanding the fricative sounds of speech. Speech understanding also decreases primarily with the speech to noise ratio (SNR). This can be especially problematic for people with previous auditory injury, who require higher signal to noise ratios to understand speech (Killion, 1997).

Auditory Devices

Auditory or ear-level devices are designed and used to provide protection from hazardous noise, enable interpersonal communication (both aided and unaided), and maintain situation awareness. Devices are often characterized by how they couple to the ear, their material characteristics, and their functional capabilities.

Class of Device

Hearing Protection Device (HPD) – any device that provides attenuation of ambient sounds for the purpose of protecting the user from the effects of hazardous noise.

Hearing Protection and Enhancement Device (HPED) – any device that is a HPD and also includes design features to enhance situation awareness or communication ability. These features may be passive, such as uniform attenuation or level dependent devices (Casali, 2010a), or active, such as active noise reduction or electronically-modulated sound transmission devices (Casali, 2010b).

Tactical Communications and Protective Systems (TCAPS) – are devices that "contain talk-through capabilities and can connect to at least one radio and/or an intercom" (Department of the Army, 2008, p. 4-3).

How Coupled to the Ear

In-the-ear (ITE) – a hearing protector that creates an acoustic seal and is held in place when inserted into the ear canal or concha bowl. These are often called earplugs and create an acoustic seal using expandable foam, soft flanges, or a custom earmold (Figure *2*) (Berger, 2000; Department of the Army, 2006b).

Figure *2.* In-the-ear hearing protection, from left to right: expandable foam (Department of the Army, 2006b), flanged (Department of the Army, 2006b), and custom (Key Hearing).

Semi-Insert – a hearing protector that creates an acoustic seal with the opening to the ear canal, and is held in place with a headband that compresses the ear-tip to the ear canal (Berger, 2000; Department of the Army, 2006b). Semi-inserts are a type of in-the-ear earplug. The headband may be placed above or behind the head, or under the chin (Figure *3*).

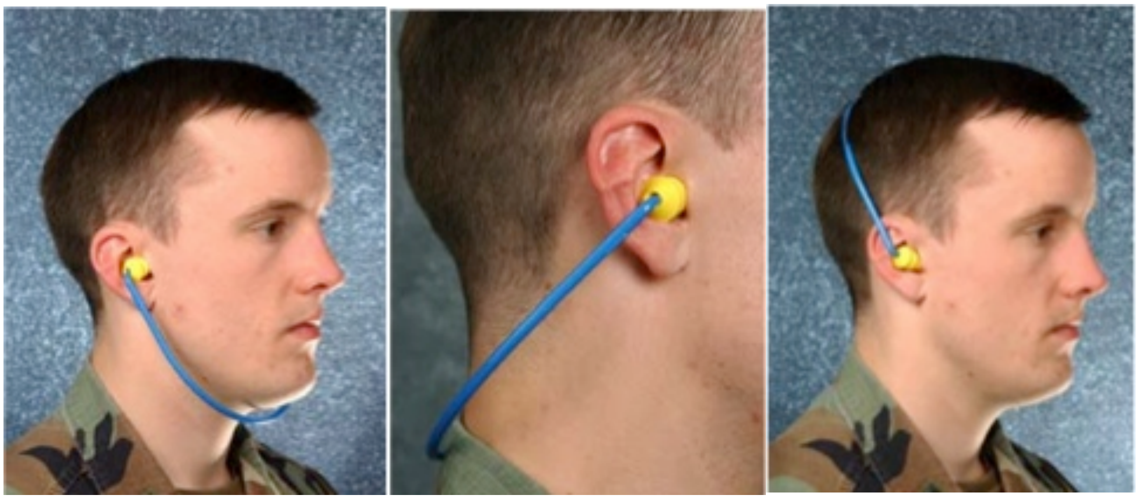


Figure *3.* Semi-Insert hearing protection, from left to right: headband under the chin, behind the head, and over the head (Department of the Army, 2006b, fig. 98-100).

<ins>Over-the-ear (OTE) or muff type</ins> – a hearing protector that creates a circumaural acoustic seal with the head, and is held in place with a headband that compresses the ear-cups to the head (Berger, 2000; Department of the Army, 2006b).. The headband may be placed above or behind the head, or under the chin (Figure *4*)

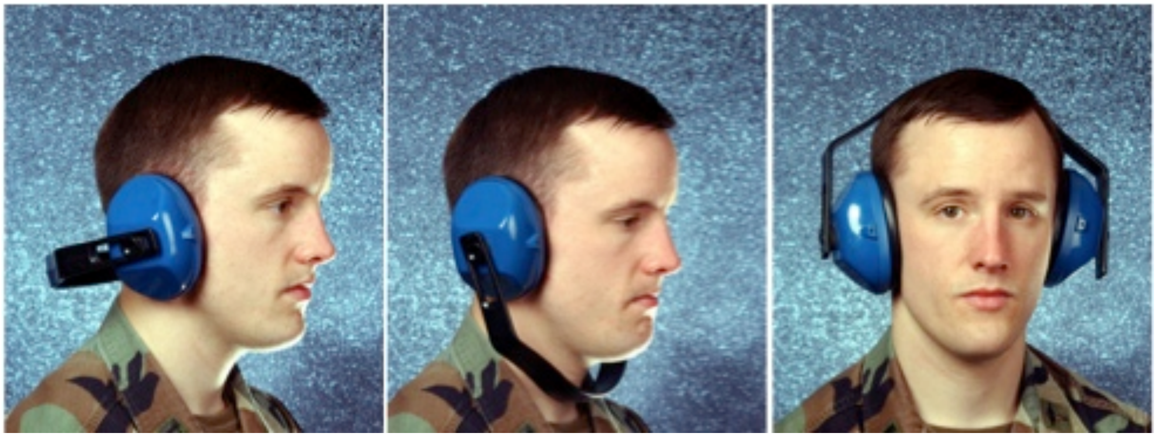


Figure *4.* Over-the-ear hearing protection, from left to right: headband behind the head, under the chin, and over the head (Department of the Army, 2006b, fig. 85-87).

Integrated Helmet – a hearing protector that is similar to an over-the-ear device but is held in place by the helmet (Figure *5*) (Berger, 2000; Department of the Army, 2006b).

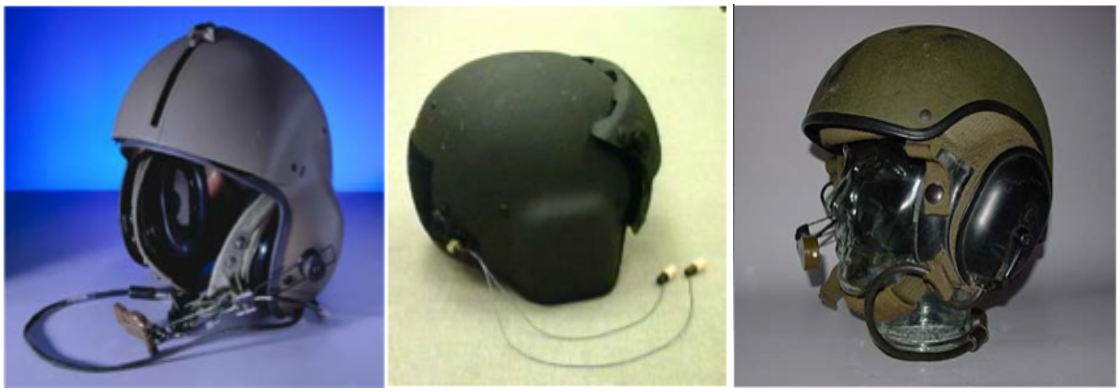


Figure *5.* Integrated helmet hearing protection (Department of the Army, 2006b, fig. 105, 108, 111).

Material Characteristics

Hand-Formed – an ITE type hearing protector that requires the user to compress the plug prior to insertion into the ear. The user then waits for the plug to expand and create an acoustic seal with the ear canal (Figure *6*), or molds the material by hand to fit the concha bowl (Figure *7*).

Figure *6*. Hand-formed hearing protection, from left to right: forming the plug, insertion, and expansion (Department of the Army, 2006b, fig. 57-59).

Figure *7.* Hand-formed hearing protection (accurateshooter.com, 2011).

Pre-Formed – an ITE type hearing protector that contains flanges that, when inserted into the ear canal, create an acoustic seal (Figure 8).

Figure 8. Pre-formed hearing protection (Department of the Army, 2006b, fig. 11).

Function

Because of the limitations encountered with traditional occlusion type protection, several hearing protectors have been designed to provide improved functionality to the user while maintaining the protective properties of the device. Improved functionality has resulted in several classes or types of devices (Casali, 2010a, 2010b).

Linear – a hearing protector that provides the same level of attenuation regardless of the input level.

Non-Linear or Level Dependent – a hearing protector that provides different levels of attenuation as a function of input level. These protectors are usually designed to provide greater amounts of protection with increased input levels.

Flat Frequency Response – a hearing protector that provides the same amount of attenuation at all frequencies.

Electronic or Active – a hearing protector that uses electronic circuitry to provide radio communication and/or ambient sounds to the user.

Passive – a hearing protector that does not use electronics.

Active Noise Reduction (ANR) – a hearing protector that introduces sound that is out of phase with the ambient sound in such a way as to effectively cancel or minimize the amplitude of the sound heard by the listener.

Pass-Through – an electronic hearing protector that uses a microphone to collect ambient sounds, which are then passed to the user. The user may have a volume control that allows unity gain, amplification, or attenuation of the signal.

In the past, HPD were only tested for "for their attenuation characteristics, durability, and freedom from toxic effects" (Donahue & Ohlin, 1993, p. 234). Factors affecting situation awareness (localization, distance detection, communication, etc.) were not considered when approving HPD's for use in the Army. Whether this lack of attention resulted from a paucity of technological solutions or simple ignorance is not evident. With recent advances in technology, the ability to develop HPED and TCAPS devices has grown. Current efforts within the military are now attempting to develop new evaluation and approval standards that include communication and situation awareness metrics.

Human Auditory Sensitivity

Human auditory sensitivity can be described both in its envelope (the range within which sounds are audible) and perceivable differences within that envelope. The envelope is defined by the limits of frequency, level, and duration parameters of a sound. Perceivable differences use the same three parameters (frequency, level, and duration) to define the difference limens (DL), or just noticeable differences (JND) for a given combination of parameters. The following sections will discuss the envelope and differential sensitivity of humans with normal hearing ability.

Envelope

The envelope of human audibility includes sound levels as low as 0 dB (re 20µPa) and as high as 140 dB (Gelfand, 1990). The upper limit, while not a physical limit, is the point at which humans experience physical pain (Gelfand, 1990; Scharine, Cave, & Letowski, 2009). Sound frequencies can be heard between 20 Hz and 20,000 Hz (Scharine et al., 2009). Sounds below 20 Hz can be audible, but are atonal and not generally considered in the range of hearing (Gelfand, 1990; Moller & Pedersen, 2004). Both frequency and level (intensity) interact with each other to shape the audible envelope, requiring greater intensities at the frequency extremes (Gelfand, 1990). The temporal pattern of a sound also interacts with both frequency and level. Constant level sounds decrease in loudness as their durations become less than one second in length and may become inaudible or atonal, i.e. creating a broadband “click” sensation

(Gelfand, 1990; Scharine et al., 2009). The threshold for tonality ranges from 60 ms at 50 Hz to approximately 10 ms above 1000 Hz (Gelfand, 1990).

Differential Sensitivity

A minimum detectable change of sound parameters is known as a difference limen (DL) or just noticeable difference (JND). Difference limens can be measured in either absolute (ΔP) or relative terms ($\Delta P/P$), where P is the value of interest of a parameter. Difference limens can be categorized as monaural (monotic), binaural (diotic), or interaural (dichotic). While the differences may be rather subtle, they can be significant. Monaural and binaural cues are often not differentiated and are combined within this document.

Difference Limens

The relative DL for intensity (DL_I) rapidly decreases as the intensity of a sound increases to about 10 Phons (Deutsch & Richards, 1979; Durrant & Lovrinic, 1977), with a relatively constant DL above 40 to 50 dB SL (Deutsch & Richards, 1979). Difference limens for intensity also vary by frequency, with the smallest DLs in the 1000-4000 Hz range (Deutsch & Richards, 1979). In the most sensitive frequency and intensity range, an intensity change as small as ½ - 1 dB can be detected (Durrant & Lovrinic, 1977).

The relative DL for frequency (DL_F) decreases as the intensity of a sound increases to about 20-30 phons (approximately 20-30 dB at 1000 Hz), at which point DLs remain relatively constant (Deutsch & Richards, 1979; Durrant & Lovrinic, 1977). Difference limens for frequency also vary by frequency, with the smallest DLs in the 1000-2000 Hz range (Deutsch & Richards, 1979; Durrant & Lovrinic, 1977). In the most sensitive frequency and intensity range, a frequency change as small as 1-2 Hz can be detected (Durrant & Lovrinic, 1977).

The relative DL for time (DL_T) decreases as the duration of a sound increases from 0.4 ms to a duration of one second (Deutsch & Richards, 1979). When the stimulus duration is 0.4 ms, the relative DL is 2 and a 0.8 ms duration change is needed to detect a difference. When the stimulus duration is 1000 ms (1 s), the relative DL is .15 and a 150 ms duration change is needed to detect a difference.

Interaural Difference Limens

Interaural DLs are directly related to the interaural cues used to localize sounds (discussed later). Interaural DLs can be measured for the same parameters (intensity, frequency, and time or phase) discussed previously. Studies of interaural DLs indicate that dichotic interaural DL_I are larger than monotic (monaural) or Diotic interaural DLs (Freigang et al., 2011; Rowland & Tobias, 1967). Rowland and Tobias (1967) measured DLs at various frequencies (250, 2000, and 6000 Hz) and intensities (20, 35, and 50 dB). The largest DLs (mean = 1.99 dB) were found at low intensity levels (20 dBHL) and these decreased (mean = 0.93 dB) as intensity increased (to 50 dB). The smallest DL_I were at 2000 Hz.

Freigang et al. (2011) found that relative DL_F increased with an increase in frequency (≈0.02 @ 500 Hz to ≈ 0.04 @ 2000 Hz). They also found that interaural DLs were equal to monaural DLs at 500 and 1000 Hz, but were slightly larger at 2000 Hz. Their studies of DL_T show much smaller absolute interaural DLs compared to monaural DLs. DLs were near 20 ms for all frequencies tested (500, 1000, and 2000 Hz.).

Minimum Audible Angle

The minimum audible angle (MAA) detectable varies by frequency and azimuth. Mills (1958) measured the MAA of a pure tone stimulus and found the smallest MAA (≈1° @ 500-750 Hz.) at midline (Figure 9). The MAA increased with azimuth reaching approximately 8° at an azimuth of 75° for the same frequency region. There was a noticeable increase in MAA between 1000 and 3000 Hz and again above 6000 Hz as azimuth increased. The MAA improved (decreased) between 3000 and 6000 Hz, but remained higher than the values found below1000 Hz. Altshuler & Comalli (1975) found that localization accuracy (minimum audible angle at midline) was poorer at 3000 Hz than at 500 and 8000 Hz when measured using a narrow band noise burst. W. M. Hartmann and Rakerd (1989) suggested that the Mills MAA test methods resulted in an absolute identification task rather than a discrimination task. By refining MAA test methods (to ensure discrimination) they found that the Mills method overestimated the MAA by a factor of about 1.5°.

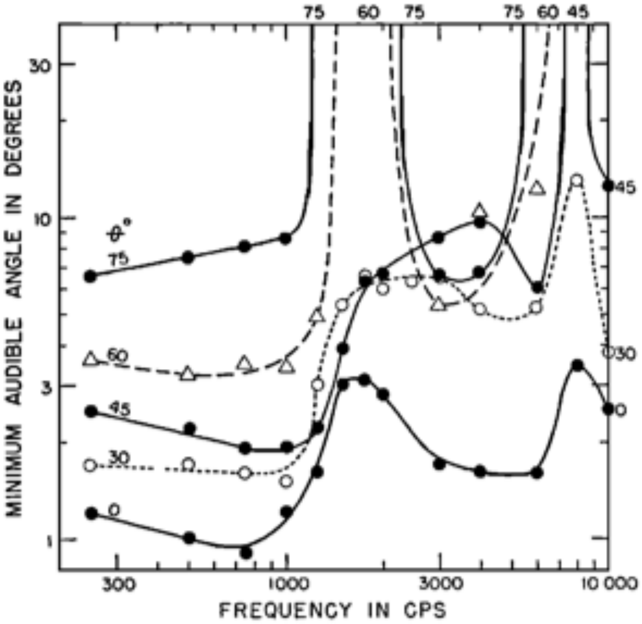


Figure 9. Average minimum audible angle as a function of the stimulus frequency. The parameter (Ø) is the azimuth of the reference tone pulse. (Mills, 1958, fig. 5).

Auditory Localization

Humans can localize sounds in azimuth and elevation with various degrees of accuracy. Localization accuracy depends on several characteristics of the sound (relative spatial location, spectral content, bandwidth, onset duration, overall duration, intensity, and movement), the environment (reflecting surfaces, obstructions, and background noise), and the listener (head movement, hearing loss, and hearing protection).

Auditory Sensation/Perception Aspects of Localization

The human auditory system is capable of localizing sounds in three-dimensional space (azimuth, elevation, and distance) as well as sound movement over time. Detection of sound in azimuth (horizontal) is performed primarily through binaural sound localization cues (Mills, 1958; Oldfield & Parker, 1986). Binaural sound localization cues allow for the processing of interaural differences in a sound’s time of arrival, phase, and level. Determination of a sound source’s elevation (vertical) is performed primarily through monaural sound localization cues (Oldfield & Parker, 1986; Scharine & Letowski, 2005). Monaural localization cues arise from the spectral changes of high frequency sounds through interaction with the folds of the pinna (Figure 10). These changes allow sounds to be localized in the vertical plane, and to some degree in the horizontal plane (Scharine & Letowski, 2005). They also help resolve potential confusions caused by identical binaural cues arising from differing locations. When combined, binaural and monaural cues can provide for rather accurate sound localization in two-dimensional space. Judgments of a sound’s distance from the listener (the third dimension) occurs by comparing differences in level, spectrum, and decay of a known sound to the target sound (Scharine & Letowski, 2005). While not as accurate as azimuth or elevation, distance estimations can be made (Coleman, 1963; J. C. Middlebrooks & Green, 1991). The movement or speed of a sound source combines binaural, monaural, and distance cues, along with Doppler cues, to detect movement and estimate the speed of a sound source (Pavel Zahorik, Brungart, & Bronkhorst, 2005).

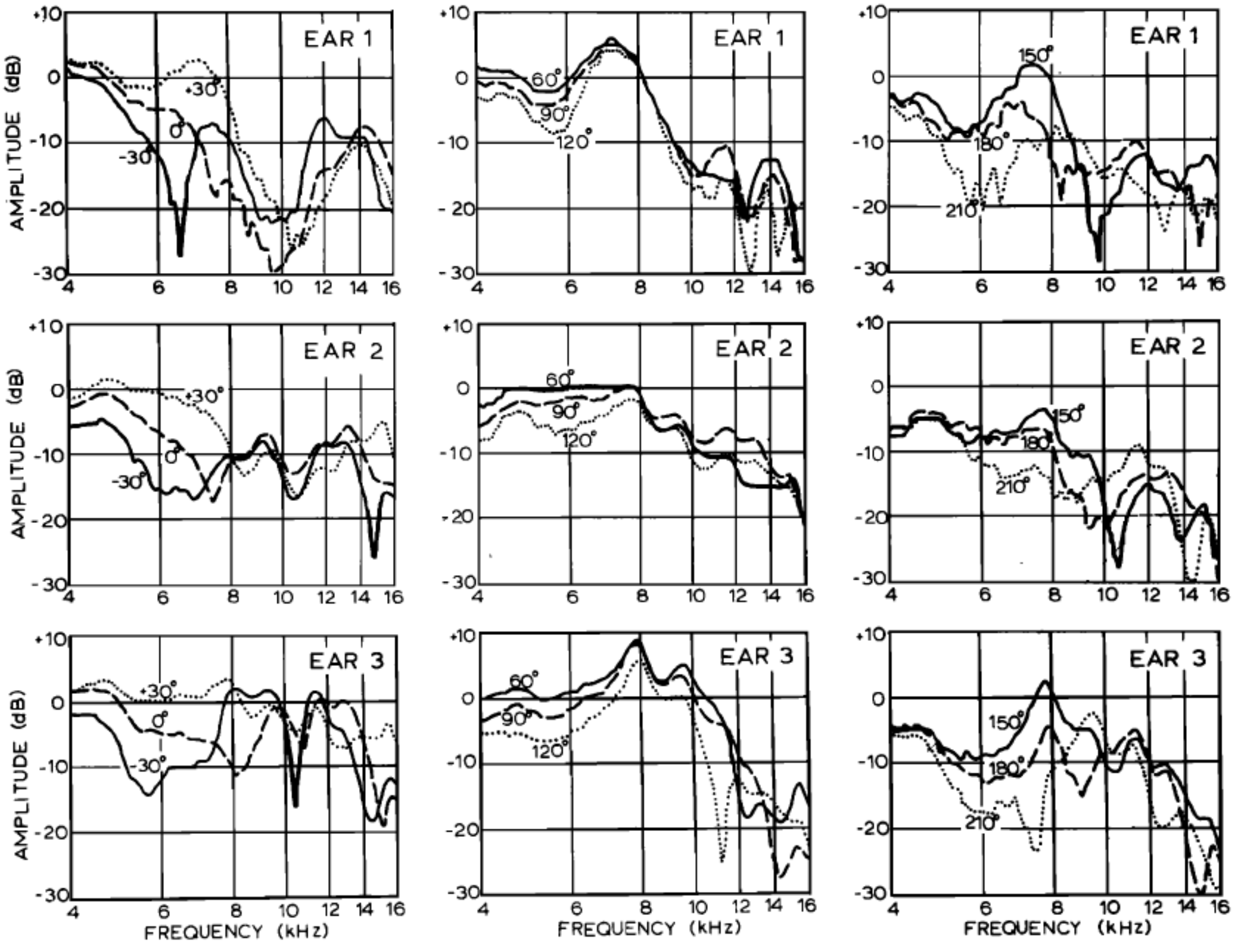


Figure 10. Frequency response at the eardrum of three artificial ears for nine angles of median plane incidence (0° is frontal horizon) (from Hebrank & Wright, 1975, figure 4)

Binaural Localization Cues

Interaural Time Differences (ITD) are frequency independent, and occur because of the differences in arrival time of sounds that do not originate on the midline. The difference in time arrival can be up to 0.8ms between ears (when the speed of sound is 340m/s and the radius of the head is 0.1m) (Scharine & Letowski, 2005). ITDs can be used to detect the arrival of the initial onset of a sound, as well as changes in the arrival time of the sound's amplitude envelope (John C. Middlebrooks, 1997; Scharine & Letowski, 2005). This binaural cue works well for sounds with a sudden onset or dynamic envelope, but not for sounds with very slow onset times or subtle frequency and level differences (Rakerd & Hartmann, 1985).

Interaural Phase Differences (IPD) are frequency dependent and are detected because of the relatively slow speed of sound combined with the longer wavelengths of low frequencies. The use of IPDs requires both ears to hear the same cycle of a sound with no more than a 180° phase difference (Scharine & Letowski, 2005). For example, as a sound moves from midline to the right side of a listener, the sound (or a given phase angle of the sound) will be heard in the right ear slightly sooner than the left ear. This difference in phase or phase shift is used to detect the location of the sound similar to the ITD. However, if the phase shift exceeds 180°, the phase angle of the sound can appear to be heard first in the left ear. This apparent change in leading ear can introduce potential left/right confusions that may or may not be resolved with head movements. This is usually seen for frequencies above 1500 (John C. Middlebrooks, 1997; Scharine & Letowski, 2005). Wavelengths below 500 Hz are rather large and do not create enough interaural difference to be useful for localization (Scharine & Letowski, 2005). Figure 11 illustrates how, given a fixed time difference, a high frequency sound can create a large phase shift and a low frequency sound creates a much smaller phase shift. Because the maximum time difference created by the human head is limited (by the size of the head and the speed of sound), frequencies below 500 Hz do not create a large enough phase shift to be useful for sound source localization. Consequently, IPDs are useful for frequencies in the 500-1800 Hz range.

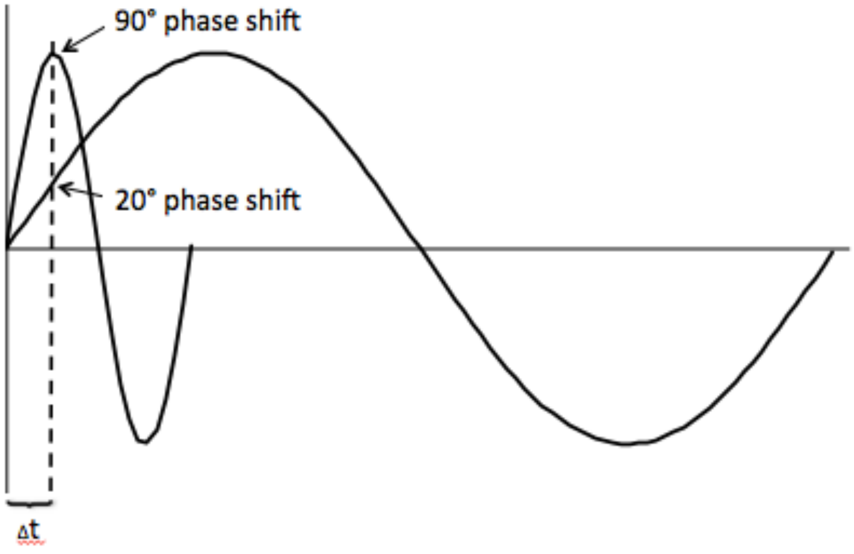


Figure 11. Relation between time delay Δt and phase shift for different frequencies (adapted from Gelfand, 1990, figure 13.8)

Interaural Level Differences (ILD) are frequency dependent and occur because of baffling, or the acoustic shadow of the head (Blauert, 1997). When a sound wave encounters an obstacle (such as the human head), it will diffract (i.e., bend) around the object to some degree. Both the size of the object and frequency of the sound determine how much sound will diffract (Scharine & Letowski, 2005). Low frequency sounds are capable of more diffraction than high frequency sounds, and smaller objects require less diffraction (offer less resistance) than larger objects (Scharine & Letowski, 2005). The drop in sound level caused by the human head allows for usable localization cues for frequencies above 3000 Hz (John C. Middlebrooks, 1997; Scharine & Letowski, 2005). In this frequency range a sound (off midline) will be heard at different levels in each ear with the far ear hearing the lower level. While there is no drop in sound level when a sound is at midline, the drop in sound level increases (for the far ear) as the sound moves from midline toward the interaural axis.

Cone of Confusion

Interaural differences can account for much of the localization accuracy in azimuth. However, interaural differences cannot explain vertical localization or front-back discrimination. Simply looking at interaural differences would suggest that a cone of confusion would occur for sounds presented at different locations but with the same interaural cues (Figure 12) (Duda, 1997). Sounds presented along the surface of this cone could not be accurately localized. This would result in front-back confusions and errors in elevation that approximate chance. However, actual localization testing indicates that front-back confusions and elevation errors are not common for broadband sounds, suggesting other cues assist the listener in localization (Makous & Middlebrooks, 1990).

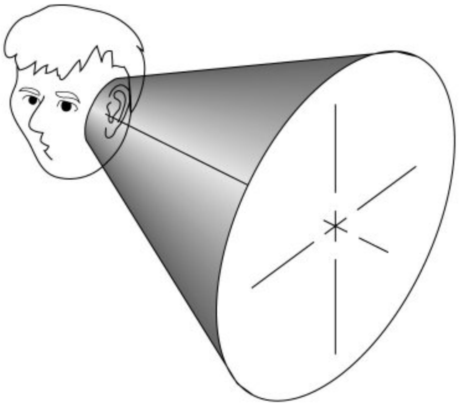


Figure 12. Cone of Confusion (from Steele, 2010)

One method of resolving cone of confusion errors is through head movements (Buser & Imbert, 1992). When head movements alter the relative position of the interaural axis to the sound source, interaural cues will differ. This difference will indicate the relative movement of a sound. By comparing the known movement of the head and the relative movement of the sound, the actual sound location can be determined. When head movements are not possible, or the duration is too brief to allow for adequate head movement, monaural localization cues must be used to aid in localization (Perrett & Noble, 1997).

Monaural Localization Cues

The pinna has been found to distort the frequency response of sounds in the range above 3000 Hz (Blauert, 1997; Scharine & Letowski, 2005). The type and magnitude of these distortions is dependent on the direction of the sound wave as it contacts the folds of the pinna (J. C. Middlebrooks & Green, 1991; John C. Middlebrooks, 1997). Because these distortions are dependent on the direction or location of a sound source, they can be used to localize the sound source (J. C. Middlebrooks & Green, 1991; John C. Middlebrooks, 1997). Localization is performed best with the ipsi-lateral ear when listening to a high frequency broadband sound (Oldfield & Parker, 1986). Using pinna cues allows humans to more accurately localize sounds within the cone of confusion and reduce front-back confusion errors (Scharine & Letowski, 2005).

Sound Characteristics

Spatial Location, Spectral Content, & Bandwidth

Sounds are localized best when presented directly in front of, and level with, the listener’s head (Oldfield & Parker, 1984; Stevens & Newman, 1936). As the signal is moved, in azimuth or elevation, localization accuracy decreases (Stevens & Newman, 1936). This loss of accuracy is also frequency dependent (Mills, 1958; Oldfield & Parker, 1984).

Butler (1986) tested localization accuracy using an 8000 Hz centered stimuli of increasing bandwidth (2, 4, 6, & 8 kHz). He found that the mean accuracy for binaural listening conditions increased with an increase in bandwidth. Accuracy in the smallest bandwidth (2 kHz) was within 30°-40° and increased to 10°-15° at the largest bandwidth (8 kHz). When the data was corrected for front-back errors, the overall accuracy improved dramatically for the narrow bandwidth conditions.

Stevens & Newman (1936) also found that front-back confusion occurred in 33-40% of the low frequency stimuli, but improved to less than 20% for a high frequency stimulus. Front-back confusion also decreases with an increase in bandwidth (J. C. Middlebrooks & Green, 1991; John C. Middlebrooks, 1992). Blauert (1997) reported that front-back errors that were equal in azimuth along the interaural axis (cone of confusion) occurred most often for narrow-band noise.

John C. Middlebrooks (1992) found that localization accuracy differed between narrowband noise and wideband noise. A 250ms noise burst was used for both stimuli. He found wideband (2-15 kHz) noise stimuli were localized with good accuracy (better in azimuth than elevation). Narrowband noise (6-12 kHz) was localized just as accurately as wideband noise in azimuth, but not in elevation.

Oldfield and Parker (1984) studied sound localization to white noise in both azimuth and elevation. They found that the absolute error in azimuth was approximately 4-6° between front-midline 0° to the lateral 90° azimuth. Accuracy worsened significantly at azimuth angles greater than 90°, with a peak error of almost 20° at 150° in azimuth (error numbers based on visual interpretation of graphic data in (Oldfield & Parker, 1984)). Errors in elevation ranged from 5-7° from front midline to about 110°, at which point they increased to a maximum near 12° at 170°(to the rear). Localization accuracy in azimuth was also measured at elevations above and below midline. While mean accuracy was rather stable 8-10° below midline, accuracy decreased to approximately 12° at 30-40° above midline. These error data are based on this author's visual interpretation of graphic data (Figures 3 & 4) in (Oldfield & Parker, 1984).

Alali and Casali (2011) studied horizontal localization accuracy using a standard, and spectrally modified, vehicle backup alarm as the stimuli. The frequency response of the standard backup alarm contained dominant frequency components at 1000, 1250, and 3150 Hz. The spectrally modified alarm added frequency components of 400 and 4000 Hz to the standard alarm. With the addition of the 400 and 4000 Hz frequency components localization accuracy showed slight but significant improvement.

Blauert (1997) performed a rating scale of several horizontal localization studies. Table 1 consolidates Blauert's data, showing accuracy in the midline by signal type. For a complete listing of Blauert's data sources see Table 2.1, p39 in (Blauert, 1997).

Table 1. Localization in azimuth accuracy at midline by signal type.

Signal type	Accuracy	Number of Studies
Impulse	0.75° – 2°	2
Sinusoids	1 – 4.4°	4
Narrowband noise	1.4° – 2.8°	1
Speech	0.9° – 1.5°	2
Broadband noise	3.2°	1

Studies using a variety of traditional stimuli (tone, hiss, or click (Stevens & Newman, 1936)), and nontraditional stimuli (speech, finger snap, or plucked guitar string (Chau & Duda, 1996)) of varying bandwidths, found that localization accuracy decreased with decreasing bandwidth. Speech was also found to be more difficult to localize (in elevation) than broadband noise (Davis & Stephens, 1974).

Onset Duration

Rakerd and Hartmann (1985) found that sounds with sudden or short onset times are more accurately localized than those with rather long (a few seconds) onset times. Rakerd further suggested that the increased accuracy was the result of envelope cues not available in slow onset stimuli, and a broadened spectral content of the stimuli. The broadened spectral content is expected to excite more neurons and also allow for monaural localization cues from the pinna.

Overall Duration

Localization in elevation and azimuth are rather accurate for stimuli with durations equal to or greater than 100ms (Macpherson & Middlebrooks, 2000). Blauert (1997) reported on two large-scale (n=600, 900 respectively) studies (Haustein & Schirmer, 1970; Preibisch-Effenberger, 1966b) that measured accuracy, in azimuth, of a 100ms pulse of white noise. The findings indicate that accuracy was ±3.6° at front midline, ±9.2° abeam to the left, ±10° abeam to the right, and ±5.5° to the rear. He also reported that absolute accuracy was biased toward the midline by approximately 10° for stimuli presented abeam left and right. Below 100ms, the greatest errors occur for elevation accuracy. Vliegen and Opstal (2004) measured the accuracy of wideband stimuli with durations ranging from 3 to 100ms. They found that accuracy for elevation increased with stimulus duration, while accuracy for azimuth remained constant. Macpherson and Middlebrooks (2000) found similar results, i.e., that elevation accuracy increased with stimulus duration.

Intensity

The intensity or sensation level (SL) of a signal can also affect how well a sound can be localized. Comalli and Altshuler (1976); (as cited by Sabin, Macpherson, & Middlebrooks, 2004) and Altshuler and Comalli (1975) found that horizontal localization errors increased as the intensity of a narrow band noise was reduced. The accuracy of vertical localization is also decreased with lower intensity levels. Davis and Stephens (1974) studied this effect with both speech and (white) noise. Each signal was two seconds in duration and was presented in the vertical plane at midline. Overall accuracy was better with higher intensities and with noise stimuli over the speech stimuli. Their results indicate that the mean accuracy in localization continuously improved from 9-12° (@10 dB) to an asymptotic level near 2-3° (@50-70 dB). Other studies (Hebrank & Wright, 1975) have suggested that vertical localization accuracy remains independent of intensity until the intensity drops below 40 dB SL. At this point, accuracy decreases with the intensity.

Sabin et al. (2004) performed a rather comprehensive study of auditory localization at a variety of intensities using a 250ms broadband noise (0.5-16 kHz). Unlike other studies, they tested accuracy down to audibility intensity thresholds for both vertical and horizontal stimuli. They found that audibility thresholds were lowest (best) at a 45° angle (in azimuth) from the front midline position. Thresholds were worse to the rear (180°) with the front midline position falling almost halfway between the best and worst threshold values. Localization accuracy for sounds near threshold was poor, with a bias towards localizing the sound in the front midline position, for both horizontal and vertical planes. As the sensation level of the stimulus increased, so did the accuracy in azimuth, reaching an asymptote at 10 dB SL. Vertical accuracy lagged behind horizontal accuracy, and did not asymptote until 30 dB SL. Differences were noted between front and rear vertical localization, due in part to the poorer thresholds to the rear of the listener. Low intensity stimuli were not audible to the rear, but when they were increased to become audible, accuracy was quickly gained (sooner than for frontal localization).

Vliegen and Opstal (2004) and Macpherson and Middlebrooks (2000) found that while horizontal accuracy was not affected by loud sounds, vertical accuracy was. When presented with a short duration (3-100ms) stimulus, accuracy in elevation decreased as the intensity increased from 48 dB to 73 dB (Vliegen & Opstal, 2004) or ≈30 to ≈55dB (Macpherson & Middlebrooks, 2000). William Morris Hartmann and Rakerd (1993) found that vertical localization also decreased as the intensity of the stimulus increased from 80 to 98 dB. In their study, this effect was seen in a click stimulus but not in broadband noise

Movement

Movement of a sound source can change its relative elevation, azimuth, and/or distance. Localization of a moving sound source that is relatively slow and near the listener will use the same cues as when the listener moves his/her head (see listener movement in next section). A rapid and somewhat prolonged movement of a sound, however, can include Doppler cues. Doppler cues are the perceived frequency shift of a sound as it approaches, passes, and then retreats from the listener. The Doppler effect is dependent upon the rate of change in the linear distance from the listener to the source and is independent of the perceived direction of movement (vertical or horizontal). When a sound source is moving rapidly, the frontal sound waves are compressed while rearward waves are expanded. This compression or expansion causes the frequency of the sound to increase or decrease respectively for a stationary listener (Johnson, Walker, & Cutnell, 1977). The Doppler effect is most apparent (sudden and intense) when a sound source passes near the listener. As a fast moving sound source approaches and passes the listener there is a sudden decrease in the apparent frequency of the sound. The closure rate, between the source and the listener, will determine how salient the drop in frequency is to the listener. Closure rate will increase with increased source speeds, and as the path of travel becomes closer to the listener. A listener may also experience intensity differences for sounds that pass near them. However sounds that do not pass near the listener may contain frequency changes without apparent intensity changes. Accuracy of distance estimation using Doppler cues is poor and subject to the same bias experienced by other distance cues (Scharine & Letowski, 2005; Pavel Zahorik et al., 2005).

Environmental Characteristics

Roles of Direct and Reflected Rays

Sound can take several paths between the source and the human listener. The direct path is often dominant, with greater intensity and the least amount of distortion (Pavel Zahorik et al., 2005). However, hearing only the direct sound is rare and would require an anechoic environment void of any obstacles between the source and receiver. More commonly, sounds are heard from a combination of direct and reflected paths. The addition of reflected sounds provide a wealth of information to the trained listener and allow for a greater understanding of the surrounding environment.

Reflected sounds can be classified into early reflections that occur within 50ms of the direct source, and late reflections that occur after 50ms (Scharine & Letowski, 2005). Early reflections cannot be distinguished from the direct source sound, and are perceived as the same. They often will increase the overall level of the sound. When localizing direct and early reflections, the sound that arrived first to the listener is used to determine the location of the source. This phenomena is called the precedence effect (Scharine & Letowski, 2005). Localization accuracy can improve when early reflections contain the same location cues or it can deteriorate when location cues differ from the direct source (Rakerd & Hartmann, 1985). Rakerd and Hartmann (1985) studied the effect of localization accuracy when early reflections provided inaccurate localization cues. They caused reflection to originate above, below, and to either side of the direct source. Their findings indicate that mean localization errors remained below 5° for impulsive tones and 11° for slow-onset tones. They expected reflections from above and below to improve accuracy but they did not. This may be a result of poorer accuracy (in azimuth) at elevations other than level with the head (0°) (Bolia, D'Angelo, Mishler, & Morris, 2001).

Late reflections will either be perceived as lengthening the duration of the direct sound, (reverberation) or as a second separate and distinct sound (echo) (Scharine & Letowski, 2005). When late reflections extend the perceived duration of a sound, they provide information about the physical properties’ of the acoustic environment (size and surface types). When localizing sound with late reflections, localization performance will degrade with increased reverberation time (W. M. Hartmann, 1983). W. M. Hartmann (1983) found that localization error for broadband noise increased in a reverberant room compared to a non-reverberant room. The magnitude of mean error in both rooms remained below 5° for frontal localization.

Obstructions

Obstructions are physical objects or conditions in an acoustic environment that affect sound transmission through “diffusion (scattering), diffraction (bending around the edges), refraction (bending during transmission to other media), acoustic shadow, interference (e.g., acoustic beats), standing waves, amplification (resonating), and attenuation (damping)” (Scharine & Letowski, 2005, pp. 11-12). Sound localization can be affected to some degree by any or all of these distortions. The most significant effect is seen when the direct sound is not the first or loudest source received by the listener. When this occurs, the listener will not localize on the direct sound but rather a reflected sound. The reflected sound may not represent the veridical source location and can cause extreme errors in accuracy. These types of localization errors often occur in an urban combat setting. For example, a listener may be in an acoustic shadow (from a building) that prevents hearing the direct sound (around the corner of the building). However, sounds reflected from a building across the street are heard (first and loudest) and localized, albeit in the wrong direction. High frequency sounds are more vulnerable to sound path barriers due to their relatively short wavelengths and inability to effectively diffract around obstacles.

Background Noise

While many studies of localization performance are performed in quiet environments, the modern battlefield is often filled with a cacophony of sounds. These sounds are sometimes desired by the combatants to “surprise and startle the opposition and to convey speed and authority” (Scharine & Letowski, 2005, p. 18). Sound can also be used to mask troop movement and annoy or disorient enemy forces (Scharine & Letowski, 2005). However, these sounds can also degrade speech communication and sound localization. Background noise can mask the direct as well as reflected sounds. Reflected sounds are easily masked, as they are often heard at a lower level than direct sounds. When the reflected sounds are masked, many of the localization and distance cues are also masked. Studies of sound localization in noise show that a signal-to-noise ratio of -7 to -9 is needed to accurately localize a sound source at least 50% of the time (K. S. Abouchacra, Emanuel, Blood, & Letowski, 1998; Letowski, Mermagen, & Abouchacra, 2004; as cited by Scharine & Letowski, 2005). Other studies showed that the sensation level of the signal needs to be at least 9 dB to obtain similar performance

(K. Abouchacra & Letowski, 2001; as cited by Scharine & Letowski, 2005; Smith-Abouchacra, 1993).

Listener Characteristics

Movement

The ability and natural tendency to move the head when attempting to localize a sound source can improve localization ability (Buser & Imbert, 1992). It can be argued that head movement allows for increased spatial information as well as accuracy. Without head movement, and disregarding the spectral effects of the head and pinna, a listener can erroneously localize a sound source that is within a cone about the interaural axis (Wallach, 1939). Movement of the interaural axis, such that the intersection of several cones (generated by the movement) represent the veridical source, can overcome this cone of confusion (as cited by Perrett & Noble, 1997; Woodworth & Schlosbert, 1954). Perrett and Noble (1997) tested this hypotheses and found head movement to improve localization. Specifically, natural head movements reduced front-back errors and improved accuracy in azimuth with small improvements in elevation (Table 3). The improvements were most noticeable when the stimulus duration was longer (3 seconds vs. 500 ms). Due to the relatively slow reaction time needed to actually move the head in response to a stimulus, head movement is only beneficial for longer duration stimuli. However, a head movement that was initiated prior to the stimulus onset, and which continues throughout stimulus presentation, can also increase localization accuracy. This type of pre-movement can result in accuracy that is better than natural (reactionary) movement (Table 2) under the Pre-stimulus Movement column). In a review of the effects of head movement, J. C. Middlebrooks and Green (1991) found that some studies indicate that head movements do not account for much improvement in localization accuracy.

Table 2. Effects of head movement on localization. (adapted from Perrett & Noble, 1997)

Metric	Stimulus (seconds)	Reactionary Movement	Motionless	Pre-stimulus Movement
Front-back error	3.0	1%	30%	2%
	0.5	17%	24%	3%
Accuracy – Azimuth	3.0	22°	42°	26°
	0.5	37°	41°	30°
Accuracy – Elevation	3.0	21°	28°	23°
	0.5	26°	28°	25°

Hearing Loss

Individuals with hearing loss may experience difficulty localizing a sound source. Hearing loss that is symmetrical and no worse than 30-40dB should cause little, if any, loss in horizontal localization accuracy or blur (Blauert, 1997). Studies with participants over age 60 show decreased localization ability (Blauert, 1997; Freigang et al., 2011; W. Noble, Byrne, & Lepage, 1994; W. Noble, Byrne, & Ter-Horst, 1997). It is unclear if this decrease in performance is related to hearing loss or age, as it is difficult to separate the two.

Individuals with asymmetrical hearing loss, up to total deafness in one ear, will experience a decrease in localization accuracy and an increase in localization blur (Abel & Lam, 2008; Blauert, 1997; Slattery III & Middlebrooks, 1994). However, with time, accuracy and blur may improve (Slattery III & Middlebrooks, 1994). Preibisch-

Effenberger (1966a) as cited in (Blauert, 1997) studied several (n=32) people with unilateral deafness. They reported localization blur of ±32° for sounds located abeam the deaf ear, ±39° for sounds abeam the hearing ear, ±33.7° for sounds located in front (0°), and ±42° for sounds located to the rear (180°). Mean accuracy was within 7° abeam the deaf ear, 20° abeam the hearing ear, 19° to the front and 1° to the rear. Slattery III and Middlebrooks (1994) found that localization abilities of individuals with a congenitally deaf ear showed results ranging from poor to near normal.

Attempts have been made to correlate hearing thresholds to localization abilities. W. Noble et al. (1994) and W. Noble et al. (1997) found that the type and configuration of hearing loss could be associated with various types of localization deficits. They found that symmetrical high frequency sensorineural hearing loss decreased vertical localization accuracy, and mid to high frequency sensorineural hearing loss increased front-back confusion. Conductive or mixed hearing losses were associated with horizontal localization problems. Koehnke and Besing (1997) tested binaural and monaural localization cues in people with normal hearing, bilateral symmetrical, and unilateral asymmetrical hearing loss. Their findings indicate that people with similar audiometric thresholds do not perform localization equally well. Also, people with high frequency loss can show poor discrimination of both high and low frequency binaural localization cues.

Hearing Protection

The primary means of preventing hearing loss in the military has been the use of health education and hearing protection. While hearing conservation efforts within the military have reduced the prevalence and severity of hearing loss, the recent increase in operational tempo and combat deployments have reversed these trends (Chandler, 2006). Many veterans and active duty service members report that they are aware of the need for and importance of hearing protection in a combat environment. However, many report that they do not wear hearing protection because of the decreased situational awareness they experience during use (Abel, 2008). Specifically, they indicate that when wearing hearing protection they cannot hear and understand speech in quiet environments, or detect, identify, and localize sounds made by friendly and enemy forces. The amount and severity of hearing loss in the military has increased, as many service members choose not to wear hearing protection in combat due to a loss of situational awareness when wearing hearing protection.

When using hearing protection, the ITD/ILDs (that rely on a specific interaural distance and head size/shape) and the pinnae effects (that rely on the shape and folds of the pinna) are distorted or completely lost. Distortions of low frequency temporal cues were found when wearing uniform attenuation earplugs (Vause & Grantham, 1999). Distortions in the interaural level differences can be experienced when either earplugs or earmuffs are not providing the same attenuation for each ear. This can easily occur when the earplugs are not inserted uniformly or when earmuffs have a seal leak caused by hair, glasses (Ahroon, Gordon, & Ostler, 2002), or other objects breaking the seal (Robinette, Ahroon, & Ostler, 2003). (Bolia et al., 2001) found that horizontal localization errors increased with the use of either earmuffs or earplugs. They suggested that the loss of pinna cues might negatively affect horizontal localization accuracy in the absence of ITD/ILD changes. (Bolia et al., 2001) also found that localization errors, in elevation, increased with the use of either earmuffs or earplugs. The loss of elevation cues with earmuffs is understandable, as the muffs cover the pinna and distort the pinna cues. The loss of localization accuracy with earplugs is not as apparent. It is possible that the non-uniform attenuation and greater amount of attenuation in the high frequencies found in earplugs may account for the loss of elevation accuracy.

As the magnitude of these distortions increases, localization accuracy and situation awareness decrease. In an attempt to overcome the negative effects of traditional hearing protection, many electronic devices (in-the-ear and over-the-ear) have been developed for ground combat forces. These devices are designed to allow audition of soft and moderate sounds, while still providing protection from hazardous levels of impulse and continuous noise. The acceptance of these devices has been mixed. While the protective effects of these devices are well known and desired, their deleterious effects on sound localization are still considered unacceptable by Soldiers. This is especially true for those who require keen localization abilities (Alali & Casali, 2011; Atherley & Noble, 1970; John G. Casali, Ahroon, & Lancaster, 2009). The use of both passive or electronic HPEDs alters auditory localization cues enough to prevent accurate localization (D. S. Brungart, Kordik, Simpson, & McKinley, 2003; W. G. Noble & Russell, 1972).

Auditory cues used to enable localization are vital to ground combat operations (John G. Casali et al., 2009; Scharine & Letowski, 2005). Unfortunately, the use of an over-the-ear HPED effectively distorts both azimuth and elevation cues that allow for accurate localization (Abel, Boyne, & Roesler-Mulroney, 2009). This loss of localization and situation awareness leads Soldiers to lay aside their hearing protection at critical times. The effect of an HPED with external microphones is to effectively widen the head, which results in a loss of localization for sounds near the median plane (Durlach, Shinn-Cunningham, & Held, 1993). The folds in the human pinna (external ear) allow for vertical localization to occur (Hofman, Riswick, & Opstal, 1998; J. C. Middlebrooks & Green, 1991; Van Wanrooij & Van Opstal, 2005) and allow the sound source to be externalized (perceived outside of the head) (Batteau, 1963). The physical position of the ears on either side of the human head enables localization on the horizontal axis. The distance and path sound is required to travel to be heard in both ears creates interaural time differences (ITD) and interaural intensity differences (IID). ITDs enable sound localization for low frequency sounds, while IIDs enable localization of high frequency sounds (J. C. Middlebrooks & Green, 1991). While this distortion alters veridical localization cues, phase and intensity cues are still present and allow for higher order processing such as speech intelligibility with competing signals (D. S. Brungart, Kordik, & Simpson, 2004). The fact that these cues are still present, albeit distorted, suggests that sound localization may still be possible if the brain can learn or adapt to the new (altered) localization cues.

Use of over-the-ear, and some in-the-ear, hearing protection will distort monaural cues provided by the folds of the pinna (Bolia et al., 2001; Borg, Bergkvist, & Bagger-Sjoback, 2008; Chung, Neuman, & Higgins, 2008; W. G. Noble & Russell, 1972). Hearing protectors can also distort interaural intensity and phase cues (Abel & Hay, 1996; Borg et al., 2008; Chung et al., 2008). Protectors that do not provide uniform attenuation between ears will alter ILD cues. This can occur with seal leaks, or when in-the-ear devices are not uniformly inserted. Electronic pass-through hearing protectors will distort localization cues if the attenuation/amplification is not uniform between ears (Borg et al., 2008; Chung et al., 2008). Electronic devices can also affect ITDs because of the signal processing that is required (Borg et al., 2008; Chung et al., 2008). The bandwidth of electronic devices is also a limiting factor as it can limit the cues (especially high frequencies) available to the listener (D. S. Brungart, Kordik, et al., 2003; King & Olfield, 1997).

Studies of localization with hearing protection indicate that, in general, in-the-ear protection allows for better localization than over-the-ear protection (Borg et al., 2008; D. S. Brungart, Eades, & Simpson, 2006; W. G. Noble & Russell, 1972). Abel and Hay (1996) found that earmuffs caused more problems, than earplugs, for high frequency stimuli and front-back confusion. They felt that this was due to the loss of pinna cues when wearing earmuffs. The use of both earplugs and earmuffs (double protection) is much worse than the use of either type of single protection (D. S. Brungart, Simpson, & McKinley, 2003; Simpson, Bolia, McKinley, & Brungart, 2005). Bolia et al. (2001) found the use of double protection increased localization errors by 5° in azimuth, 15° in elevation, and 24-27% in front-back confusion.

When using an electronic hearing protector, that provides pass-through of low level ambient sounds, dichotic signal presentation is more effective than diotic (Alali & Casali, 2011; W. Noble, Murray, & Waugh, 1990) and front-back confusion is still a problem for over-the-ear devices, as pinna cues are lost (Abel & Hay, 1996). Talcott, Casali, Keady, and Killion (2012) studied localization with in-the-ear and over-the-ear HPED's that provide electronic pass-through. They found that localization accuracy of in-the-ear HPED was better than over-the-ear HPED. However, none of the HPED conditions was as good as the open ear condition. They also found that all HPEDs had similar front-back errors and none of the HPEDs were as good as the open ear.

Brungart, Hobbs, and Hamil (2007) studied localization of eight HPEDs with electronic pass-through. Four were in-the-ear devices and four were over-the-ear devices. Their results indicate that localization performance with all HPEDs was worse than the open-ear condition. Table 3 shows their results for the open-ear condition as well as the range of results for all HPED conditions combined.

Table 3. Horizontal localization accuracy for eight HPEDs and open-ear condition for a 65 dB (SPL) stimulus (adapted from Brungart et al., 2007)

Condition	Stimulus	Accuracy
Open-ear	350 ms burst	12°
	Continuous	2-3°
HPED	350 ms burst	35-50°
(combination of 4 ITE and 4 OTE)	Continuous	18-30°

Abel, Tsang, and Boyne (2007) studied localization of two HPEDs with electronic pass-through. The ITE HPED was the Nacre QuietPro in the push-to-talk (PTT) mode) and the OTE HPED was a Racal Slimgard II in the talk-through-circuit (TTC) mode. They placed four speaker pairs, with 30° separation, centered at 0°, 90°, 180°, and 270°. The listeners were asked to identify the speaker where they heard the stimulus. Their results indicate that localization performance with the HPEDs was worse that the open-ear condition. Table 4 shows their results for the open-ear condition as well as each HPED condition.

Table 4. Horizontal localization accuracy for two HPEDs and open-ear condition for a 75 dB (SPL) 300 ms broadband noise (adapted from Abel et al., 2007)

Condition	Stimulus	Accuracy
Open-ear	300 ms broadband noise	94.1%
Racal (OTE) TTC	300 ms broadband noise	69.2%
Nacre (ITE) PTT	300 ms broadband noise	71.1%

Alali and Casali (2011) studied localization of two OTE HPED with electronic pass-through, four passive ITE and one passive OTE HPDs. Of the OTE HPEDs, one was Diotic (custom built muff) and the other was dichotic (Bilsom). The Bilsom dichotic muff was similar to all other products (except the custom muff) and the open-ear condition for both localization accuracy and front-back errors. Table 5 shows the range of horizontal accuracy and front-back error for the Bilsom dichotic muff with other passive devices and the open-ear condition.

Table 5. Horizontal localization accuracy and front-back error for a standard and spectrally modified back-up alarm with both 60 dB and 90 dB of pink noise

Condition	Horizontal Accuracy	Front-Back Error
Bilsom dichotic muff	24.5°	11.6%
Other passive devices	11.8° – 26.1°	4% – 12.7%
Open-ear	15°	6.3%

Hearing Protection Technical Features

Passive HPD are evaluated by determining their attenuation as a function of frequency for both continuous and impulse noise. These measure provide the frequency response and the overall noise reduction rating NRR of the HPD. With the introduction of level dependent devices (both passive and active) the frequency response can now be measured as a function of the input level as well. This provides a more complete understating of the acoustical properties of a HPD.

HPEDs with electronic pass-through have now added another, even more complex, layer to the design and evaluation of HPEDs. Electronic pass-through HPED provide both passive attenuation and electronically modulated gain to the ambient signal (Casali, 2010b). The electronically modulated signal can also be measured to determine its operating envelope and functional characteristics. The operating envelope is the dynamic range and bandwidth of the system. Within this envelope the parameters of gain/attenuation as a function of frequency (frequency response) and input level (input/output gain) can be evaluated. These parameters can be manipulated by changing the hardware (microphone, receiver (speaker), microprocessor) or adjusting the microprocessor settings (e.g., compression ratio, knee-point, attack/release time, and crossover frequency)

Brungart et al. (2007) studied the performance of several HPEDs, with pass-through technology, using the following measures: Input/output gain curve, frequency response, interaural time delay, interaural level difference, and Head Related Transfer Function (HRTF) magnitude. These parameters are important to the localization process. They found that while some of these measures were very close to open-ear results, localization performance could not be predicted. They concluded that more research is needed to determine what design parameter influence localization performance with HPEDs.

The ability to easily understanding a speech signal is equally important. The quality of a speech signal can be evaluated by measuring the sampling/bit rate, attack/release time, signal phase, unwanted signal distortion (e.g., intermodulation distortion, total harmonic distortion, equivalent input noise, wind noise, and internal feedback), speech recognition, and the speech intelligibility index.

Other parameters that may be of interest to the user would include the current draw, battery capacity, life expectancy, performance in extreme temperature, humidity, dust, altitude, impact/abrasion resistance, and electromagnetic fields.

Distance Judgments

Localizing the distance of a sound source is not as well studied or understood as localizing in azimuth and elevation (J. C. Middlebrooks & Green, 1991; Pavel Zahorik et al., 2005). Distance estimations are generally underestimated for sounds greater than one meter, but overestimated for sounds closer than one meter (Pavel Zahorik et al., 2005). Distance localization uses different types of cues, depending on the actual distance of the sound source. Near sounds (within 3m) use intensity cues, spectral cues, and interaural phase/intensity difference. Intermediate sounds (3-15m) rely primarily on intensity, but can also use spectral cues, sound decay, and interaural phase/intensity differences. Distant sounds (15m or more) use intensity cues, spectral cues, and sound decay.

Intensity changes of a sound are used at all distances. Sound intensity is known to decrease as a function of distance traveled. This is commonly known as the inverse square law, and states that a sound level will decrease by 6 dB every time the distance is doubled (Coleman, 1963; Mershon & King, 1975). This law assumes a free field condition, which may or may not be experienced by the listener. Accuracy of distance estimation in an anechoic room is poorer than accuracy in a reverberant space (Mershon & King, 1975), suggesting that intensity cues alone are not very useful for normal environments. Sound intensity in a reverberant space will decrease at a smaller rate due to the addition of reflections. Interestingly, listeners in a reverberant space can detect changes in a sound's distance even when the intensity of the sound was kept uniform at the listeners ear (P. Zahorik & Wightman, 2001). This finding suggests that intensity is not the only cue used in distance estimation (Pavel Zahorik et al., 2005).

The spectrum of a sound can change in two ways. First, a sound spectrum is known to increase in the low frequencies as it nears the listener in a near sound condition (within 3m) (Coleman, 1963). This is a result of the more curved wave front experienced for near sounds when compared to a more planar wave front for distant sounds (Blauert, 1997). Bekesy (1960) explained this phenomenon by examining the particle velocity of a near sound source. He found that the increase in low frequencies was due to the relationship between flow velocity and it first time derivative (pressure change). A sound source within 3m will also experience changes in the ITD and IID with changes in distance. As the distance decreases the IID and ITD will increase due to the increased relative distance sound is required to travel to reach the far ear. The spectrum of sounds traveling greater distances (distant sounds) will decrease in the high frequencies (Blauert, 1997; Coleman, 1963). This drop in high frequencies is the result of sound absorption in air, and is affected by both the humidity and temperature of the air (Coleman, 1963). Because these environmental changes affect the spectrum, absolute distance estimation is difficult. Relative estimations, however, can be made.

To estimate the absolute distance of a sound, using either the intensity or spectrum cues, requires the listener to have prior knowledge of the sound (Pavel Zahorik et al., 2005). Without this prior knowledge, judgments of distance are limited to relative comparisons to the same sound at a different distance.

The interaural intensity and phase ratio is similar to ILDs and IPDs used in azimuth localization. Here they are being used to determine the distance of a sound with a fixed azimuth. This distance cue is only useful for near and intermediate sounds (within 15m) (Coleman, 1963; Pavel Zahorik et al., 2005).

Increased reverberation or sound decay time is also a distance cue. As reflected sounds are combined with the direct sound signal, the sound will appear to decay slower or contain reverberation. The addition of reflected sound also changes the ratio of direct to reflected sound heard by the listener. As distances increase, this ratio favors reflected sounds over direct sounds (Pavel Zahorik et al., 2005). This effect not only helps describe the physical environment of the sound space, but also provides information about the distance of the sound from the listener. Sounds presented over a greater distance, in a reverberant environment, will have greater amounts of reverberation and sound decay (Mershon, Ballenger, Little, McMurtry, & Buchanan, 1989; Mershon & King, 1975). By masking the amount of decay or reverberation with masking noise, the sound can be made to appear closer (Mershon et al., 1989). Sounds presented in an anechoic environment will also lack these cues and distance localization will be underestimated. For reverberation and sound decay cues to be effective, the listener must have a veridical mental model of the sound space and its effect on sounds in the environment.

Speed Judgments

Estimating the speed (velocity) of a moving sound requires detecting a change in a sounds' horizontal, vertical, or distance location over time. The speed of a sound moving in azimuth or elevation can be estimated based on the distance (or arc) traveled for a given time period ($average\ velocity = \Delta distance / \Delta time$). The accuracy of this method is tied to the accuracy of static localization in azimuth and elevation. The minimum audible movement angle (MAMA) is used to determine the minimum arc that is required to detect movement in a given direction (Grantham, 1997). Estimates of speed will require movement that meets or exceeds the MAMA. The MAMA, for horizontal movement, is generally thought to be double the minimum audible angle (MAA). Under ideal conditions (frontal position), and for a slow moving target, the MAMA is about 2-5° (Grantham, 1986).

Chandler and Grantham (1992) found that MAMAs increased with increased velocity, increased frequency, decreased bandwidth, and increased deviation from the frontal (0° azimuth) position. Velocity changes resulted in mean MAMAs of 8.8° @ 10°/s to 20.2° @ 180°/s. Grantham (1986) measured horizontal MAMAs for angles of 30° and velocities of 22° to 360°/s. He found MAMAs of 5° to the front (0° azimuth) and 30° or more to the side (±90° azimuth). When determining the differential velocities (ranging from 0° to 150°/s) of two sources, a velocity DL of 4 to 10°/s is required. Altman and

Viskov (1977) found velocity DLs of 10.8 – 19.3°/s for velocities of 14-140°/s respectively. Grantham (1986) also suggested that listeners responded to changes in static spatial position rather than the actual velocity of a sound source.

Estimation of speed for a sound that is moving toward or away from the listener requires the use of distance estimation cues. Detecting the rate of change for distance estimation cues (near, intermediate, and distant), in addition to Doppler cues, will enable speed estimations. Intensity of the sound will change (increase/decrease) more rapidly when close to the listener. Spectral changes will become more broad-based (increased high frequency sounds) with less reflected sound as it approaches the listener. A frequency shift in the spectrum will also be heard as the sound passes the listener. This is known as the Doppler effect.

Auditory Learning

Auditory sensory adaptation (auditory learning) occurs gradually throughout childhood and adolescence (Clifton, Clarkson, Gwiazda, Bauer, & Held, 1988; Held, 1955b; Welch, 1978). Gradual changes in head size and the pinna throughout these years continuously changes the binaural and monaural cues used in sound localization. Yet, our overall localization abilities remain intact throughout this time period. It is also possible to acquire the ability for rapid auditory sensory adaptation (Lewald, 2002; G. H. Recanzone, 1998). Hofman et al. (1998) found that modifying the shape of the folds in the pinna, using a custom earmold, resulted in an immediate loss of vertical localization abilities. However, within 4 to 6 weeks of continued earmold use, adaptation was evident as vertical localization was restored. Van Wanrooij and Van Opstal (2005) found similar adaptation results within 11 days when a modified pinna earmold was placed in only one ear.

Pseudophones have been used to distort horizontal localization cues by rotating the horizontal axis 20-30° to either the left or right (Canon, 1971; Freedman & Gardos, 1965; Freedman & Stampfer, 1964; Freedman, Wilson, & Rekosh, 1967; Held, 1955b; Mikaelian, 1969) (Figure 13). Use of the pseudophones with passive or active training allowed for various levels of adaptation within 5 minutes to 7 hours. Greater adaptation was achieved through active training or longer durations of time. Active training includes methods that enable or increase sensory adaptation and often include physical interaction with the environment (Held, 1955b). Zwiers, Opstal, and Paige (2003) distorted horizontal localization cues by compressing the visual field from 50° to 20°. Over the course of 2-3 days, participants carried out normal interaction with their environment and received visual feedback training. All participants showed significant adaptation to sound localization.

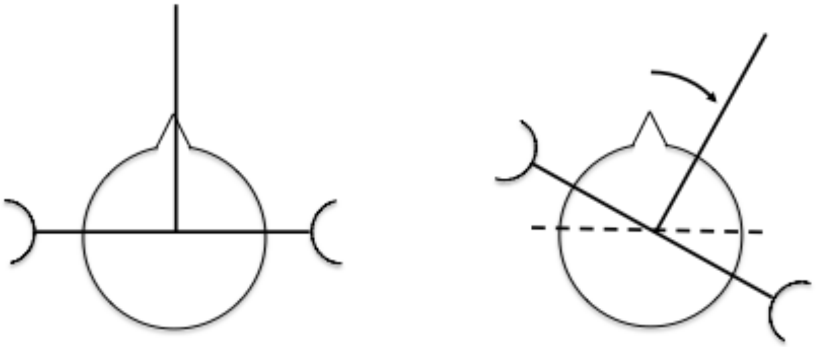


Figure 13. Pseudophones (top down view) showing normal axis (left panel) and axis rotated to the right (right panel) (adapted from Held, 1955b, figure 3).

Palmer, Nelson, and Lindley (1998) reviewed several studies that explore the plasticity of the adult auditory system. It has been long known that the human auditory system is tonotopically arranged from the cochlea through the auditory cortex (Talavage et al., 2004). Because of the apparent hard wiring of the auditory system, the possibility of neural plasticity was in question. If there is plasticity, where in the auditory system could it occur? Plasticity has been found to occur in both the cortical (as cited by Palmer et al., 1998; Salvi, Henderson, Fiorino, & Colletti, 1996) and subcortical (M. Devor & Wall, 1978; Marshall Devor & Wall, 1981; Dostrovsky, Millar, & Wall, 1976; Pollin & Albe-Fessard, 1979; Wall & Egger, 1971) level in mammalian adults. While the majority of these studies are performed on animals, some studies have also shown central plasticity to sudden changes in the human auditory system (Vasama & Makela, 1995). In their review of the literature, Palmer et al. (1998) concluded that plasticity occurred primarily at the cortical level, with only limited change occurring at subcortical levels.

Many studies either induced or observed an acute lesion of the auditory sense organ and later measured plastic changes. The evidence of plasticity was measureable between 30 to 90 days after the initial insult (Rajan, Irvine, Wise, & Heil, 1993; Robertson & Irvine, 1989; Schwaber, Garraghty, & Kaas, 1993). Other studies were able to measure plasticity and performance improvements through training alone (G. H. Recanzone, Merzenich, & Jenkins, 1992; G. H. Recanzone, Schreiner, & Merzenich, 1993; Gregg H. Recanzone, Merzenich, Jenkins, Grajski, & Dinse, 1992). Kraus et al. (1995) was able to measure plasticity in humans after only one week (6 hours total) of training in speech discrimination. The effects of training were also measured, with similar results, one month after the training was complete.

Russell (1977) studied auditory adaptation to passive earmuffs with a horizontal localization task. The study lasted seven days. Participants were tested on day one and seven and received two practice/training sessions on days two through six. It is not clear if participants wore the earmuffs throughout the day or only when in testing/training sessions. They do not indicate the length of the practice/training sessions either. They do indicate that a total of 240 signals were presented during each practice session. Participants were encouraged to improve their overall localization score but were not provided feedback for each localization response. Their findings indicate that overall accuracy improved from approximately 50% on day one to 70% on day seven. However, they concluded that adaptation was not complete and that "listeners cannot adapt to earmuffs" (Russell, 1977, p. 220). This conclusion seems a bit premature given the short duration (7 days) and limited feedback of this study. The trend in improved accuracy with such limited feedback suggests that adaptation is possible given enough time and adequate feedback.

Measures of performance with hearing aid use in humans has shown that improvements to syllable recognition increase rapidly in the first week of use, and continue to improve for up to eight weeks. In this study the participants were older (43 to 84 years old, mean = 66.7 years old) than the typical combat soldier. In light of the potential decline in cognitive plasticity with increased age (Blamey et al., 1996; Kliegl, Smith, & Baltes, 1989), the potential for young soldiers to benefit from plasticity to active hearing protection devices, which are similar to hearing aids, is good.

Some investigators have been concerned that the remapping of auditory information may have negative outcomes for other cognitive processes that rely on those cues (as cited by Palmer et al., 1998; J.F. Willott, 1996; James F. Willott, 1996). While these concerns are real, there is evidence from hearing aid literature that suggests that potential effects are minimal at best. Palmer et al. (1998) suggests that the same plasticity that allowed for the initial changes will also allow for the changes to be reversed, given the right conditions. Studies with hearing aid users demonstrated their ability to localize better without their hearing aids than with, yet not as good as normal hearing listeners (Van den Bogaert, Klasen, Moonen, Van Deun, & Wouters, 2006). Considering the negative effects of hearing loss on localization in general (W. Noble et al., 1994), this finding suggests that hearing aid use will have little effect on localization in an unaided condition.

Wright and Zhang (2006) performed a review of auditory adaptation to various types of altered localization cues. They presented five general conclusions from their review 1) adaptation to altered localization cues could be complete for vertical cues but only partial for horizontal cues, 2) adaptation occurred rapidly, usually within 1-2 hours, 3) aftereffects were small in magnitude and only lasted a few minutes, 4) adaptation was not possible for some alterations (e.g., left-right reversals), and 5) adaptation was highly variable across subjects. Wright and Zhang (2006) also noted that adaptation appeared to be more complete in the left hemisphere (Shinn-Cunningham, Durlach, & Held, 1998; Wells & Ross, 1980) and perceived to be complete for subjects who experienced the alterations in every day environments (Held, 1955a; Javer & Schwarz, 1995).

While these findings are significant and interesting, it should be noted that the complete adaptation found in vertical localization studies was accomplished with constant sensory cue alteration (modified pinna earmold) over the course of 19 to 39 days (Hofman et al., 1998) and 7 to 49 days (Van Wanrooij & Van Opstal, 2005). Studies showing partial adaptation in horizontal localization occurred with intermittent sensory cue alteration and a shorter overall exposure period. The adaptation period for horizontal localization studies included 3 to 5 full days (Javer & Schwarz, 1995), 7-8 hours (Held, 1955a), and 16 hours in a 2-6 week period (Shinn-Cunningham et al., 1998). The large discrepancy in total exposure time between vertical and horizontal adaptation studies may account for the limited adaptation seen in horizontal localization studies.

In the Palmer et al. (1998) review of several hearing aid benefit studies, the improvements were often measured between 3-16 weeks, at which point the improvements reached a plateau. These findings are consistent with the animal data that measured plastic re-mapping between 4-12 weeks. It is reasonable to expect that consistent use of a hearing protector, especially an active protector that provides pass-through capabilities, will induce cognitive changes in the auditory cortex that will result in improved performance over a period of 3-4 months.

Auditory Fitness For Duty

Many occupations require good hearing to detect, identify, localize, and interpret a sound. Good hearing is also required to understand speech both in quiet and noisy conditions. While employee performance of these tasks may be desired simply to improve efficiency and productivity (interpreter, etc.), many organizations require good hearing to ensure safety (air traffic control, commercial drivers, mining) and survivability (police, military, firefighters).

The limited availability of AFFD tests, and the time/resources required to administer such tests has limited the ability of employers to test and evaluate an employee's auditory fitness for duty. While many employers do not perform formal tests of auditory ability, those that do often rely on pure tone auditory threshold measures. These measures are useful clinically in determining the type and severity of hearing loss. As such, they can also accurately determine what sounds will be audible, i.e., detectable (Laroche, Giguere, Soli, & Vaillancourt, 2008). However, their ability to accurately determine or evaluate sound identification, localization, interpretation or speech understanding (especially in noise) is somewhat limited (Laroche et al., 2008). Many AFFD standards are pass/fail criteria that are based on the medical-legal definition of hearing handicap rather than job performance (Laroche et al., 2008; Tufts, Vasil, & Briggs, 2009). That has not stopped employers from using pure tone thresholds as auditory fitness for duty standards. Pure tone threshold standards are currently being used by several organizations within state and national government (Table 6).

Table 6. Organizations that use pure tone thresholds as an AFFD for an occupational specialty or activity (adapted from Tufts et al., 2009)

Organization	Occupational Specialty or Activity
Department of Defense	Appointment, Enlistment, Induction
Department of the Army	Aviation and Air Traffic Control
	Police and Guard Series
	Retention (Profile)
Department of the Air Force	Academy
	Retention (Profile)
Department of the Navy	Aviators & Aviation Personnel

Table 6. Organizations that use pure tone thresholds as an AFFD for an occupational specialty or activity (adapted from Tufts et al., 2009)

	Submarine Duty
	Landing Craft (air cushion)
U.S. Department of Interior Law Enforcement —U.S. National Park Service	Commissioned Park Rangers, Criminal Investigators, Correctional Officers
U.S. Department of Interior Law Enforcement —U.S. Fish and Wildlife Service	Special Agents
U.S. Office of Personnel Management	U.S. Dept. of Treasury – U.S. Customs Service – Canine Enforcement Officer and Border Protection Officer Series
	U.S. Dept. of Treasury Enforcement Agents
	U.S. Dept. of the Interior – Surface Mining Reclamation Specialists
	Federal Correctional Officers
	Federal Mine Health and Safety Series
	Federal Air Traffic Control
U.S. Department of Homeland Security	Border Patrol Agents
U.S. Marshals Service	Court Security Officers
U.S. Department of Justice	Federal Bureau of Investigation— Police Officers
Federal Motor Carrier Safety Administration	Federal Motor Carrier Safety Administration Commercial Motor Vehicle Operators and Longer Combination Vehicle Driver Instructors
State of Michigan	Michigan State Police
State of New York	New York Entry-Level Police Officer Candidates
State of New Hampshire	New Hampshire Police/Corrections Academy
State of Maryland, Frederick County	Firefighters
National Interagency Fire Center	Wildland Arduous Firefighters

As seen in Table 6, the U.S. Military actively uses AFFD measures (Department of Defense, 2005; Department of the Air Force, 2006; Department of the Army, 2006a, 2010; Department of the Navy, 2005). However, the measures currently in use do not adequately evaluate sound recognition, localization, or speech understanding requirements. The U.S. Army classifies a Soldiers hearing status in one of four “Profiles” (H-1 through H-4). Profiles are designed to classify and document medical conditions and their severity as well as provide assignment limitations to either facilitate the recovery of a temporary condition or prevent a permanent condition from becoming worse. An H-1 profile indicates that a Soldier has normal or near normal hearing and is acceptable for any job that doesn’t have more restrictive hearing standards (e.g., aviation). An H-2 profile indicates some permanent hearing loss and usually places no additional restrictions on the Soldier. An H-3 profile indicates that this Soldier may have a loss that limits their ability to perform their job, is at risk for more severe, handicapping, hearing loss, and may need to be placed in a non-noisy job or leave the military. When a Soldier receives an H-3 profile they are required to be evaluated, using a speech in noise test. The results of this testing is used by a medical review board that determines if the Soldier will reclassify into another job or start the separation process. The audiometric criteria for each profile are outlined in Table 7. Because these criteria are based on audiometric thresholds and not performance, it is possible that Soldiers meeting the H-1 profile criteria may have extreme difficult with understanding speech-in-noise or with localization tasks, while Soldiers meeting H-3 profile criteria have little if any difficulty with the same tasks.

Table 7. Hearing Profile Classification (adapted from Department of the Army, 2010, Table 7-1)

Profile	Criteria
H-1	Audiometer average level for each ear not more than 25 dB at 500, 1000, 2000 Hz with no individual level greater then 30 dB. Not over 45 dB at 4000 Hz.
H-2	Audiometer average level for each ear at 500, 1000, 2000 Hz, not more than 30 dB, with no individual level greater than 35 dB at these frequencies, and level not more than 55 dB at 4000 Hz; or Audiometer level 30 dB at 500 Hz, 25 dB at 1000 and 2000 Hz, and 35 dB at 4000 Hz in better ear. (Poorer ear may be deaf.)
H-3	Speech reception threshold in best ear not greater than 30 dBHL, measured with or without hearing aid; or acute or chronic ear disease.
H-4	Functional level below H3.

Many Soldiers have discussed with this author, who is a military audiologist, the problems they have experienced understanding speech and localizing sounds during combat operations. Some of these Soldiers have normal pure tone thresholds and word recognition (in quiet) audiometric results. The use of hearing protection by these Soldiers is especially problematic, as their ability to localize and understand speech is often degraded even further. The military is currently designing methods of evaluating “Total Force Fitness”, which will include measures of physical, behavioral, psychological, medical, environmental, nutritional, spiritual, and social fitness (Land, 2010). Auditory fitness for duty falls under the medical and environmental components of Total Force fitness (O'Connor, Deuster, DeGroot, & White, 2010). Medical and environmental fitness has been combined, because “a warfighter must be able to function, free of any anticipated medical condition that could compromise either individual or unit effectiveness, while potentially confronting multiple environmental challenges…Environmental fitness is defined as the ability to perform mission-specific duties in any environment and withstand the multiple stressors of deployment and war” (O'Connor et al., 2010, p. 56). By combining both medical and environmental fitness, the military is now better poised to consider and implement metrics that assess auditory performance in more realistic environments, such as speech understanding and localization in various operational (auditory) environments.

RESEARCH GAPS

From the preceding literature review, several conclusions can be drawn. The military requires Soldiers to work in austere environments that require high levels of situation awareness, specifically sound localization. In these environments, the situation awareness of each individual is a key requirement for individual and unit survivability, lethality, and mission success. However, the military does not currently ensure that Soldiers have the requisite abilities and/or equipment to enable an appropriate level of situation awareness. This is especially true when hearing protection is worn. Data showing the relationship between accident/injury rates and auditory situation awareness in the military are lacking with only anecdotal information being reported. Sources of potential data are currently classified and not available for public review.

This investigation addressed the localization aspect of situation awareness. In addressing localization abilities in the military, the following tools/metrics are needed. These metrics should allow for appropriate job placement/return-to-duty evaluations, and informed selection of hearing protection and other head worn equipment.

1) An AFFD test battery that assesses open-ear localization.

2) An AFFD test battery that assesses localization with various types of hearing protectors and head worn equipment.

3) An AFFD test battery that will predict potential localization performance for a specific hearing protector.

RESEARCH OBJECTIVES/HYPOTHESIS

The ability of an individual to localize depends on his or her ability to receive and accurately interpret localization cues (such as ILD and ITD). These localization cues may be distorted when an individual wears a HPD, HPED, or TCAPS. This investigation addressed the ability to adapt to HPEDs and improved localization accuracy. HPEDs were chosen, as they have the *potential* to be acoustically transparent while still providing protection from hazardous sounds. To maintain situation awareness, the HPED must collect, process, and present localization cues to the listener in a form that will afford their accurate interpretation. When the cues are present but distorted, the user may be able to experience auditory learning, hopefully beneficial in effect, with continued use of the HPED. This auditory learning can allow the user to improve his ability to accurately interpret localization cues, and thus improve his localization accuracy with an HPED. Because the ability to localize accurately depends on both the individual and HPED (if used), and may require auditory learning, an AFFD measure should be capable of evaluating all of these elements (can the human localize, does the device pass localization cues to the user, and can the user improve localization skills through auditory learning when wearing the device).

Objectives

The objectives of this study were to explore and develop an AFFD measure for horizontal auditory localization that can be used quickly and easily in a clinic setting or small office space in support of military Hearing Readiness operations. Specifically this study was designed to:

1) Develop AFFD measures and determine if they are capable of evaluating localization performance of an individual with an open ear, in-the-ear HPED (Etymotic EB15), and over-the-ear HPED (Peltor Com-Tac II). The stimuli used for localization and AFFD tasks included both high and low frequencies as well as long and short durations. Frequency ranges were determined based on the location of hearing loss prevalent in the military and to test the two general methods of localization (ILD and ITD) dependent upon signal spectral profiles. Determining which subset of AFFD stimuli can best approximate overall localization performance will allow for efficient AFFD testing.
2) Determine if repeated use of a HPED with performance feedback will result in auditory learning and improved localization performance. Participants were trained with one of the two HPEDs (either the Peltor Com-Tac II or the Etymotic EB15) and received pre and post-training testing with both HPEDs. Testing with both HPEDs allowed for the determination of auditory learning for the training device as well as the non-training device (crossover). Open ear performance was also tested before and after training. Open ear performance was used as a baseline and accounted for any improvement from training effects. During training, participants were given various tasks to interact with a sound. The sound used in training was generally similar, but slightly different from the test stimuli.
3) Develop an AFFD protocol and determine if it is capable of predicting if auditory learning is possible for a given device/individual combination. The AFFD was

tested pre-training and compared to post-training results. The goal was to predict post-training performance using pre-training AFFD measures.

Hypotheses

1) Open-ear AFFD measures are predictive of open-ear performance in a high-fidelity field simulation.
2) HPED AFFD measures are predictive of HPED performance in a high-fidelity field simulation.
3) Experience with an HPED can improve localization performance.
4) Dynamic AFFD measures can predict which HPEDs will afford auditory learning (adaptation) with repeated and regular use.

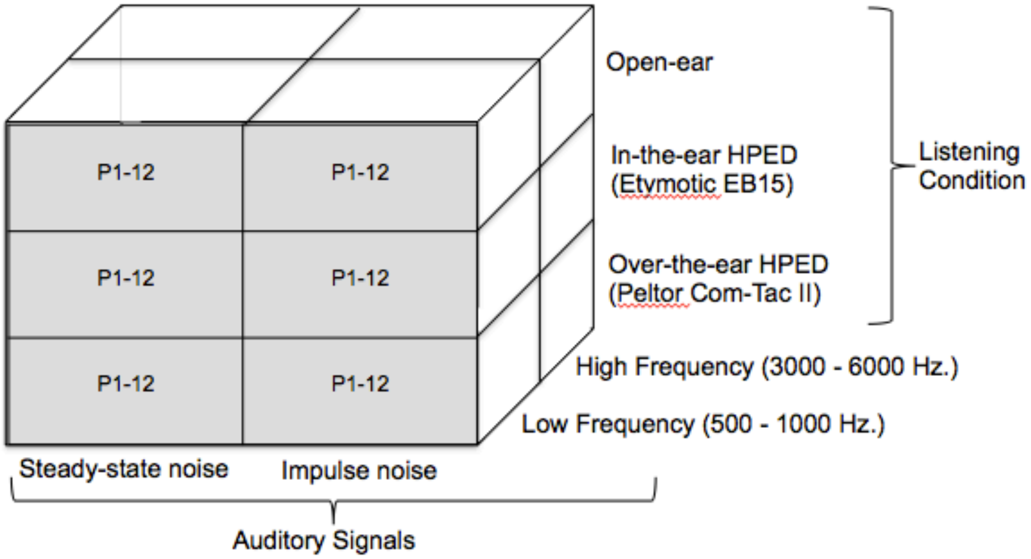
METHODOLOGY

Experimental Design

This investigation was conducted in three phases (Table 8). In Phase I, participants underwent a series of tests to determine both their localization performance in a high-fidelity field simulation (LPHFFS), as well as several AFFD performance measures. Participants were tested under three listening conditions (in-the-ear HPED, over-the-ear HPED, and open-ear) and with four distinct auditory stimuli (Figure 14); all independent variables were within-subject. These data were used to determine which AFFD measures best predict overall localization performance. At the conclusion of Phase I, participants rated their confidence in localization performance for each listening condition. During Phase II, participants conducted localization training with either an ITE or OTE HPED. Training sessions lasted one hour and were conducted on 12 separate and nearly consecutive days. Measures of localization performance (LPHFFS) with their assigned HPED were also conducted throughout this phase, to determine if or when their performance plateaued. In Phase III, participants underwent testing of LPHFFS for all three listening conditions (similar to Phase I). These data, along with data from Phase I, demonstrate the potential for auditory learning with the training device, the crossover of auditory learning to the non-training device, and which AFFD measure can best predict overall localization performance after training has occurred. At the conclusion of Phase III, participants again rated their confidence in localization performance for each listening condition. A description and rationale for each dependent and independent variable follows.

Table 8. Dependent measures/training conducted during each experimental phase.

	Phase I (Pre-Training)			Phase II (Days 1-12)		Phase III (Post-Training)	
Condition	LPHFFS	AFFD	Rating	Training	LPHFFS	LPHFFS	Rating
OE	X	X	X			X	X
ITE	X	X	X	X (ITE Group)	X	X	X
OTE	X	X	X	X (OTE Group)	X	X	X



Dependent Measures

Localization Performance in a High-Fidelity Field Simulation (LPHFFS) Test:
1. Accuracy – Mean Absolute Error
2. Front-Back Confusion – Percent accuracy
3. Response Time (for each task) – Seconds

AFFD Tests:
1. 30°/60° Accuracy – Mean Absolute Error
2. Front-Back Confusion Test (FBCT) – Percent Correct
3. Interaural Cues Test (IACT) – Percent Correct
4. Front-Back Difference Test (FBDT) – Percent Correct
5. Response Time (for each task) – Seconds

Post-use Rating
1. Semantic rating of accuracy confidence for each listening condition

Experimental Design Notes:
1. Order of:
   Listening Condition - Counterbalanced
   LPHFFS/AFFD Test - Latin Square
   Stimuli - Latin Square
   Speaker - Random
2. Subjects at least 80% male to approximate military male/female ratio
3. Hearing loss not to exceed the Army H-2 profile criteria
4. Participants have used HPDs ≤ 5 hours a month in past 6 months

Figure 14. Experimental design for Phase I and III, with independent variables, subject assignment, and dependent measures shown (Phase III did not include AFFD dependent measures).

Independent Variable – Listening Condition

Three listening conditions (open-ear, in-the-ear HPED, and over-the-ear HPED) were used to represent the most common conditions experienced by military personnel who are required to have good situation awareness. While there are several ITE and OTE HPEDs currently being marketed to the military, this study only used one device from each category as an AFFD test proof-of-concept. These devices were chosen based on their ability to provide electronic pass-through of ambient sounds and their use in prior situation awareness experiments as representative devices. To best approximate localization under open-ear conditions, each device was adjusted to provide unity gain (see glossary). The order of each listening condition was determined using a 3X6 counterbalance that was repeated for every six participants. The following sections describe the characteristics of each listening condition used in this study.

Listeining Condition: Open-ear

The open-ear condition was used as a baseline of performance in an unaided, natural condition. When using an HPED to protect hearing and preserve situation awareness, the goal is to preserve as much natural (open-ear) performance as possible. Obtaining open-ear performance data allowed for a direct comparison with various devices to see how much performance loss is experienced. It was also used to determine the level of auditory learning achieved from the training provided.

Listening Condition: In-the-ear HPED (Etymotic EB15)

The Etymotic EB15 is an in-the-ear hearing protector that uses electronic circuitry to provide pass-through of ambient sounds (Figure 15). It is similar to a hearing aid in appearance, but with different dynamic characteristics to provide protection in gunfire. The EB15 has a manual toggle switch that allows the user to select a “LO” or “HI” setting. The “LO” setting allows users to hear soft and moderate sounds (below 60 dB) at their natural level, while providing attenuation for loud or hazardous impulse sounds. According to the manufacture’s data, the “HI” setting provides a 15 dB boost for soft sounds (below 60 dB) while maintaining natural volume (unity gain) for input sounds levels above 90 dB (Figure 16). The frequency response and impulse attenuation data for this HPED are shown in Figure 17 and Table 9 respectively, as measured by Classing, 2012. For this study, the “LO” setting was used so that unity gain would be provided to the listener. Talcott et al. (2012) studied the localization of the EB15. They found the mean accuracy (± 22.5°) to be 61%, compared to 81% for the open ear. Front-back confusion errors occurred on 36% of trials, compared to 12% for the open-ear condition.

Figure 15. Etymotic EB15: High-Fidelity Electronic BlastPLG Earplugs (from The Money Times, 2011)

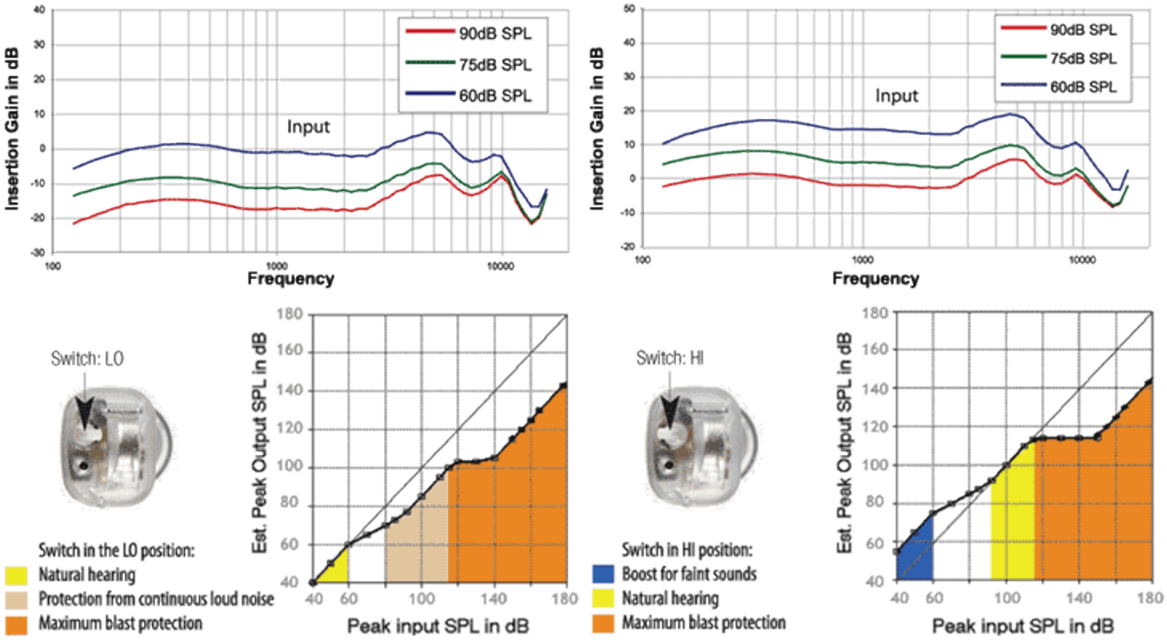


Figure 16. Insertion gain and input-output graph for the Etymotic EB15 in the LO (left panel) and HI (right panel) position (from Etymotic Research Inc.).

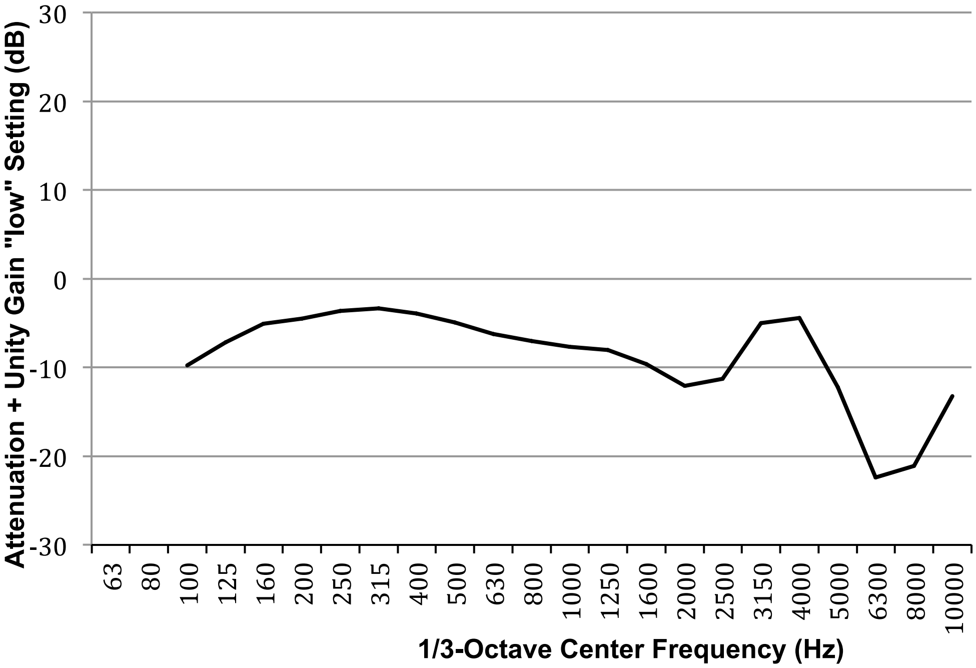


Figure 17. Frequency response of the EB15 in the unity gain "LO" setting for a 70 dB pink noise input (from Clasing, 2012). Note that this device is compressing the 70 dB signal. Input signals below 60 dB are not compressed (not depicted here).

Table 9. Impulse attenuation at 150 and 166 dB for various HPEDs and gain settings (from Clasing, 2012)

		Mean dB level under device			
HPED	Setting/Gain	150 dB	Δ	166 dB	Δ
Etymotic EB15®	OFF (no battery)	116.6	33.4	131.4	34.6
	LO	115.5	34.5	130.3	35.7
	HI	122.4	27.6	129.3	36.7
Peltor Com-Tac II™	Off	129.8	20.2	147.8	18.2
	Min	129.8	20.2	147.8	18.2
	Unity	130.0	20.0	147.5	18.5
	Max	129.9	20.2	147.6	18.4

Listening Condition: Over-the-ear HPED (Peltor Com-Tac II Earmuff)

Peltor's Com-Tac II Electronic Earmuff (Figure 18) is an over-the-ear HPED commonly used by military personnel. Its ease of use, durability, ability to fit many head sizes, and its ability to accommodate other headgear and radio communications have reportedly made it a popular device for many ground combat forces. The Com-Tac II is an electronic earmuff that provides dichotic ambient sound pass-through using a single, directional microphone placed on the front of each earcup. The gain of ambient pass-through is symmetric between ears and controlled by the user. Gain can be adjusted to provide only passive attenuation (off position) and four levels of electronic ambient sound pass-through. The third highest gain setting (G=3) is used as the unity gain. In the highest setting (G=4) there is approximately 10 dB of gain (K. A. Talcott, 2011) for input sounds below 65 dB, and the reported gain range is 18 dB. This suggests that pass-through of ambient sound levels can be adjusted to be both louder or softer than normal (Aearo, 2005). The frequency response and impulse attenuation data for this HPED are shown in Figure 19 and Table 9 respectively. Talcott et al. (2012) studied the localization ability of subjects who wore the Peltor Com-Tac II. They found the mean "ballpark" accuracy (± 22.5°) to be 53% compared to 81% for the open ear. Front-back confusion errors occurred on 28% of trials compared to 12% for the open-ear condition.

Figure 18. Peltor Com-Tac II (from Peltor)

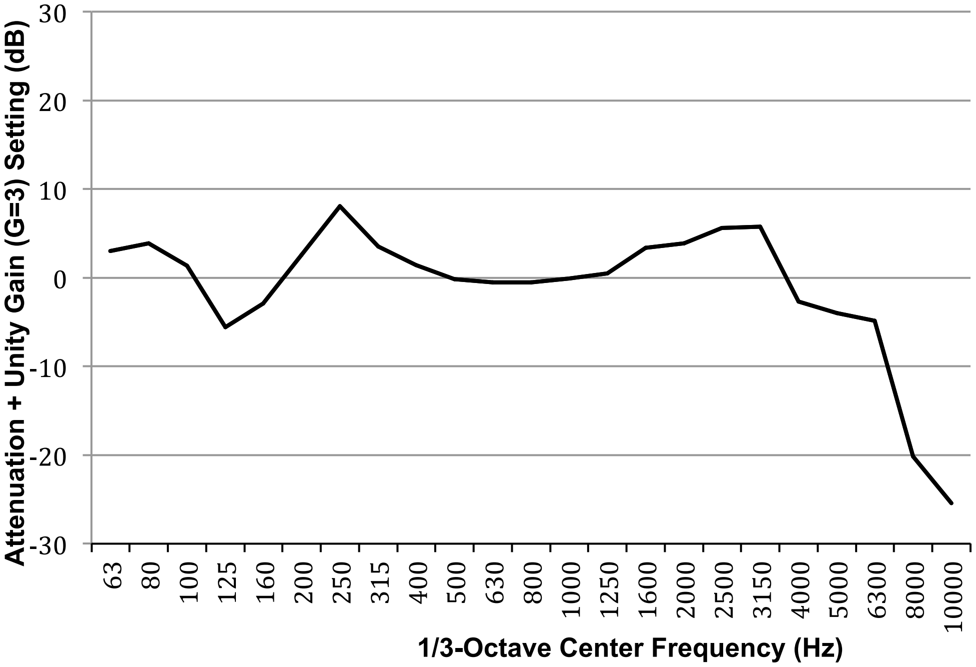


Figure 19. Frequency response of the Peltor Com-Tac II in the unity gain (G=3) setting for a 70 dB pink noise input (from Clasing, 2012)

Independent Variable – Auditory Stimuli

A total of four auditory stimuli were used to conduct LPHFFS and AFFD testing, a within-subject variable. Each test stimulus was differentiated by its frequency range and duration. There were two frequency ranges and two durations that were crossed with each other to obtain four distinct stimuli (Table 10). The two frequency ranges were chosen to represent sounds localized using interaural level differences (ILD) cues (high frequency range), and interaural time/phase differences (ITD) (low frequency range). The selection of the high frequency range was done to detect changes in localization ability from noise-induced hearing loss and the potential loss/distortion of pinna cues. Each stimuli used a one octave-wide filtered pink noise. The two stimulus durations represented a 300 ms impulse noise, with a 100% duty cycle, (where head movement initiated after onset of the stimulus are not fast enough to aid localization) and a 3 s steady-state or continuous noise (where head movement initiated after onset of the stimulus is fast enough to aid localization). Stimuli were created using Audacity® (version 1.3.12-beta). To create each stimulus, a pink-noise was first generated. High and low-pass filters were then applied to obtain the desired frequency range. These filters employed a 48 dB per octave rolloff. The rise/fall time was controlled to ensure a rapid onset, while preventing overshoot or other unwanted distortions. Rise/fall time was set by creating a fade-in and fade-out for the first and last 10 ms of the total stimulus time (Figure 20).

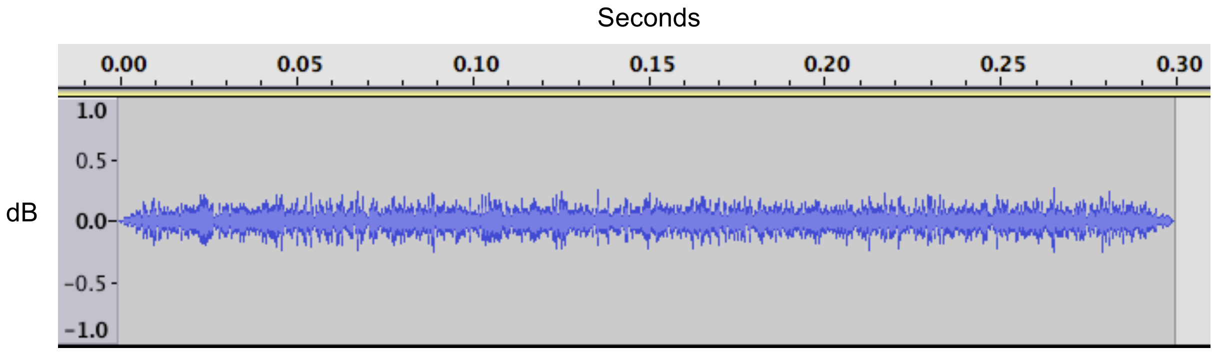


Figure 20. Audacity screen capture of the high-frequency (3000-6000 Hz) short-duration (300 ms) pink noise showing a 10 ms rise and fall-time.

Table 10. Test stimulus parameters.

High Frequency Impulse Noise (H-Short)	High Frequency Steady-State Noise (H-Long)
Frequency range: 3000-6000 Hz	Frequency range: 3000-6000 Hz
Intensity: 60 & 70 dB SPL	Intensity: 60 & 70 dB SPL
Duration: 300 ms	Duration: 3 s
Rise/fall time: 10 ms	Rise/fall time: 10 ms
Low Frequency Impulse Noise (L-Short)	Low Frequency Steady-State Noise (L-Long)
Frequency range: 500-1000 Hz	Frequency range: 500-1000 Hz
Intensity: 60 & 70 dB SPL	Intensity: 60 & 70 dB SPL
Duration: 300 ms	Duration: 3 s
Rise/fall time: 10 ms	Rise/fall time: 10 ms

Front-back discrimination is often aided by comparing the signal level from front and back signal locations. The comparison of signal levels is often not possible in a field environment, when Soldiers are required to localize a signal that is heard just once from an unknown distance. To ensure level cues are not the dominant cue in front-back determination, the stimulus level for all tests requiring front-back determination varied between two discrete levels (60 and 70 dB), both known to be suprathreshold in there conditions, as described later. This variation in stimulus level was designed to prevent participants from discriminating front-back differences based purely on signal level and required the listener to use other localization cues. When stimulus levels varied, the levels presented from each azimuth angle were balanced. Tests that did not require front-back discrimination (e.g. 30°/60° accuracy test and interaural cues test) used a fixed 60 dB stimulus level.

The level of the stimuli was selected to ensure that all stimuli could easily be heard above the noise floor of the test environment while not presenting stimuli at a level that could startle the listener. The signal-to-noise (S/N) ratio for the two signals was 29.4 and 28.4 dB for the 60 dB signal and 39.0 and 37.7 dB for the 70 dB signal, using 10 s Leq measurements for signal and noise for the low and high frequency stimuli respectively (Table 11). The presentation order of each stimulus was determined using a 4X4 Latin Square that was repeated for every four tests.

Table 11. Leq and signal-to-noise ratio for the 60 and 70 dB signal using a 10 second Leq measurement.

	Low Frequency Signal		High Frequency Signal	
Signal	Leq(A)	S/N	Leq(A)	S/N
60 dB	61.3	29.4	60.3	28.4
70 dB	70.9	39.0	69.6	37.7
Ambient	31.9		31.9	

The stimulus used in localization training (Phase II) was an unfiltered pink noise with a 1 s duration. Rise and fall times were set at 10 ms. The presentation level of training stimuli varied randomly within a 60 to 70 dB SPL range, which was the range of the actual experimental stimuli.

Dependent Measures

Dependent measures consisted of a test of localization performance (LPHFFS), static and dynamic AFFD measures, and a rating scale. These dependent measures were designed to assess both accuracy and front-back confusion, two common problems encountered when using hearing protection. The outcome of the LPHFFS test, utilizing all test stimuli, was deemed as the gold-standard which AFFD measures attempt to predict. There were four types of AFFD measures 1) 30°/60° Accuracy Test, 2) Front-Back Confusion Test (FBCT), 3) Interaural Cues Test (IACT), and 4) Front-Back Difference Test (FBDT). The 30°/60° Accuracy Test comprised four sub-tests that measured accuracy in a given quadrant (Left-Front, Right-Front, Left-Rear, and Right-Rear). The IACT contained 2 sub-tests, one in each of the front two quadrants (Left-Front and Right-Front). The order of test presentation, for all 9 tests, was determined using a 9X9 Latin Square that was repeated. The rating scale was administered after all trials were completed.

Localization Performance

The LPHFFS is a static test of overall localization performance using all stimuli and speaker locations (Figure 21). During the LPHFFS test, each stimulus was presented twice from each speaker, for a total of 96 stimulus-response data points for each listening condition (2 presentations x 12 speakers x 4 stimuli = 96). The order of stimulus presentation, from each speaker, was randomized using a random number generator. Performance was determined by measuring the mean absolute difference, in azimuth, between the stimulus presentation and the listener response. Listeners responded by rotating a dial displayed on a computer screen. The selection of the response azimuth was controlled with a mouse interface. Upon selecting the desired azimuth, the participant indicated he had made his selection and was ready for the next stimulus by selecting an on screen button (Figure 22).

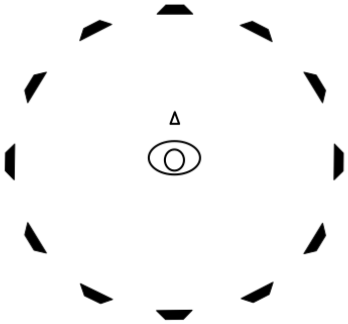
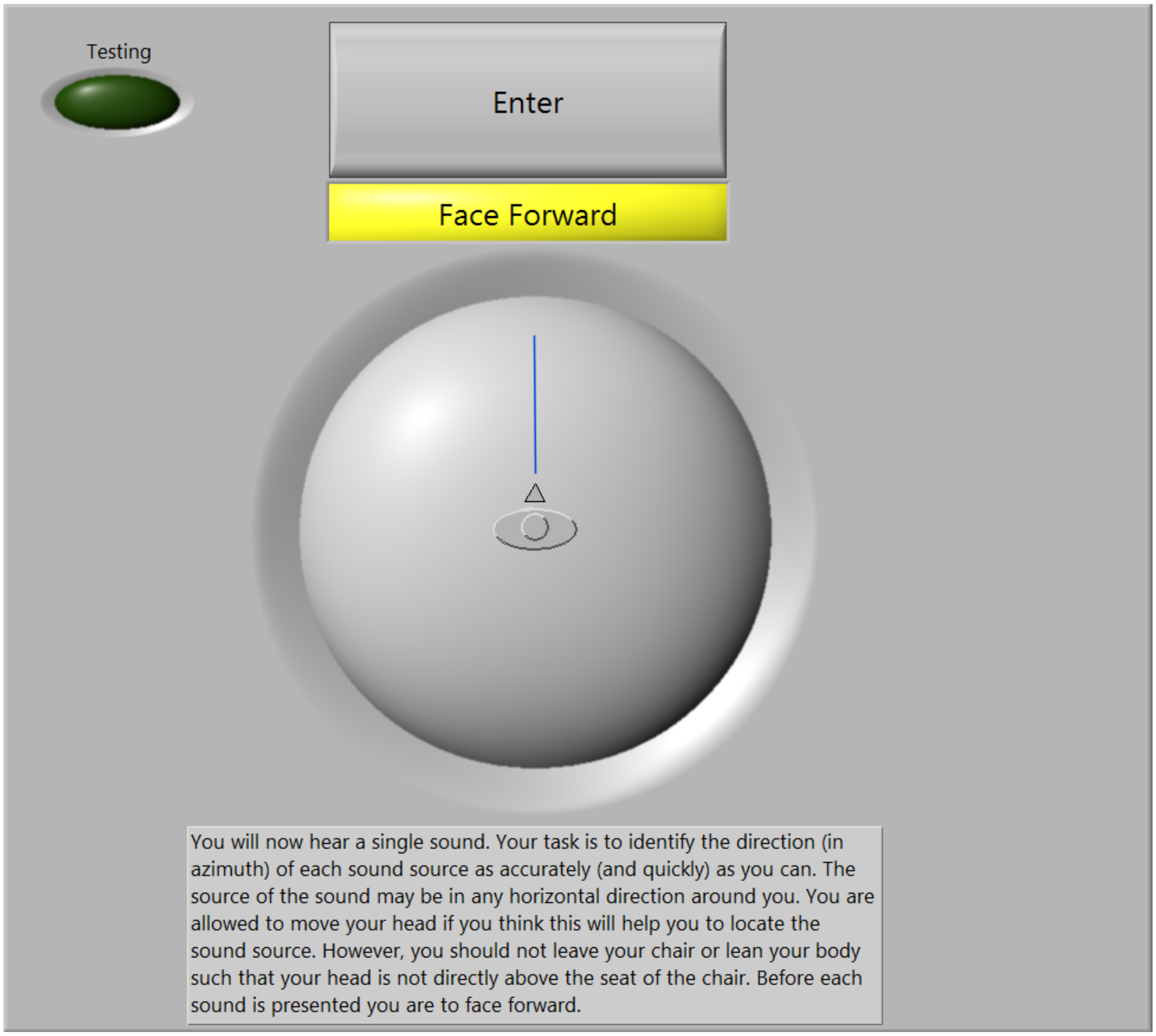


Figure 21. Participant (center) and active speaker positions for the LPHFFS test. Performance was assessed using all speakers and all stimuli, with ordering of presentation via random number generator.



You will now hear a single sound. Your task is to identify the direction (in azimuth) of each sound source as accurately (and quickly) as you can. The source of the sound may be in any horizontal direction around you. You are allowed to move your head if you think this will help you to locate the sound source. However, you should not leave your chair or lean your body such that your head is not directly above the seat of the chair. Before each sound is presented you are to face forward.

Figure 22. Participant Screen for the LPHFFS and the 30°/60° Accuracy test.

AFFD

The 30°/60° Accuracy test is a static test to determine localization performance within a given quadrant; Right-Front (0°-90°), Right-Rear (90°-180°), Left-Rear (180°-270°), and Left-Front (270°-360°). Stimuli were presented from the 30° and 60° relative locations within each 90° quadrant (Figure 23). Each quadrant was tested separately. During the 30°/60° Accuracy test, each stimulus was presented three times from each speaker location, for a total of six stimulus-response data points for each listening condition/quadrant/stimulus combination (3 presentations x 2 speakers = 6). The order of stimulus presentation, from each speaker, was randomized using a random number generator. Participants responded in the same manner as in the LPHFFS test. Mean absolute accuracy was determined for each quadrant, listening condition, and stimulus separately.

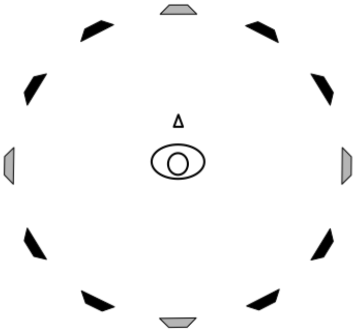


Figure 23. Participant (center) and active speaker (solid black) positions for all four quadrants of the 30/60 Accuracy test. Performance was assessed using the two speakers located in a given quadrant (Left-Front, Right-Front, Left-Rear, and Right-Rear).

The FBCT is a static test to determine the relative number of front-back confusions. In the FBCT, listeners responded to a single stimulus that is presented to either the front (0°) or back (180°). Each stimulus was presented six times from each speaker, for a total of 12 stimulus-response data points for each listening condition/stimulus combination (6 presentations x 2 speakers = 12). The order of stimulus presentation from each of the two speakers was randomized using a random number generator. The listener responded by indicating the perceived location (front or back) (Figure 25). The total number of front-back confusions was converted to a percent error. Figure 24 shows the speaker/listener arrangement.

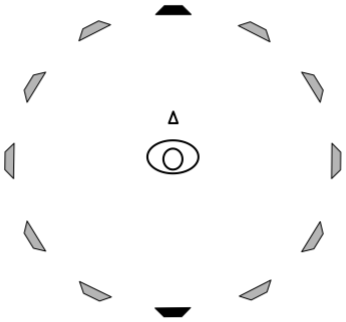
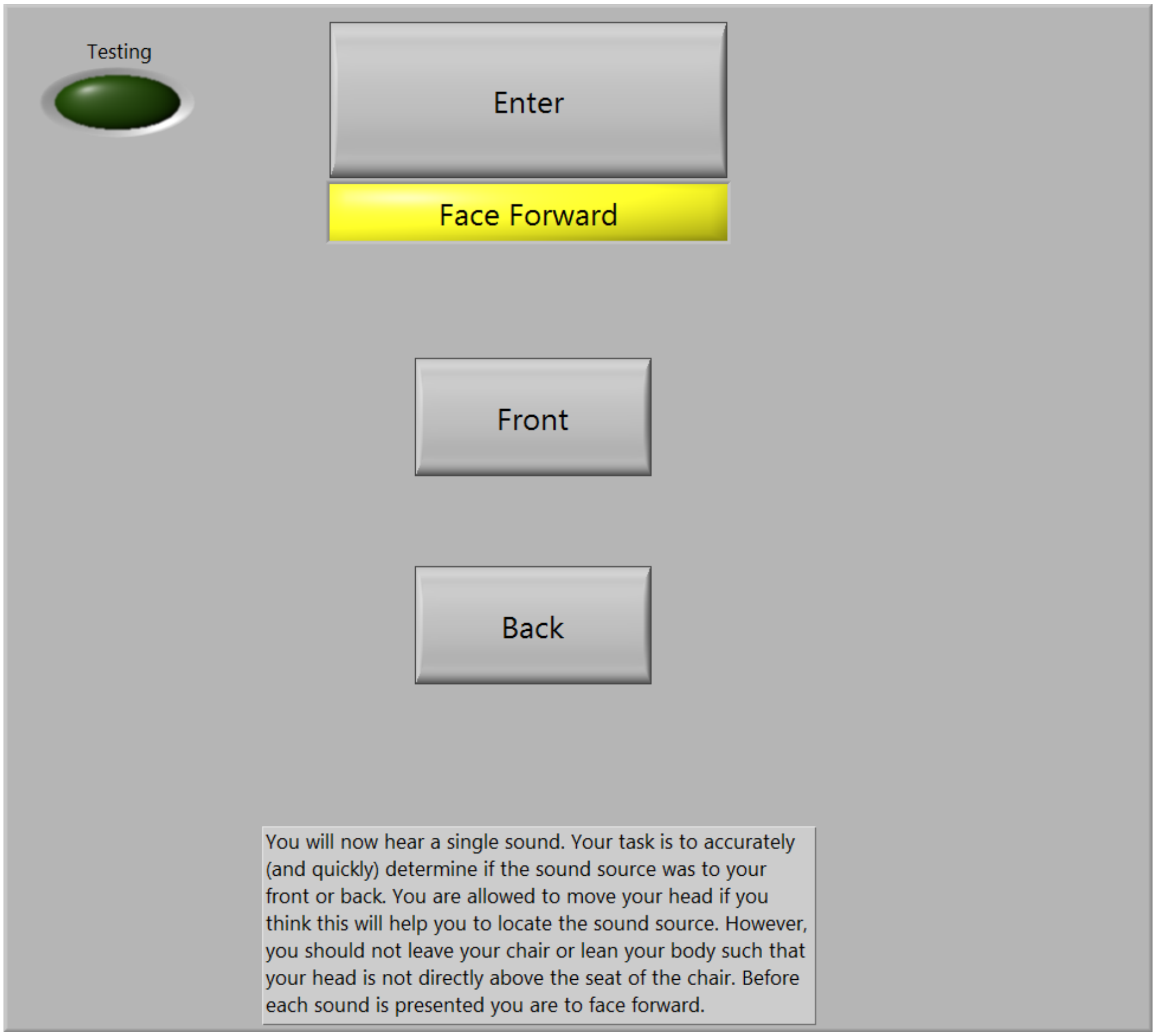


Figure 24. Participant (center) and active speaker (solid black) positions for the Front-Back Confusion Test. Active speakers are solid black and inactive speakers are grey.



You will now hear a single sound. Your task is to accurately (and quickly) determine if the sound source was to your front or back. You are allowed to move your head if you think this will help you to locate the sound source. However, you should not leave your chair or lean your body such that your head is not directly above the seat of the chair. Before each sound is presented you are to face forward.

Figure 25. Participant Screen for the Front-Back Confusion Test (FBCT).

The IACT is a dynamic test designed to detect the presence of interaural cues in the signal heard by the participant, the essence of binaural localization. In this test, a participant responded to a series of two sequential stimulus presentations, separated by a 500 ms delay. Each stimulus was presented from either the same speaker or two different speakers within a quadrant. Speaker locations were at 30° and 60° within each quadrant. The participant indicated if the stimulus presented remained stationary (presented from the same speaker on both presentations) or moved (presented from two different speakers). If movement was indicated, the participant indicated the direction of movement (left or right). The IACT was tested in the Left-Front and Right-Front quadrants separately. Each stationary stimulus pair was presented twice at each speaker location and each movement stimulus pair originated twice from each speaker location. For example, the stationary stimulus pairs were presented twice at 30° and twice at 60°, and movement stimulus pairs originated twice at 30° and twice at 60°. This resulted in a total of four movement stimulus pairs and four stationary stimulus pairs, for a total of eight stimulus-response data points for each listening condition/quadrant/stimulus combination (4 movement + 4 stationary = 8). Each quadrant and stimulus were tested separately. The order of stimulus presentation, from each speaker, was randomized using a random number generator. The listener indicated if the signal remained in the same location, moved left, or moved right (Figure 27). These data were converted to a percent error. Figure 26 shows the speaker/listener arrangement.

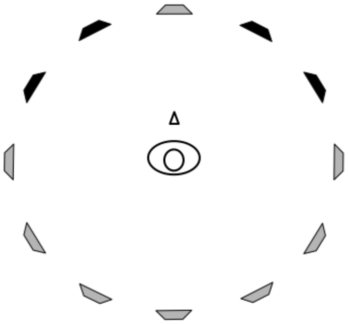
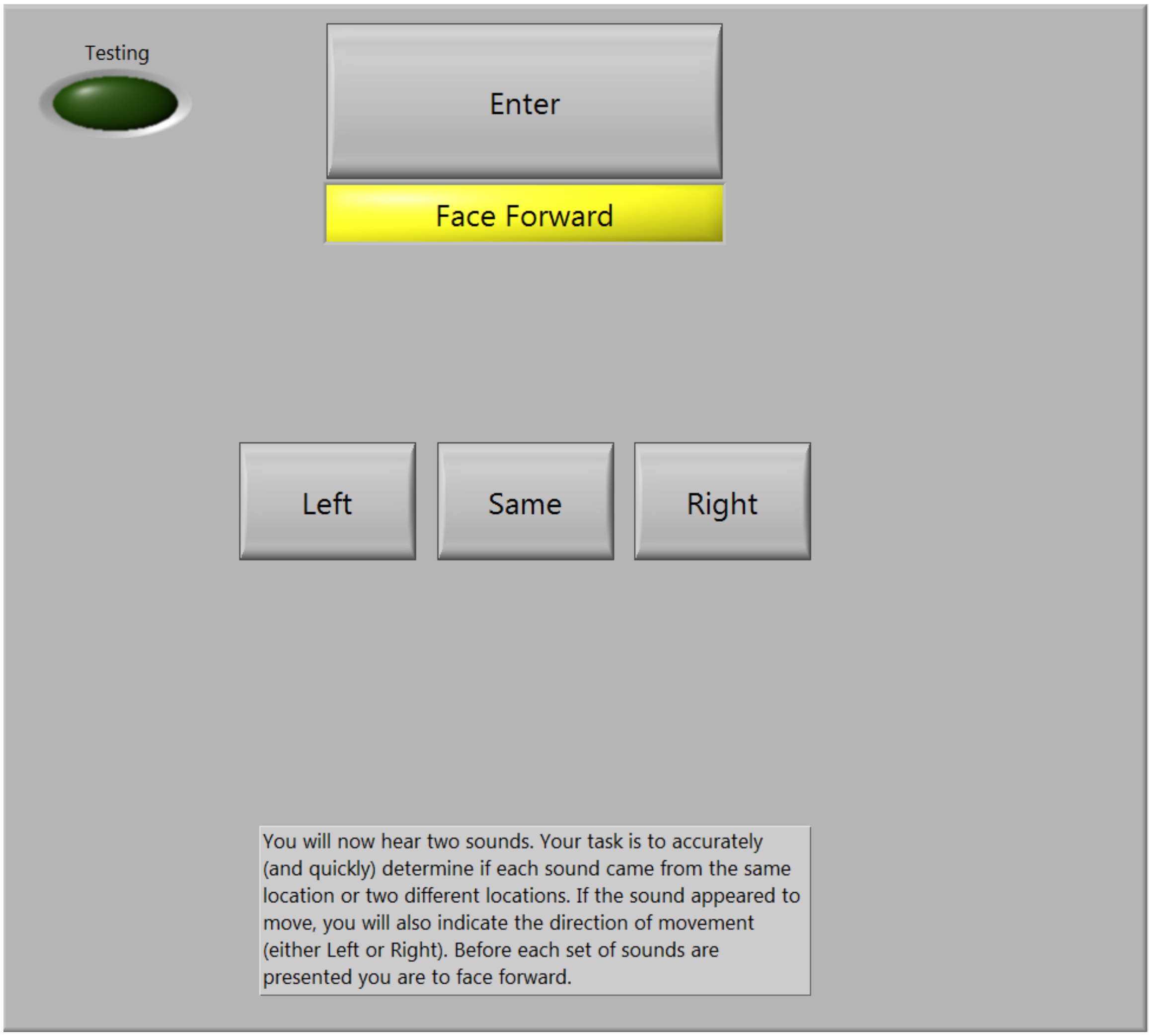


Figure 26. Participant (center) and active speaker (solid black) positions for the Interaural Cues Test. Active speakers are solid black and inactive speakers are grey.



You will now hear two sounds. Your task is to accurately (and quickly) determine if each sound came from the same location or two different locations. If the sound appeared to move, you will also indicate the direction of movement (either Left or Right). Before each set of sounds are presented you are to face forward.

Figure 27. Participant Screen for the Interaural Cues Test (IACT).

The FBDT is a dynamic test, designed to detect spectral cues in the signal heard by the participant. In this test, listeners responded to a series of two stimulus presentations, separated by a 500 ms delay. Each stimulus pair was presented a total of 16 times with eight stationary and eight movement pairs. Each stimulus presentation pair was presented from the front (4 times), back (4 times), or both speakers (originating from the front and back speaker 4 times each) for a total of 16 stimulus-response data points for each listening condition/stimulus combination (8 stationary + 8 movement = 16). The order of stimulus presentation from each speaker was randomized using a random number generator. The listener indicated if the stimuli presented appeared to originate from the same location or two different locations (Figure 29). These data were converted to a percent error. Figure 28 shows the speaker/listener arrangement.

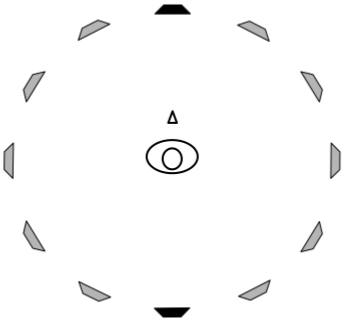
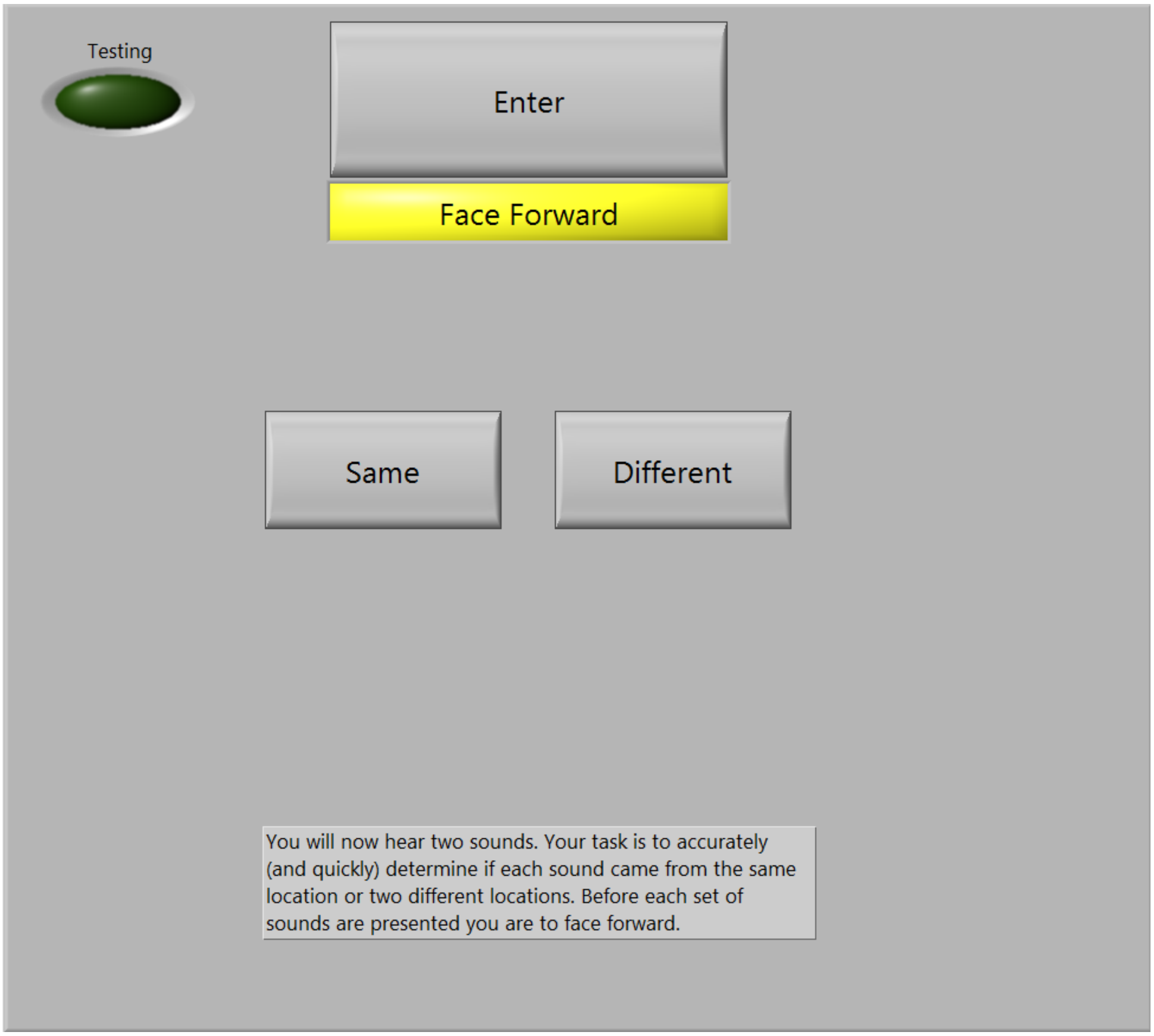


Figure 28. Participant (center) and active speaker (solid balck) positions for the Front-Back Difference Test. Active speakers are solid black and inactive speakers are grey.



You will now hear two sounds. Your task is to accurately (and quickly) determine if each sound came from the same location or two different locations. Before each set of sounds are presented you are to face forward.

Figure 29. Participant Screen for the Front-Back Difference Test (FBCT).

Response Time

Response time was determined by calculating the mean time from the onset of the stimulus presentation to the response execution. Response time was measured automatically as part of the software that administered the stimuli and recorded the response. Timing began at the onset of the second stimulus for tests that presented two stimuli. Response time was measured in milliseconds with a resolution of 100 ms. The maximum allowable response time for any stimulus-response pair was 10 seconds.

Post-use Rating Scale

A semantic rating scale (Appendix C) was completed by each participant after he or she completed all testing in Phase I and III. The rating scale assessed the participant's perceived confidence for each listening condition. Figure 30 shows the semantic scale, and the entire rating form is found in Appendix C. Talcott (2011) found that accuracy confidence was significantly correlated with localization performance (percent correct) in her study with various HPEDs. Petrusic and Baranski (2003) discuss the relation between confidence rating and reaction time when making accuracy judgments. While the intuitive rational and popular theories suggest that reaction time will decrease as confidences increases, under divided attention conditions this expectation may be reversed. While divided attention is common during military operations, this study did not present a divided attention task.

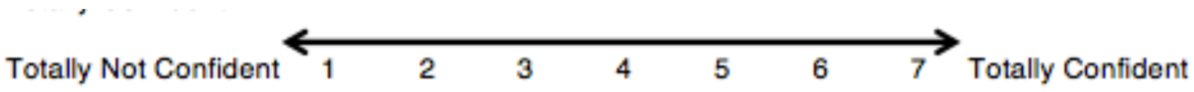


Figure 30. Post-use rating scale.

Participants

Twelve individuals from the Virginia Tech community participated in this study. Participants were required to be 18-45 years of age with no more than 20% being female, to match similar demographics of military personnel. All participants were Virginia Tech students, with 10 males and two females with an average age of 20.9 (range 19-28). One participant (male) was later removed from the study due to inconsistencies in his data as compared to the remainder of the subject pool (discussed later). All subsequent analysis and reporting do not include this participant's data unless otherwise stated. Participants were required to be novice hearing protection users, with less than five hours of use per month in the last six months. Participants reported little if any hearing protection use in the six months preceding their involvement in the study. Hearing protection use ranged from no use to six hours of total use in the preceding six months. Participant age and hearing protection use are shown in Table 12 and are further broken down by training group. Hearing thresholds were required to be equal to or better than 35 dB at 500, 1000, and 2000 Hz bilaterally and 55 dBHL at 4000 Hz in at least one ear. These levels are considered acceptable for most U.S. military forces. All participants met these criteria, and the mean hearing levels were relatively balanced between the ITE and OTE test groups (Table 13).

Table 12. Participant demographics.

	ITE Group (n=6)	OTE Group (n=5)	Overall (n=11)
Age (yrs.)			
Range	20-28	19-22	19-28
Mean	22.0	20.2	21.2
Median	21	20	20
HPD use in last 6 months (hrs.)			
ITE mean	0.2	1.4	0.7
ITE range	0 - 1	0 - 6	0 - 6
OTE mean	0.8	0.2	0.5
OTE range	0 - 4	0 - 1	0 - 4

Table 13. Mean hearing threshold level (dBHL)

		Frequency (Hz)					
		500	1000	2000	3000	4000	6000
ITE Group (n=6)	Left Ear	9.2	8.3	7.5	12.5	10.0	18.3
	Range	0 - 20	5 - 15	0 - 20	5 - 20	0 - 20	0 - 25
	Right Ear	8.3	8.3	10.0	9.2	9.2	14.2
	Range	5 - 10	5 - 10	5 - 15	5 - 15	0 - 20	5 - 25
OTE Group (n=5)	Left Ear	11.0	12.0	2.0	4.0	3.0	10.0
	Range	5 - 15	10 - 15	0 - 5	-5 - 10	0 - 10	0 – 20
	Right Ear	12.0	12.0	5.0	7.0	9.0	7.0
	Range	5 - 30	5 - 25	0 - 10	5 - 10	0 - 20	0 - 15

Experimental Facility:

Test Room

All data for this study were collected in the Virginia Tech, Auditory Systems Laboratory, Large-Scale Acoustical Test Chamber. The room is 18 ft wide by 19 ft long by 8.5 ft high with a tile floor, acoustic drop panel Celotex ^{TM} ceiling, and two-inch thick eggshell (Sonex ^{TM}) acoustic foam on all walls. This room was large enough for the experimenter and participant, as well as for a small sound booth for initial audiometric tests (Figure 31). The noise floor and reverberation time (RT60) were measured for this room in octave bands, and are shown in Table 14. These measurements were made with a Larson-Davis (Model 831) Sound Level Meter (SLM) using a Larson-Davis (model 377B02) 1/2 –inch microphone. Calibration was performed using a Quest QC-20 calibrator at 94 dBA (1000 Hz tone). The RT60 values shown in Table 14 are calculated using a 30 dB decrease in level, with extrapolation to 60 dB, to avoid interference by the noise floor. This calculation is performed automatically within the SLM.

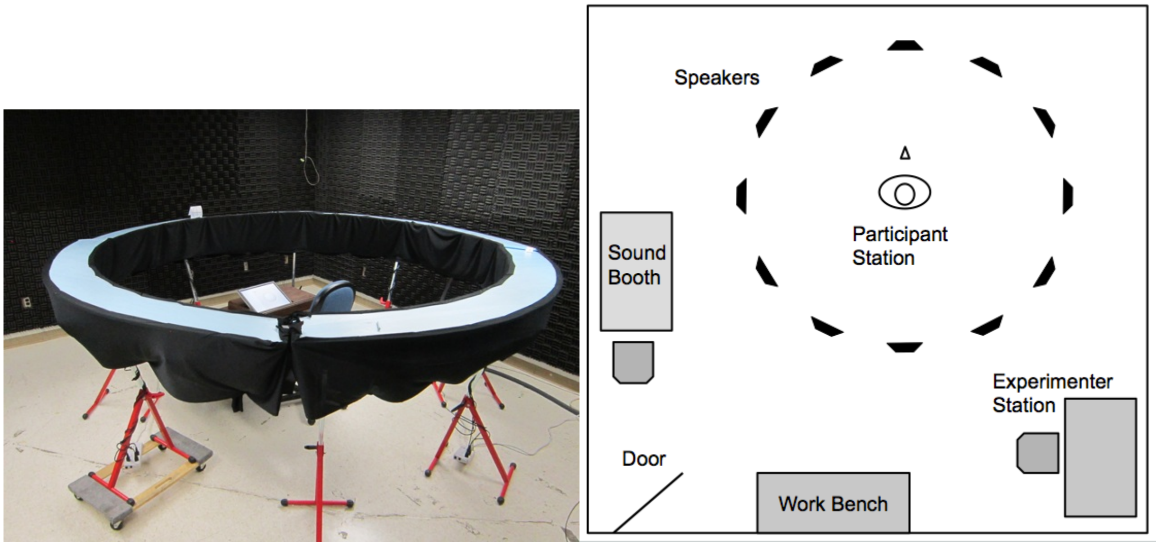


Figure 31. Photo and layout of room showing sound booth, speakers, participant location, experimenter station, work bench, and door (not to scale).

Table 14. Noise floor and reverberation time (RT60) of the Auditory Systems Laboratory Large-Scale Acoustical Test Chamber, as measured in octave bands.

Frequency (Hz)	250	500	1000	2000	4000	8000
Noise Floor (dB SPL)	33.9	32.5	37.5	37.4	35.9	39.3
RT60 (ms)	685	378	261	213	138	--

Maximum Permissible Ambient Noise Levels (MPANL) for all experiments needed to allow for a 60 dB stimulus to be easily heard. To ensure the stimulus was easily heard in the test frequency range, a recommended MPANL was established in Table 15. These MPANLs allow for average noise levels to exist and should not prevent the use of most meeting rooms when conducting AFFD measures (Bradley & Gover, 2004). Under controlled test conditions, signal levels that are 6 to 10 dB above the masked threshold are 100% detectable (Sorkin, 1987 as referenced by J.G. Casali, 2011, p. 80). Octave bands adjacent and below signal frequency ranges may be 7.5 dB greater in level and still avoid upward spread of masking (ISO7731). Room acoustics that result in early and/or late reflections are expected to have minimal effect on localization accuracy.

Minimal localization effects from reflections of the stimuli are expected, with no more than a 5° error from early reflections (<50ms) (Rakerd & Hartmann, 1985) or late reflections (>50ms) (W. M. Hartmann, 1983).

Table 15. Recommended Maximum Permissible Ambient Noise Levels (MPANL) for conducting AFFD and Field Localization measures.

Frequency	250	500	1000	2000	4000	8000
dB (SPL)	57.5	50	50	57.5	50	50

Speakers

Speakers consisted of 12 Behringer Behrtone C50A Reference Studio Monitors. The C50A is a 5.25 inch diameter round speaker housed in a 6.25 inch cube. It is a 30-Watt powered speaker with a frequency response of 90 – 17,000 Hz, flat within ± 3 dB.

Speakers were suspended beneath a circular metal tube frame and faced inward toward the subject (Figure 32). The height of the center of each speaker was 1.14 m from the floor and approximately level with the ear of the seated participant. The diameter of the circle of speakers was 3 m, when measured at the inward face of the speaker. This speaker distance was established to ensure that the participants were not in the near-field of the stimulus presentation. The near field was calculated using two methods. The first method considers the near-field to end at a distance equal to the wavelength of the lowest frequency in the stimulus. The wavelength of the lowest frequency (500 Hz) was calculated to be 69 cm. The second method considers the near-field to end at a distance equal to three times the largest dimension of the source. The largest distance (diagonal surface) of the speaker box was 26 cm., which indicated that the near-field would end 78 cm away from the speaker. Under either method, the participant had a circle that was approximately 1.42 – 1.60 m in diameter in which they could move and avoid being in the near-field.

Figure 32. Behrtone C50A speakers, suspended from custom fabricated metal structure, facing the listener position in the center of the circle (acoustically-transparent fabric, used to conceal speakers, removed here for photo).

Each speaker was separated by a 30° arc, as measured from the center of the circle (listener position). Other studies of localization have used a speaker separation of 45° (Alali & Casali, 2011; Talcott et al., 2012) and were successful in finding quantitative, objective differences in HPD performance. Therefore, a speaker separation of 30° was believed to provide adequate discrimination of HPED performance within or between HPED types. The speaker array was covered with acoustically transparent fabric to conceal the location and number of speakers present (Figure 33). Speakers were concealed to prevent participants from fixing their responses to exact angles where speakers were located.

Figure 33. Listener position showing participant monitor/display, covered speakers (black fabric surrounding listener position), and center target (white paper on top of speaker structure).

Participants were seated so that their heads were in the center of the circle of speakers. This location was also used to calibrate the stimulus level of each speaker. A visual target sign (Figure 33) was placed above the speaker located at 0°. Participants were told to position their bodies to face the target. They were also instructed to align their monitor/display so that the top of the dial (displayed on their screen) was aligned with the center target for the speakers. The experimenter checked for correct head position after the participant completed his alignment. Adjustments were made as needed using a height-adjustable and horizontally-moveable chair.

Test Administration

All localization testing and training tasks were automated using custom designed and developed software that was programmed by the author. Software was developed using LabView™ 2011 (version 11.0 and 11.0.1). The software was set up to display experimenter controls on one screen and participant controls on another. Both the experimenter and participant used their own screen and mouse to control a common cursor. The experimenter and participant coordinated, by verbal interaction, the sharing of the cursor and control of the software. The software utilized a National Instruments USB-6009 multi-function data acquisition system (DAQ) to control a SparkFun Electronics Analog/Digital Multiplexer (MUX) (model: BOB-09056) which routed the signal from the computer to the appropriate speaker (Figure 34). The multiplexer interface between the speakers and the DAQ was custom designed and built (Figure 35) by the author.

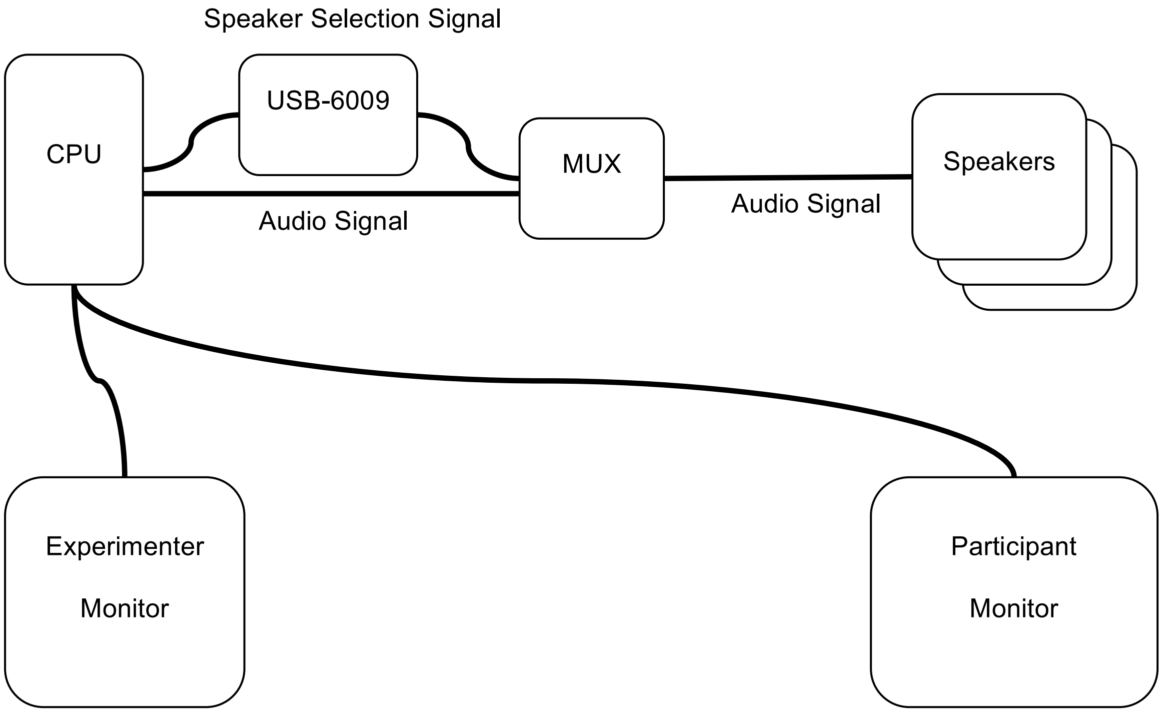


Figure 34. Computer and hardware layout.

Figure 35. Experimenter control station showing from left to right, multiplexer (black project box), experimenter screen, DAQ (white box), and desktop CPU.

Experimental Procedures: Screening Session

As part of the initial screening process, potential participants were asked if they were U.S. citizens or permanent residents. The Virginia Tech University Office of Export Control confirmed the citizenship/residency status of potential participants and approved their inclusion into the study. Potential participants received verbal information about the purpose, procedures, risks, and benefits of the study. An informed consent document was provided, reviewed with the experimenter, and all questions were answered. After the informed consent was signed participant's demographic information was collected, otoscopy was performed, and a hearing test was administered. Otoscopy was performed by the author (an audiologist) to ensure the external auditory canal was free of obstructions (e.g. cerumen) and any pathology that would contraindicate the use or insertion of earplug-type hearing protection. Hearing thresholds were then obtained, using a Beltone Model 119 audiometer in an Industrial Acoustic Company (IAC) mini-booth (Figure 36). The informed consent and demographic information forms can be found in Appendix A and B.

Figure 36. Industrial Acoustics Company (IAC) mini booth and Beltone 119 audiometer used for participant audiometric screening.

<u>Experimental Procedures: Phases</u>

Phase I

In Phase I, participants underwent LPHFFS and AFFD testing in all listening conditions. Participants progressed from one listening condition to the next, completing all testing for a given listening condition before proceeding. The order of the listening conditions was counterbalanced using a 3X6 counterbalance design that repeated for every group of six or more participants. Within each listening condition, the AFFD and LPHFFS tests were administered sequentially. The order of the tests within each listening condition was determined using a 9X9 Latin square that repeated. Each of the four stimuli was administered sequentially within each AFFD and LPHFFS tests. The order of the stimuli within each test was determined using a 4X4 Latin square that was repeated. Following these tests, participants completed a subjective rating of their accuracy confidence for each listening condition.

The experimenter began by entering the participant, listening condition, test, stimulus sequence, and speaker order into the control computer. The participant was informed of the listening condition being tested. If the listening condition required an HPED, the experimenter explained the use and operation of the device, fit it to the participant, and set the device at unity gain. The experimenter ensured that the fit was comfortable and optimal via visual inspection. The participant was also instructed how to recognize a device failure (i.e. weak/dead battery) and the importance of notifying the experimenter immediately. The experimenter ensured that the participant aligned their response display with the speaker target and that their head position was in the center of the circle of speakers. The participant was then presented with the on-screen test instructions for the selected test. The first time a test was administered, the experimenter verbally verified that the participant understood the instructions. Participants began the test when they were ready. The software presented the appropriate stimulus to the participant, who responded by interacting with the software on a separate screen. All responses and response times were recorded and saved through the software. When progressing from one test to another, or one listening condition to the next, participants were allowed to take a short break not exceeding five minutes.

Phase II

In Phase II, participants were assigned to one of two HPED training groups. Group assignment was randomized, ensuring an equal number of participants and genders in each group. Training groups were assigned either the Etymotic EB15 (ITE group) or the Com-Tac II (OTE group). Each group underwent individual localization training with their assigned HPED. Training consisted of 12 one-hour sessions in which the participant wore their assigned HPED while conducting a series of auditory localization tasks that provided accuracy feedback. Training sessions occurred between four and six times a week, with no more than two consecutive days without a training session. Participants performed no more than one training session each day. Within each training session, the participant performed four sequential tasks.

The first three training tasks were timed and lasted 15 minutes each. During the first task, the training stimulus was presented from one of the 12 speakers. The participant was instructed to swivel in their chair, face the sound source, and state its location. The participant screen was removed to allow for free rotation of the participant in their chair. Letters were placed above each speaker and inter-speaker location. A total of 24 letters (A through X) were used and were placed sequentially around the circle of speakers. Participants stated the letter that most closely corresponded to the perceived sound source. After they had stated the location, they clicked the mouse and the correct location was stated from the same speaker. This immediate feedback allowed participants to know if they were correct or not. If an error was made, the participant would know the magnitude of the error. The second test was similar to the first, except that participants were instructed to also point, with their hand, to the perceived sound source (Figure 37).

Figure 37. Participant pointing toward perceived sound source during the second training task.

During the third training task all letter markers were removed from atop the speaker structure, the center target remained, and the participant screen was returned. The participant was again instructed to align the front/center of the computer display with the actual front/center speaker target. The participant was instructed to not swivel in their chair, but was allowed to move their head for this task. The training stimulus was again presented and the participant was instructed to identify and state the letter most closely located with the perceived source, as represented on the display (Figure 38). The letter locations on the display and the letters in the first two tasks were the same. After the participant had stated the location, they clicked the mouse and the correct location was stated from the same speaker. This test was also timed and ended after 15 minutes.

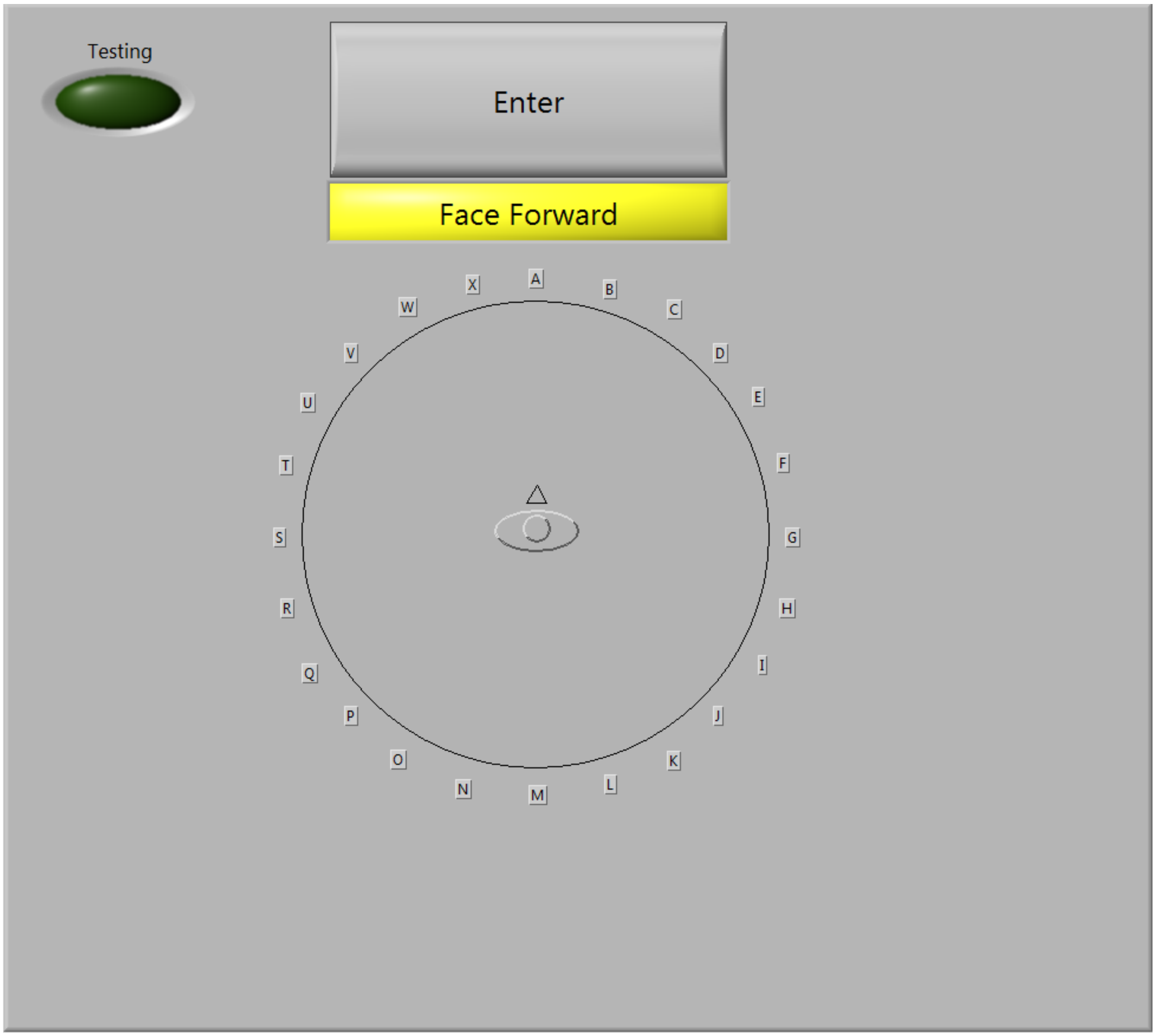


Figure 38. Participant training screen for Task 3.

Following the three training tasks, participants conducted LPHFFS testing with their assigned HPED. This LPHFFS test duration was approximately 10 minutes. During this test, no feedback was provided to indicate the actual location of the stimulus. The LPHFFS test was conducted to monitor performance improvement. Training was planned to stop when no improvement was seen for three consecutive training sessions. However, all participants continued to improve throughout the full set of 12 training sessions.

Phase III

In Phase III, participants complete the LPHFFS test for all three listening conditions. The order of the listening condition was determined using a 3X6 counterbalance design. Following these tests, participants again completed a subjective rating of their accuracy confidence for each listening condition.

Experimental Procedures: Data Collection Session

The procedures for the five distinct tests in the data collection session are best described via the instructions given to subjects, as follows.

Instructions — LPHFFS and 30°/60° Accuracy Test

“You will now hear a single sound. Your task is to identify the direction (in azimuth) of each sound source as accurately (and quickly) as you can. The source of the sound may be in any horizontal direction around you. You are allowed to move your head if you think this will help you to locate the sound source. However, you should not leave your chair or lean your body such that your head is not directly above the seat of the chair. Before each sound is presented you are to face forward.“

Instructions — Interaural Cues Test

“You will now hear two sounds. Your task is to accurately (and quickly) determine if each sound came from the same location or two different locations. If the sound appeared to move, you will also indicate the direction of movement (either left or right) if possible. Before each set of sounds are presented you are to face forward.”

Instructions — Front-Back Confusion Test

“You will now hear a single sound. Your task is to accurately (and quickly) determine if the sound source was to your front or back. You are allowed to move your head if you think this will help you to locate the sound source. However, you should not leave your chair or lean your body such that your head is not directly above the seat of the chair. Before each sound is presented you are to face forward.”

Instructions —Front-Back Difference Test

“You will now hear two sounds. Your task is to accurately (and quickly) determine if each sound came from the same location or two different locations. Before each set of sounds are presented you are to face forward.” Participants were also given verbal instruction that they should keep their head facing forward and to not move their head during this test.

DATA ANALYSIS

Data Reduction and Overall Analysis Plan

Data analysis was performed and reported in five separate sections: Predicting Current Performance (hypothesis 1 & 2); Auditory Learning, Confidence, and Response Time (hypothesis 3); and Predicting Post-Training Performance (hypothesis 4).

Predicting Current and Post-Training Performance data were analyzed separately for each listening condition. A Pearson Product-Moment Correlation was performed for all AFFD test stimulus combinations to determine the combinations that best predict localization performance (LPHFFS). A linear regression was performed for all meaningful combinations.

Auditory learning data and response time data were analyzed for each listening condition, with HPED data grouped by training vs. non-training HPED. An analysis of variance (ANOVA) was performed to determine if main effects and interactions existed. Because measures of response time included more than two factor levels, tests of sphericity were performed. Sphericity is an assumption of a repeated measures ANOVA, and occurs when the variance between the related factor level comparisons are equal. When sphericity is not present, there may be an increase in the Type I error rate. Therefore, when conducting a repeated measures ANOVA with more than two levels of a factor, sphericity should be tested. If significance is found in the ANOVA, and sphericity is violated, the chance of a Type I error rate is reduced by making a correction to the degrees of freedom of the *F*-distribution. A general strategy for dealing with violations of sphericity is to first use the Greenhouse-Geisser (G-G) adjusted *F*-

distribution. As the G-G correction is very conservative (i.e., may over-correct), a significant finding should be accepted. However, a non-significant finding should be followed by using the Huynh-Feldt adjusted *F*-distribution, which is less conservative (Williges, 2007). Post-hoc testing consisted of paired samples *t*-tests with Bonferroni correction. The Bonferroni correction was used to reduce the chance of obtaining a Type I error when performing multiple *t*-tests on the data.

Confidence rating scale data were analyzed for each training group. Data were broken down by listening condition, with HPEDs grouped by training and non-training HPED for both pre and post-training days. As confidence data was collected with a semantic differential (Likert-type) scale, it should be considered ordinal data and analyzed with non-parametric statistical tests (Kaptein, Nass, & Markopoulos, 2010; Martilla & Carvey, 1975). A Friedman non-parametric test was performed on the pre- and post-training mean confidence of each listening condition for each training group. A Wilcoxon signed-rank test, with Bonferroni correction, was used for post-hoc analysis to determine differences in pre-training, between training, and post-training confidence.

All data manipulation, analysis, and graphing were performed with Microsoft Excel 2011 (version 14.1.0), Microsoft PowerPoint 2011 (version 14.1.0), and IBM SPSS Statistics (version 21).

Visual Analysis of LPHFFS Data

An initial visual inspection of the Phase I (pre-training) LPHFFS data and 30°/60° Accuracy AFFD data showed distinct error patterns. Figure 39 shows the response azimuth as a function of the source azimuth for all Listening Conditions. LPHFFS data is shown offset to the left (blue) of AFFD data (red). A perfect response would follow the diagonal line from the bottom left to the top right of this graph.

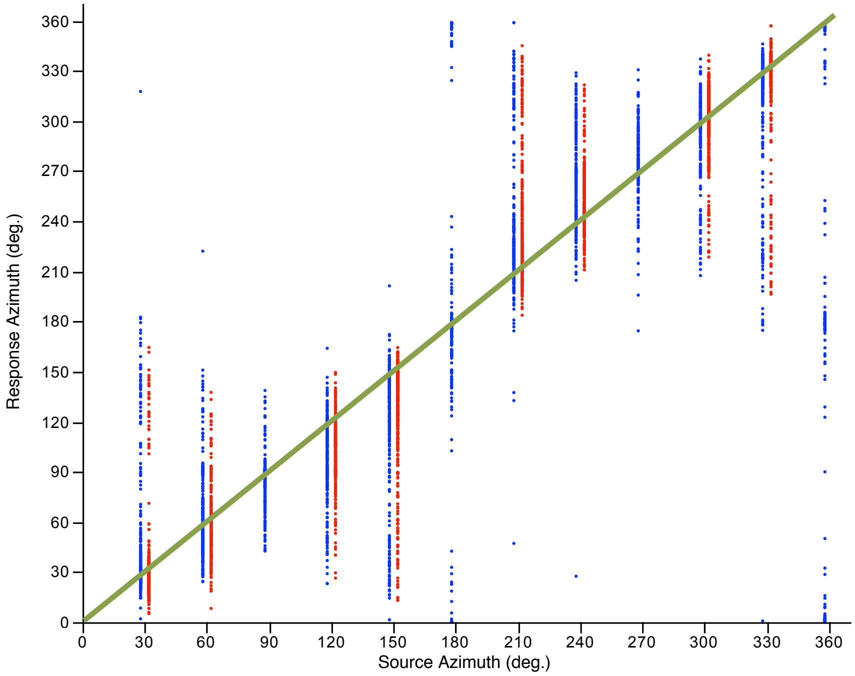


Figure 39. Composite (open-ear, ITE, and OTE), pre-training, response azimuth (ordinate) and source azimuth (abscissa) for LPHFFS (offset left in blue) and 30°/60° Accuracy (offset right in red) tests.The diagonal line (green) represents a perfect response.

Localization blur is observed in this graph by noting the data spread, both above and below the perfect response (diagonal) line. Blur is more apparent at the 90, 180, and 270 source angles due to the lack of cone of confusion errors (90° and 270°) or the distinct separation of cone of confusion errors (180°). Cone of confusion error is also seen in this graph. The expected cone of confusion error location is summarized in Table 16. A strong cone of confusion pattern can be seen by noting the high density of errors centered at the expected cone of confusion locations.

Table 16. Expected Cone of Confusion response azimuth for each source azimuth.

Source Azimuth	30°	60°	120°	150°	180°	210°	240°	300°	330°	360°
Response Azimuth	150°	120°	60°	30°	360°	330°	300°	240°	210°	180°

Responses that do not fit within the expected localization blur or cone of confusion are considered to be other errors. While it is easy to see the three types of error in this graph, it is difficult to differentiate where one type of error ends and the other begins. Since all types of error are contained in both LPHFFS and AFFD measures, it is appropriate to evaluate the composite error in LPHFFS and AFFD measures. Therefore, no attempt was made to separate the *types* of error from either the LPHFFS or 30/60 Accuracy AFFD. It is also apparent that AFFD measures strongly approximate LPHFFS measures in all listening conditions (Figures 40-42).

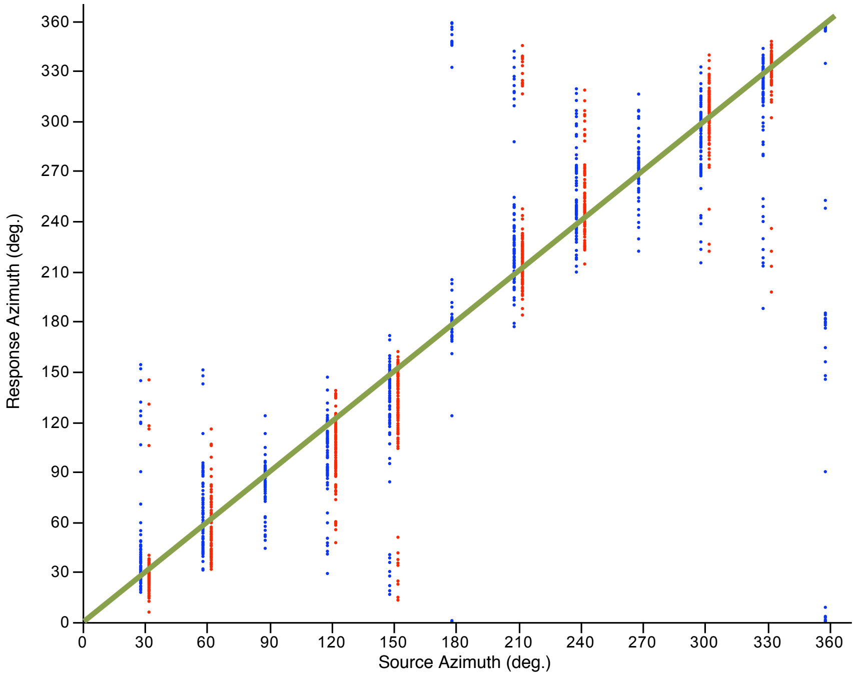


Figure 40. Open-ear, pre-training, response azimuth (ordinate) and source azimuth (abscissa) for LPHFFS (offset left in blue) and 30°/60° Accuracy (offset right in red) tests.

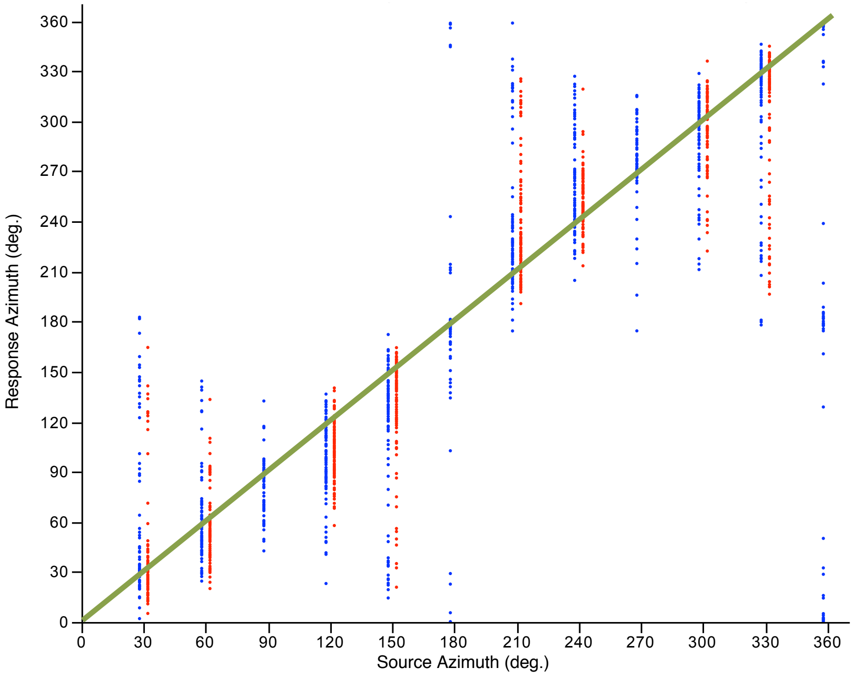


Figure 41. In-the-ear HPED (EB15), pre-training, response azimuth (ordinate) and source azimuth (abscissa) for LPHFFS (offset left in blue) and 30°/60° Accuracy (offset right in red) tests.

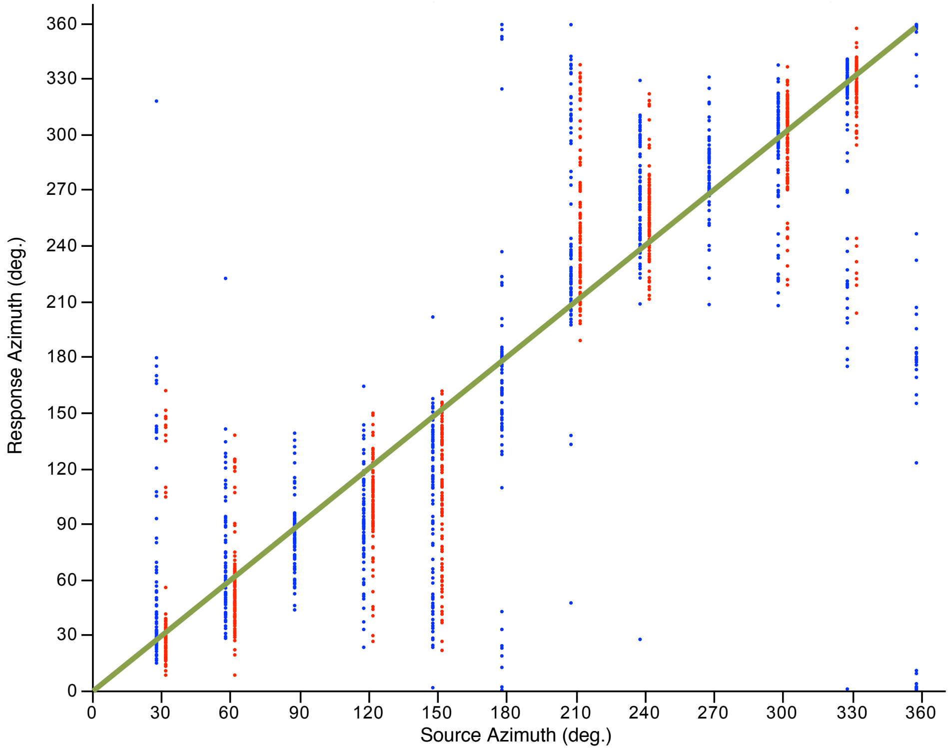


Figure 42. Over-the-ear HPED (Com-Tac II), pre-training, response azimuth (ordinate) and source azimuth (abscissa) for LPHFFS (offset left in blue) and 30°/60° Accuracy (offset right in red) tests.

Overall, pre-training, localization performance (LPHFFS) was analyzed to determine if differences existed between listening conditions. A one-way, within-subjects ANOVA for mean absolute error of LPHFFS showed a significant main effect of condition, *F* (2, 94) = 14.21, *p* < 0.0005 (Table 17). Post-hoc comparisons, using a paired samples *t*-test with Bonferroni correction (α = 0.017) for each condition, showed a significant difference between the open-ear and ITE, and open-ear and OTE listening conditions (Figure 43). There was no significant difference between the ITE and OTE listening conditions. There were no outliers in the data, as assessed by inspection of a boxplot. Values greater than 1.5 box-lengths from the edge of the box were considered to be outliers (Tukey, 1977). This method of classifying data outliers was first suggested by Tukey

(1977) as a "rule of thumb" and continues to be used today. The same criterion recommended by Tukey is used by the statistical software package (SPSS) employed in this study. Mean absolute error was not normally distributed for all three listening conditions, as assessed by Shapiro-Wilk's test ($p < 0.05$). However, the open-ear skewness ($z = 2.56$, $SE = 0.343$) and kurtosis ($z = -0.11$, $SE = 0.674$), ITE skewness ($z = 0.52$, $SE = 0.343$) and kurtosis ($z = -2.02$, $SE = 0.674$)), and OTE skewness ($z = 0.56$, $SE = 0.343$) and kurtosis ($z = -1.61$, $SE = 0.674$) were normal for all three listening conditions.

Table 17. Mauchly's Test of Sphericity & ANOVA for Localization Performance (LPHFFS) by Listening Condition.

Mauchly's Test of Sphericity					Epsilon (ε)	
Variables	Mauchly's Criterion	Chi-Square	*df*	*p*	Greenhouse-Geisser	Huynh-Feldt
Condition	0.760	12.615	2	0.002*	0.807	0.831

ANOVA for Localization Performance (LPHFFS) by Listening Condition.

Source	*df*	MS	*F*	*p*	Greenhouse-Geisser *p*
Condition (C)	2	1137.641	14.211	<0.001*	<0.001*
Error (C)	94	80.055			

* indicates statistically-significant result (p<0.05)

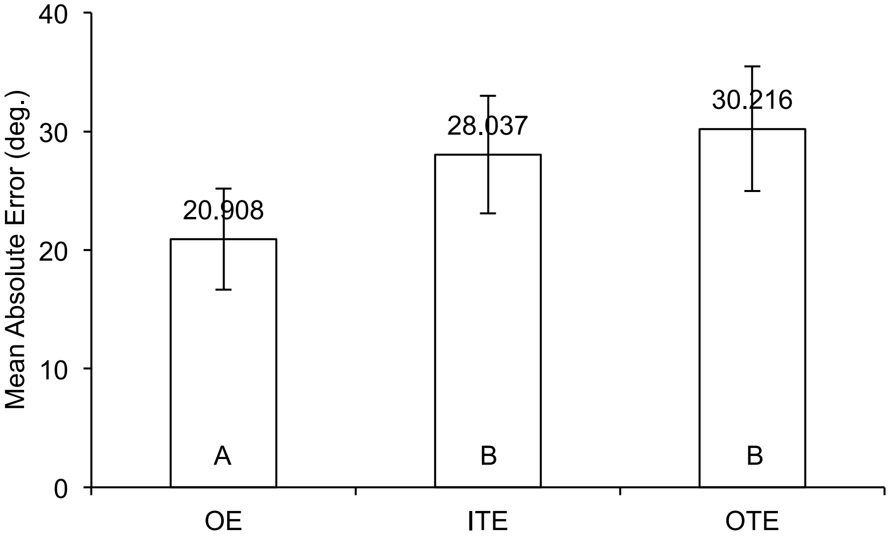


Figure 43. Localization performance (LPHFFS); means and 95% CI shown. Means with the same letter are not significantly different at $p<0.05$ using a paired samples *t*-test with Bonferroni correction.

The mean performance for each Listening Condition was then graphed for each participant (Figure 44). The same pattern (open-ear better than either HPED condition) exists for all participants except participant number seven. This participant appears to perform relatively poorly with the open-ear and rather good with each HPED. Because of this deviation from the expected results, subject 7 data was suspect, in view that it is not reasonable to expect participants to consistently perform better with a novel HPED, which distorts natural localization cues, than with their natural (open-ear) listening condition. A closer look at participant 7 performance on all open-ear tasks (LPHFFS and 30°/60° Accuracy) showed much higher error when stimuli were presented from behind the participant. In fact, all stimuli presented from the rear hemisphere showed a response in the front hemisphere. This was consistent with a complete cone of confusion error, or a assumption that stimuli could not be heard from the rear. Records indicate that the open-ear was the first listening condition for this participant. It appears that participant 7 did not discriminate sounds presented from the rear. Low error rates in the HPED conditions and subsequent (Phase III) open-ear conditions indicate that this participant could localize to the rear, but simply did not during Phase I open-ear testing.

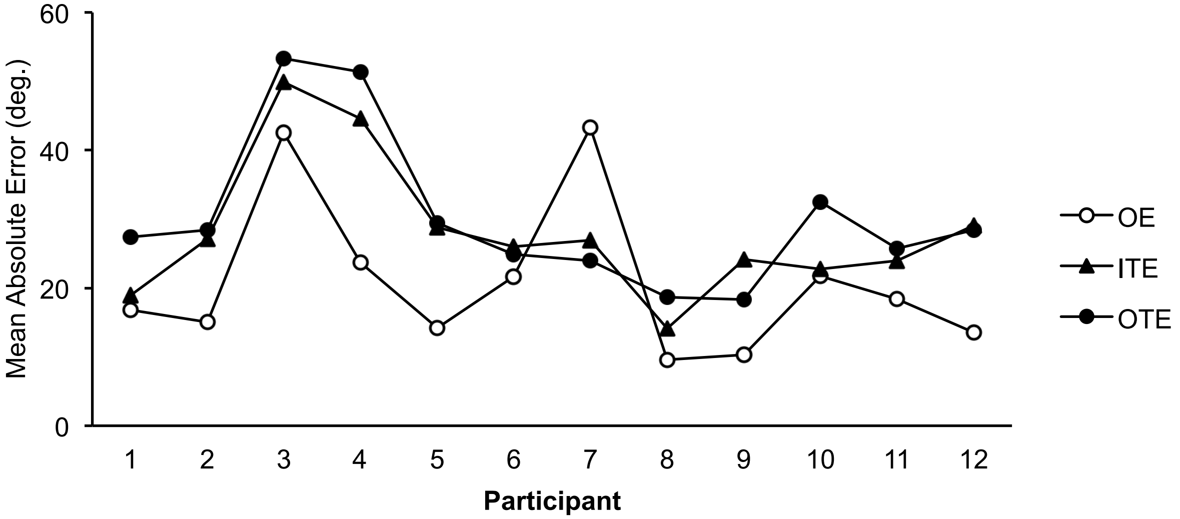


Figure 44. Pre-Training LPHFFS Error by Participant for each Listening Condition.

A Dixon *Q*-test was performed on LPHFFS data to determine if participant 7's data were considered to be outlier. When looking at the data in question, the magnitude of the mean absolute error is not what makes these data potential outliers, but rather the relationship it has with the HPED error (within participant 7). The differences between each participants' open-ear and HPED mean absolute error were used for this comparison. The analysis was performed for both open-ear vs. ITE and open-ear vs. OTE comparisons.

To perform the Dixon *Q*-test, these differences were calculated for each participant and placed in sequential order (Figures 45 & 46). The Dixon *Q*-test was then performed for each open-ear-HPED combination separately, using Dixon's r_{10} table (Dixon, 1951) for *n* ≥ 3 with one suspect outlier.

$$Q = r_{10} = \frac{|x_2 - x_1|}{|x_n - x_1|}$$

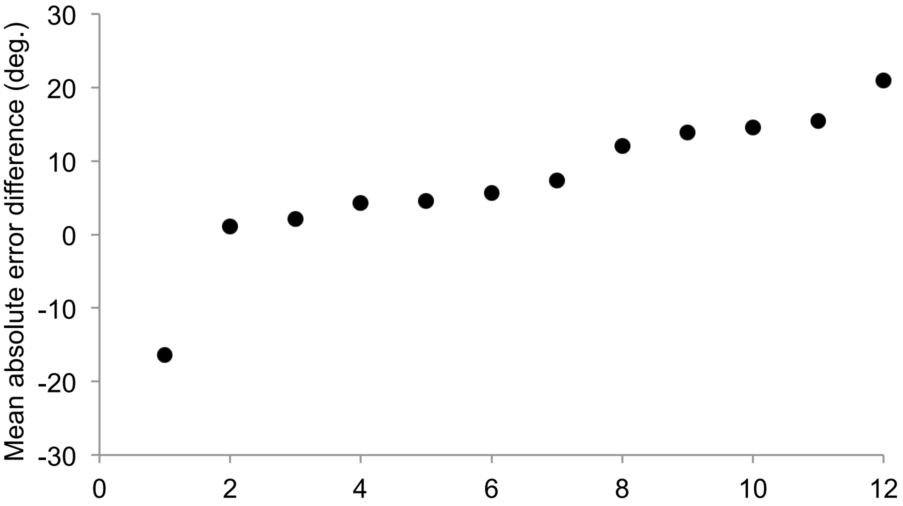


Figure 45. Difference in the mean absolute error between open-ear and ITE (EB15) Listening Conditions for each participant. Values ordered sequentially from smallest to largest.

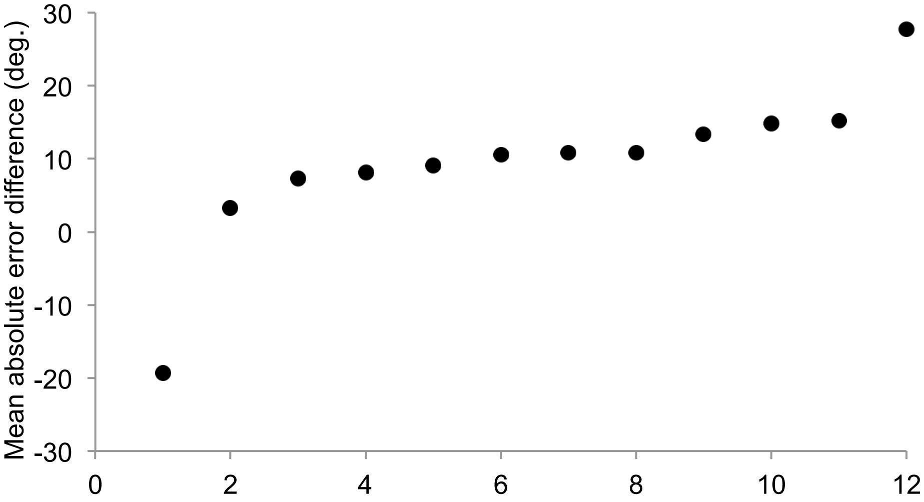


Figure 46. Difference in the mean absolute error between open-ear and OTE (Com-Tac II) Listening Conditions for each participant. Values ordered sequentially from smallest to largest.

A significant outlier was indeed found for both the open-ear to ITE comparison (*Q*=0.467, *p*<.02) and open-ear to OTE comparison (*Q*=0.48, *p*<.02). Both outliers were associated with the suspect data (from participant 7). The significant finding on the *Q*-test indicates that the suspect data can be considered an outlier and removed from the data set. All remaining data analysis was conducted with participant 7’s data removed. Participant 7 was in the OTE training group.

The subsequent presentation of results is divided into the following functional categories: Current Performance, Auditory Learning, Response Time, and Predicting Post-Training Performance. Within each of these categories, results are further subdivided by listening condition (OE, ITE, and OTE).

Results: Predicting Current Performance

The following analysis was performed to determine which AFFD measures are predictive of overall localization performance. Each training group was analyzed separately. Data used in these analyses were obtained from LPHFFS and AFFD testing during Phase I (pre-training). AFFD tests included the 30°/60° Accuracy Test and the FBCT. Data were grouped and analyzed by Listening Condition. LPHFFS accuracy results consisted of the mean absolute error composite of all stimuli; that is, the absolute value of the computed error was used as the "score" in all trials. AFFD results consisted of the mean absolute error for each 30°/60° Accuracy Test quadrant/stimulus combination and the percent error for each FBCT/stimulus combination. AFFD results were then compared to LPHFFS results to determine which AFFD/stimulus combinations could predict LPHFFS performance.

Open-ear: Correlation

A Pearson product-moment correlation of Localization Performance in the open-ear listening condition (OE LP) with all Quadrant-Stimuli combinations (including the FBCT) was performed (Table 18). Analysis showed a linear relationship between LPHFFS and most of the other AFFD measures, with some AFFD measures appearing to have no relationship. However, not all localization tasks were normally distributed, as assessed by Shapiro-Wilk's test ($p < 0.05$). Strong correlations (>0.6) were found between open-ear LP and the Left-Front quadrant with H-Long Stimuli ($r(9) = 0.904$, $p < 0.001$) and H-Short ($r(9) = 0.906$, $p < 0.001$), the Left-Rear quadrant with L-Short ($r(9) = 0.684$, $p = 0.020$), the Right-Front quadrant with H-Long ($r(9) = 0.910$, $p < 0.001$) and H-Short ($r(9)$

= 0.929, $p < 0.001$), the Right-Rear quadrant with H-Long ($r(9) = 0.742$, $p = 0.009$), L-Long ($r(9) = 0.943$, $p < 0.001$), and L-Short ($r(9) = 0.634$, $p = 0.036$), the FBCT with H-Long ($r(9) = 0.839$, $p = 0.001$), H-Short ($r(9) = 0.836$, $p = 0.001$), and L-Long ($r(9) = 0.659$, $p = 0.028$).

Table 18. Open-ear correlation of LPHFFS (pre-training) with AFFD (pre-training) measures.

	Stimulus		Left-Front	Right-Front	Left-Rear	Right-Rear	FBCT
LPHFFS	H-Long	Pearson Correlation	0.904*	0.910*	0.110	0.742*	0.839*
		Sig. (2-tailed)	<0.001	<0.001	0.747	0.009	0.001
		n	11	11	11	11	11
	H-Short	Pearson Correlation	0.906*	0.929*	0.002	0.383	0.836*
		Sig. (2-tailed)	<0.001	<0.001	0.995	0.245	0.001
		n	11	11	11	11	11
	L-Long	Pearson Correlation	0.194	0.420	0.439	0.943*	0.659*
		Sig. (2-tailed)	0.568	0.198	0.177	<0.001	0.028
		n	11	11	11	11	11
	L-Short	Pearson Correlation	0.290	-0.029	0.684*	0.643*	0.401
		Sig. (2-tailed)	0.387	0.934	0.020	0.036	0.222
		n	11	11	11	11	11

* indicates statistically-significant result (p<0.05)

While several strong and significant correlations were found, a practical correlation would include a significant finding for a given stimulus (combination of frequency and duration) in both the left and right sides of a hemisphere (for quadrant tests). Practical correlations were found in quadrant tests as well as the FBCT. The practical correlation patterns included the Front-Left and Front-Right quadrants for both H-Long and H-Short stimuli, the Rear-Left and Rear-Right quadrants for L-Short, and the FBCT with H-Long, H-Short, and L-Long stimuli.

A linear regression was performed to establish which stimulus-test (quadrant/FBCT) pair could predict open-ear localization performance. The H-Long stimuli significantly predicted open-ear localization performance in the Left-Front, F (1, 9) = 40.40, $p <$ 0.001, and Right-Front, F (1, 9) = 43.16, $p <$ 0.001, quadrants, and the FBCT, F (1, 9) = 21.44, p = 0.001 (Figure 47). The Left-Front, Right-Front, and FBCT measures explained 79.8%, 80.8%, and 67.1% of the variability (adjusted R^2) in open ear localization performance, respectively. No significant outliers were found (± 3 Std.Dev.). Independence of Errors was verified with the Durbin-Watson statistic (2.45, 2.58, and 2.13 respectively) and showed no autocorrelation. Error Variance appeared to show negative heteroscedasticity for Left-Front and Right-Front quadrants, and homoscedasticity in the FBCT. The Koenker test for Heteroscedasticity was not significant for the Left-Front ($X^2(1) = 1.167$, $p = 0.280$), Right-Front ($X^2(1) = 1.251$, $p =$ 0.263), or FBCT ($X^2(1) = 1.067$, $p = 0.3016$). Normality of Error was verified with a histogram showing a mean near zero and SD near one for all AFFD measures. The preceding assumptions, required for this statistical analysis to be considered valid, appear to have been met.

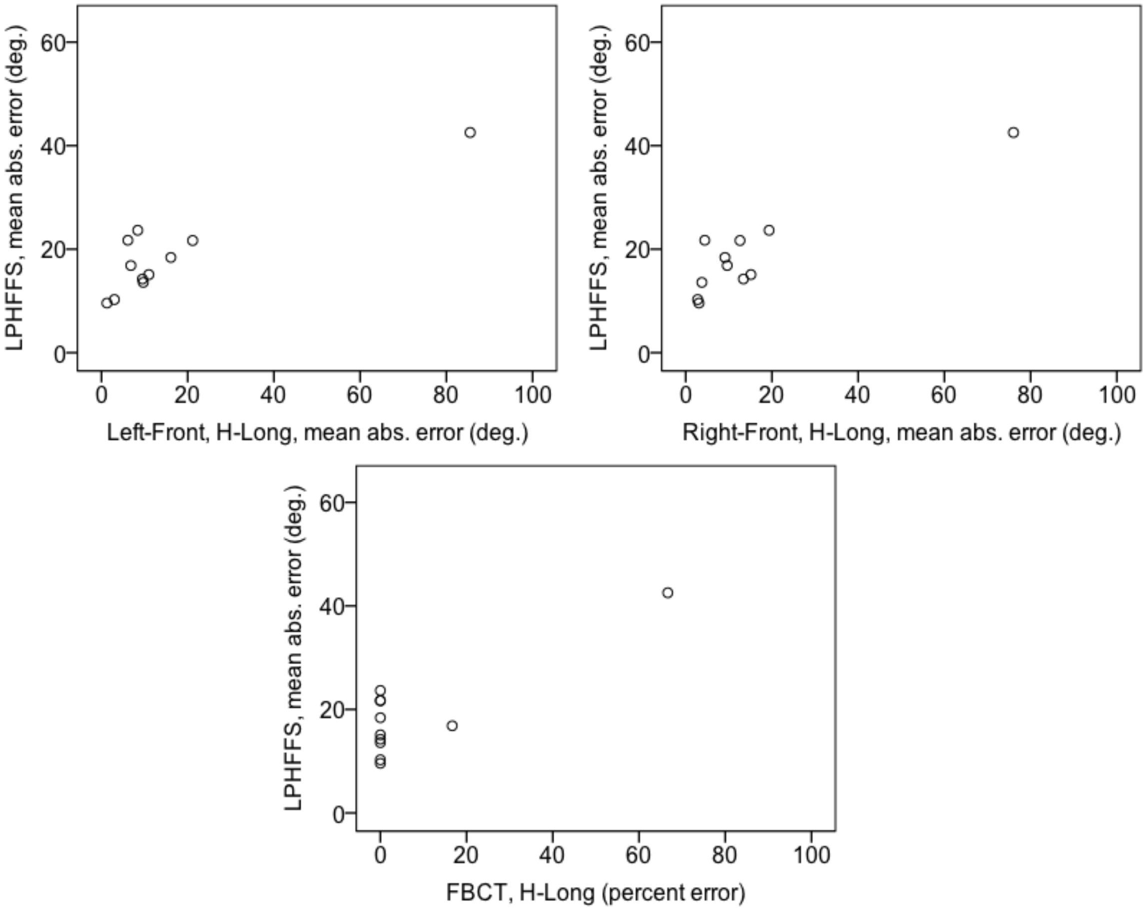


Figure 47. Open-ear, H-Long correlation between LPHFFS and 30/60 Accuracy (Left-Front & Right-Front) quadrants, and the FBCT.

The H-Short stimuli significantly predicted open-ear localization performance in the Left-Front, *F* (1, 9) = 41.26, *p* < 0.001, and Right-Front, *F* (1, 9) = 56.49, *p* < 0.001, quadrants, and the FBCT, *F* (1, 9) = 20.91, *p* = 0.001 (Figure 48). The Left-Front, Right-Front, and FBCT measures explained 80.1%, 84.7%, and 66.6% of the variability (adjusted R^2) in open ear localization performance, respectively. No significant outliers were found (± 3 Std.Dev.). Independence of Errors was verified with the Durbin-Watson statistic (2.34, 2.34, and 2.32 respectively), showing no autocorrelation. Error Variance appeared to show negative heteroscedasticity for Left-Front, Right-Front, and FBCT measures. The Koenker test for Heteroscedasticity was not significant for the Left-Front

($X^2(1) = 1.025$, $p = 0.311$), Right-Front, ($X^2(1) = 0.977$, $p = 0.323$), and FBCT ($X^2(1) = 3.200$, $p = 0.074$). Normality of Error was verified with a histogram showing a mean near zero and SD near one for all AFFD measures. The preceding assumptions, required for this statistical analysis to be considered valid, appear to have been met.

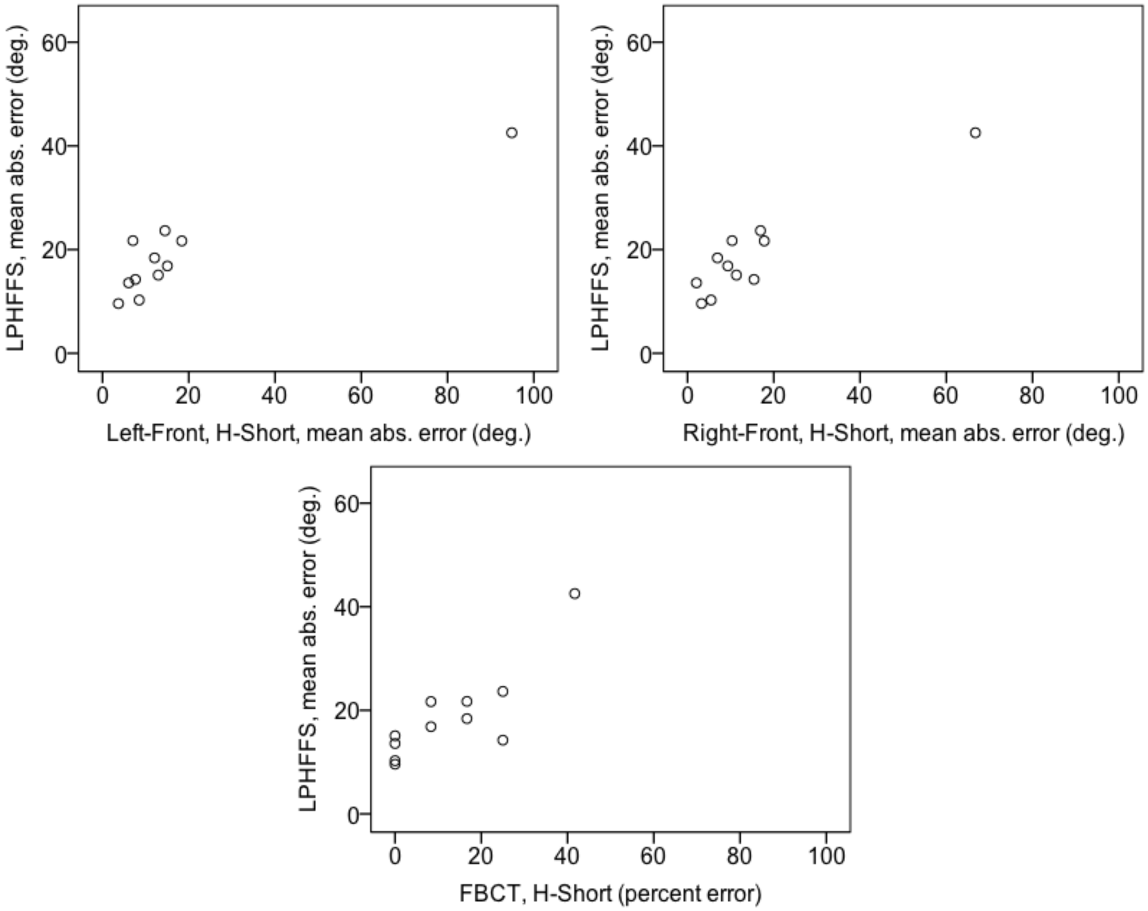


Figure 48. Open-ear, H-Short correlation between LPHFFS and 30/60 Accuracy (Left-Front & Right-Front) quadrants, and the FBCT.

The L-Long stimuli significantly predicted open-ear localization performance in the FBCT, $F(1, 9) = 6.90$, $p = 0.028$ (Figure 49). The FBCT measure explained 37.1% of the variability (adjusted R^2) in open ear localization performance. This value is generally lower than the variability explained by the other stimuli/test combinations. No significant outliers were found (± 3 Std.Dev.). Independence of Errors was verified with the Durbin-Watson statistic (2.65), showing no autocorrelation. Error Variance appeared to show positive heteroscedasticity, with a potential for Type I errors. The Koenker test for Heteroscedasticity was significant ($X^2(1) = 5.156$, $p = 0.023$). Normality of Error was verified with a histogram showing a mean near zero and SD near one. The preceding assumptions, required for this statistical analysis to be considered valid, appear to have been met. However, the potential of a Type I error exists due to positive heteroscedasticity.

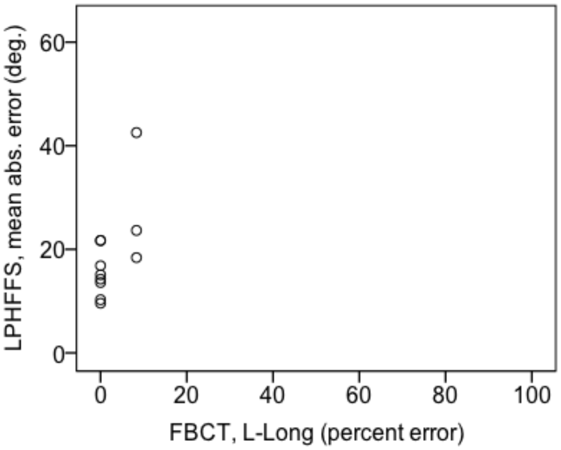


Figure 49. Open-ear, L-Long correlation between LPHFFS and FBCT.

The L-Short stimuli significantly predicted open-ear localization performance in the Left-Rear, $F(1, 9) = 7.91$, $p < 0.020$, and Right-Rear, $F(1, 9) = 6.05$, $p = 0.036$, quadrants (Figure 50). The Left-Rear, Right-Rear measures explained 40.9% and 33.6% of the variability (adjusted R^2) in open ear localization performance, respectively. No significant outliers were found (± 3 Std.Dev.). Independence of Errors was verified with the Durbin-Watson statistic (2.05 and 1.373 respectively), showing no autocorrelation. Error Variance appeared to show positive heteroscedasticity for Left-Rear and Right-

Rear measures, with a potential for Type I errors. The Koenker test for Heteroscedasticity was significant for the Left-Rear ($X^2(1) = 5.909$, $p = 0.015$) and Right-Rear ($X^2(1) = 4.788$, $p = 0.029$). Normality of Error was verified with a histogram, showing a mean near zero and SD near one for all AFFD measures. The preceding assumptions, required for this statistical analysis to be considered valid, appear to have been met. However, the potential of a Type I error exists due to positive heteroscedasticity.

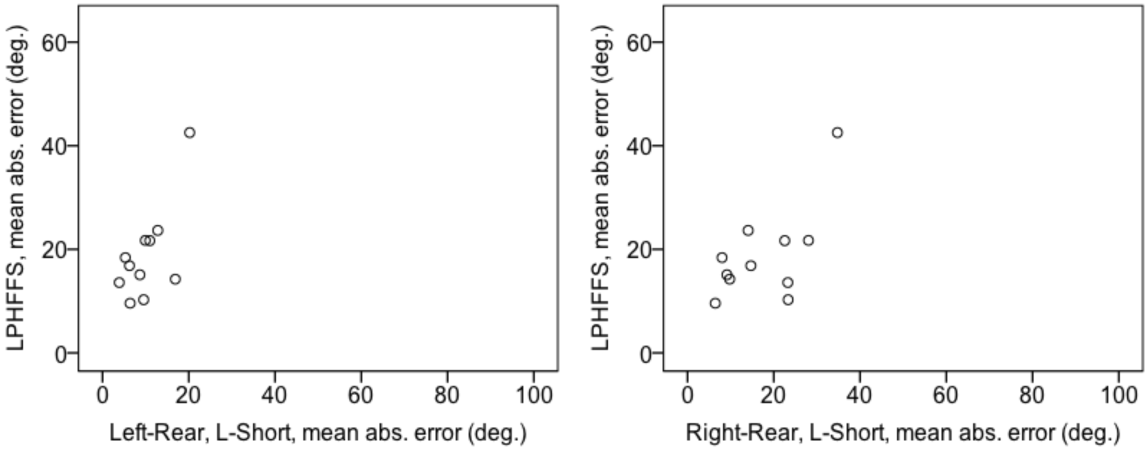


Figure 50. Open-ear, L-Short correlation between LPHFFS and 30/60 Accuracy (Left-Rear & Right-Rear) quadrants.

Open-ear: Stepwise Regression

A Stepwise Linear Regression was also performed to predict OE Localization Performance from all Quadrant-Stimuli combinations. Left and Right side quadrant-stimuli combinations and FBCT stimuli combinations were tested separately. Analysis of the Left side combinations showed that the Left-Front H-Short quadrant-stimuli combination statistically significantly predicted Localization Performance, $F(1, 9) = 41.259$, $p < 0.001$, adjusted $R^2 = 0.801$ (Table 19). Analysis of the Right side combinations showed that the Right-Rear L-Long and Right-Front L-Short quadrant-stimuli combinations statistically significantly predicted Localization Performance, *F* (2, 8) = 76.959, $p < 0.001$, adjusted $R^2 = 0.938$ (Table 20). Analysis of the FBCT combinations showed that the H-Long and H-Short stimuli combinations statistically significantly predicted Localization Performance, *F* (2, 8) = 21.138, $p = 0.001$, adjusted $R^2 = 0.801$ (Table 21). All variables added statistically significantly to the prediction, $p < 0.05$.

Table 19. ANOVA for Localization Performance and stepwise regression predictors in the open-ear listening condition using left hemisphere quadrant-stimuli combinations.

Model	*df*	MS	*F*	*p*
Regression	1	679.002	41.259	<0.001
Residual	9	16.457		
Total	10			

Predictors: Left-Front H-Short

Table 20. ANOVA for Localization Performance and stepwise regression predictors in the open-ear listening condition using right hemisphere quadrant-stimuli combinations.

Model	*df*	MS	*F*	*p*
Regression	2	393.125	76.959	<0.001
Residual	8	5.108		
Total	10			

Predictors: Right-Rear L - Long, Right Front L - Short

Table 21. ANOVA for Localization Performance and stepwise regression predictors in the open-ear listening condition using FBCT-stimuli combinations.

Model	*df*	MS	*F*	*p*
Regression	2	347.753	21.138	0.001
Residual	8	16.451		
Total	10			

Predictors: H-Long, H-Short

In-the-ear HPED: Correlation

The following analysis follows the same sequence as that presented for the open-ear. A Pearson product-moment correlation of Localization Performance in the in-the-ear HPED listening condition with all Quadrant-Stimuli combinations (including the FBCT) was performed (Table 22). Localization Performance was determined by taking the mean absolute error, in degrees, for each localization task and the percent correct for the FBCT. Analysis showed a linear relationship between open-ear LP and most of the other localization tasks, with some tasks appearing to have no relationship. However, not all localization tasks were normally distributed, as assessed by Shapiro-Wilk's test ($p < 0.05$). Strong correlations (>0.6) were found between in-the-ear HPED localization performance and the Left-Front quadrant with H-Long Stimuli ($r(9) = 0.925$, $p < 0.001$), the Left-Rear quadrant with H-Long ($r(9) = 0.693$, $p = 0.018$), H-Short ($r(9) = 0.810$, $p = 0.003$), and L-Long ($r(9) = 0.784$, $p = 0.004$), the Right-Front quadrant with H-Long ($r(9) = 0.688$, $p = 0.019$), and the FBCT with H-Long ($r(9) = 0.845$, $p = 0.001$).

Table 22. In-the-ear (EB15) correlation of LPHFFS (pre-training) with AFFD (pre-training) measures.

	Stimulus		Left-Front	Right-Front	Left-Rear	Right-Rear	FBCT
LPHFFS	H-Long	Pearson Correlation	0.925*	0.688*	0.693*	0.558	0.845*
		Sig. (2-tailed)	<0.001	0.019	0.018	0.074	0.001
		n	11	11	11	11	11
	H-Short	Pearson Correlation	0.279	0.304	0.810*	0.576	0.552
		Sig. (2-tailed)	0.406	0.364	0.003	0.064	0.078
		n	11	11	11	11	11
	L-Long	Pearson Correlation	0.108	0.118	0.784*	0.508	-0.041
		Sig. (2-tailed)	0.752	0.730	0.004	0.111	0.905
		n	11	11	11	11	11
	L-Short	Pearson Correlation	-0.036	0.424	0.454	0.116	0.528
		Sig. (2-tailed)	0.916	0.194	0.161	0.735	0.095
		n	11	11	11	11	11

* indicates statistically-significant result ($p<0.05$)

While several strong and significant correlations were found, a practical correlation would include a significant finding for a given stimulus in both the left and right sides of a hemisphere (for quadrant tests). Practical correlations were found in quadrant tests as well as the FBCT. The practical correlation patterns include the Left-Front quadrant, Right-Front quadrant, and FBCT with the H-Long stimulus (Figure 51). This suggests that the H-Long stimulus is the most appropriate stimulus for assessing performance with an ITE HPED.

A linear regression was performed to establish if each stimulus-test (quadrant/FBCT) pair could predict in-the-ear HPED localization performance. The H-Long stimuli significantly predicted in-the-ear HPED localization performance in the Left-Front, F (1, 9) = 53.24, p < 0.001, and Right-Front, F (1, 9) = 8.07, p = 0.019, quadrants, and the FBCT, F (1, 9) = 22.40, p = 0.001. The Left-Front, Right-Front, and FBCT measures explained 83.9%, 41.4%, and 68.1% of the variability (adjusted R^2) in open ear localization performance, respectively. No significant outliers were found (± 3 Std.Dev.). Independence of Errors was verified with the Durbin-Watson statistic (2.20, 1.24, and 2.02 respectively), showing no autocorrelation. Error Variance appeared to show negative heteroscedasticity for Left-Front and FBCT, and positive heteroscedasticity in the Right-Front. The Koenker test for Heteroscedasticity was not significant for the Left-Front ($X^2(1) = 1.330$, $p = 0.249$) and FBCT ($X^2(1) = 1.162$, $p = 0.281$), but was significant for the Right-Front ($X^2(1) = 5.424$, $p = 0.020$). Normality of Error was verified with a histogram showing a mean near zero and SD near one for all AFFD measures. The preceding assumptions, required for this statistical analysis to be considered valid, appear to have been met. However, the potential of a Type I error exists, in the Right-Front quadrant, due to positive heteroscedasticity.

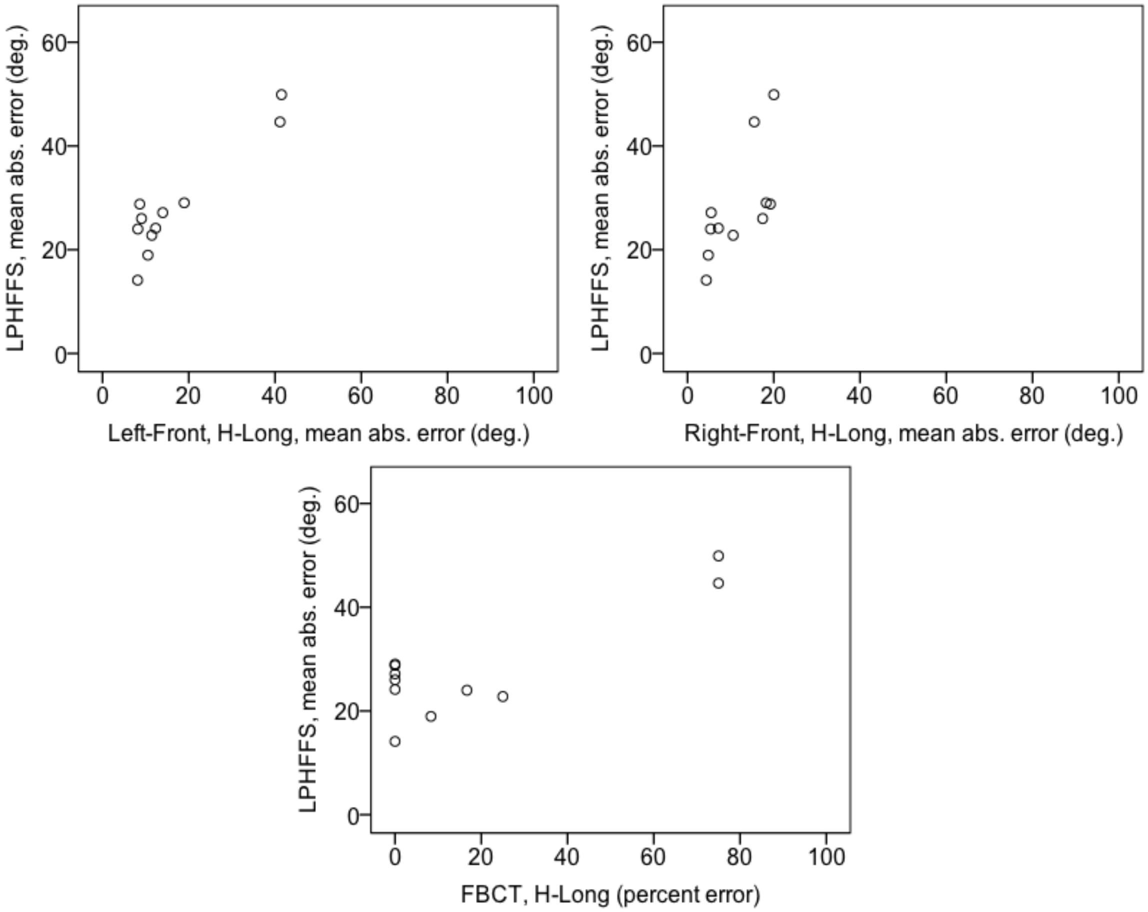


Figure 51. In-the-ear HPED (EB15), H-Long correlation between LPHFFS and 30/60 Accuracy (Left-Front & Right-Front) quadrants, and the FBCT.

In-the-ear HPED: Stepwise Regression

A Stepwise Linear Regression was performed to predict ITE Localization Performance from all Quadrant-Stimuli combinations. Left and Right side quadrant-stimuli combinations and FBCT stimuli combinations were tested separately. Analysis of the Left side combinations showed that the Left-Front H-Long and Left-Rear H-Short quadrant-stimuli combinations statistically significantly predicted Localization Performance, F (2, 8) = 83.070, $p < 0.001$, adjusted $R^2 = 0.943$ (Table 23). Analysis of the Right side combinations showed that the Right-Front H-Long quadrant-stimuli combination statistically significantly predicted Localization Performance, *F* (1, 9) = 8.072, *p* = 0.019, adjusted R^2 = 0.414 (Table 24). Analysis of the FBCT combinations showed that the H-Long stimulus statistically significantly predicted Localization Performance, *F* (1, 9) = 22.396, *p* = 0.001, adjusted R^2 = 0.681 (Table 25). All variables added statistically significantly to the prediction, $p < 0.05$.

Table 23. ANOVA for Localization Performance and stepwise regression predictors in the in-the-ear listening condition using left hemisphere quadrant-stimuli combinations.

Model	*df*	MS	*F*	*p*
Regression	2	522.128	83.070	<0.001
Residual	8	6.285		
Total	10			

Predictors: Left-Front H-Long, Left-Rear H-Short

Table 24. ANOVA for Localization Performance and stepwise regression predictors in the in-the-ear listening condition using right hemisphere quadrant-stimuli combinations.

Model	*df*	MS	*F*	*p*
Regression	1	517.531	8.072	0.019
Residual	9	64.112		
Total	10			

Predictor: Right-Front H-Long

Table 25. ANOVA for Localization Performance and stepwise regression predictors in the in-the-ear listening condition using FBCT -stimuli combinations.

Model	*df*	MS	*F*	*p*
Regression	1	780.773	22.396	0.001
Residual	9	34.863		
Total	10			

Predictor: H-Long

Over-the-ear HPED: Correlation

The following analysis follows the same sequence as that presented for the ITE HPED. A Pearson product-moment correlation of Localization Performance in the over-the-ear HPED listening condition with all Quadrant-Stimuli combinations (including the FBCT) was performed (Table 26). Localization Performance was determined by taking the mean absolute error, in degrees, for each localization task and the percent correct for the FBCT. Analysis showed a linear relationship between open-ear HPED localization performance and most of the other localization tasks, with some tasks appearing to have no relationship. However, not all localization tasks were normally distributed, as assessed by Shapiro-Wilk's test ($p < 0.05$). Strong correlations (>0.6) were found between over-the-ear HPED localization performance and the Left-Front quadrant with H-Long Stimuli ($r(9) = 0.812$, $p = 0.002$) and L-Long Stimuli ($r(9) = 0.610$, $p = 0.046$), the Left-Rear quadrant with L-Long ($r(9) = 0.686$, $p = 0.020$), the Right-Front quadrant with H-Long ($r(9) = 0.638$, $p = 0.034$), the Right-Rear quadrant with L-Long Stimuli ($r(9) = 0.721$, $p = 0.012$) and L-Short Stimuli ($r(9) = 0.742$, $p = 0.009$), and the FBCT with H-Long ($r(9) = 0.687$, $p = 0.019$) and H-Short Stimuli ($r(9) = 0.916$, $p < 0.001$).

Table 26. Over-the-ear (Com-Tac II) correlation of LPHFFS (pre-training) with AFFD (pre-training) measures.

	Stimulus		Left-Front	Right-Front	Left-Rear	Right-Rear	FBCT
LPHFFS	H-Long	Pearson Correlation	0.812*	0.638*	0.283	0.577	0.687*
		Sig. (2-tailed)	0.002	0.034	0.398	0.063	0.019
		n	11	11	11	11	11
	H-Short	Pearson Correlation	0.526	0.447	-0.175	0.168	0.916*
		Sig. (2-tailed)	0.096	0.168	0.606	0.622	<0.001
		n	11	11	11	11	11
	L-Long	Pearson Correlation	0.610*	0.339	0.686*	0.721*	0.593
		Sig. (2-tailed)	0.046	0.309	0.020	0.012	0.054
		n	11	11	11	11	11
	L-Short	Pearson Correlation	0.380	0.106	0.544	0.742*	0.481
		Sig. (2-tailed)	0.249	0.757	0.084	0.009	0.134
		n	11	11	11	11	11

* indicates statistically-significant result (p<0.05)

While several strong and significant correlations were found, a practical correlation would include a significant finding for a given stimulus in both the left and right sides of a hemisphere (for quadrant tests). Practical correlations were found in quadrant tests as well as the FBCT. The practical correlation patterns include the H-Long stimuli with the Left-Front and Right-Front quadrant and the FBCT (Figure 52), H-Short stimuli with FBCT (Figure 53), and the L-Long stimuli with the Left-Rear and Right-Rear quadrant (Figure 54). This suggests that the H-Long, H-Short, and L-Long stimuli, when used with their respective test combinations, are the most appropriate stimuli for assessing performance with an OTE HPED.

A linear regression was performed to establish if each stimulus-test (quadrant/FBCT) pair could predict over-the-ear HPED localization performance. The H-Long stimuli significantly predicted over-the-ear HPED localization performance in the Left-Front, *F* (1, 9) = 17.45, *p* = 0.002, and Right-Front, *F* (1, 9) = 6.19, *p* = 0.034, quadrants, and the FBCT, *F* (1, 9) = 8.06, *p* = 0.019. The Left-Front, Right-Front, and FBCT measures explained 62.2%, 34.2%, and 41.4% of the variability (adjusted R^2) in over-the-ear localization performance, respectively. No significant outliers were found (± 3 Std.Dev.). Independence of Errors was verified with the Durbin-Watson statistic (2.06, 1.94, and 1.67 respectively), showing no autocorrelation. Error Variance appeared to show negative heteroscedasticity, with a potential for Type II errors, for Left-Front, Right-Front, and FBCT measures. The Koenker test for Heteroscedasticity was not significant for the Left-Front ($X^2(1) = 0.183$, $p = 0.669$), Right-Front ($X^2(1) = 0.340$, $p = 0.560$), and FBCT ($X^2(1) = 0.055$, $p = 0.814$). Normality of Error was verified with a histogram showing a mean near zero and SD near one for all AFFD measures. The preceding assumptions, required for this statistical analysis to be considered valid, appear to have been met.

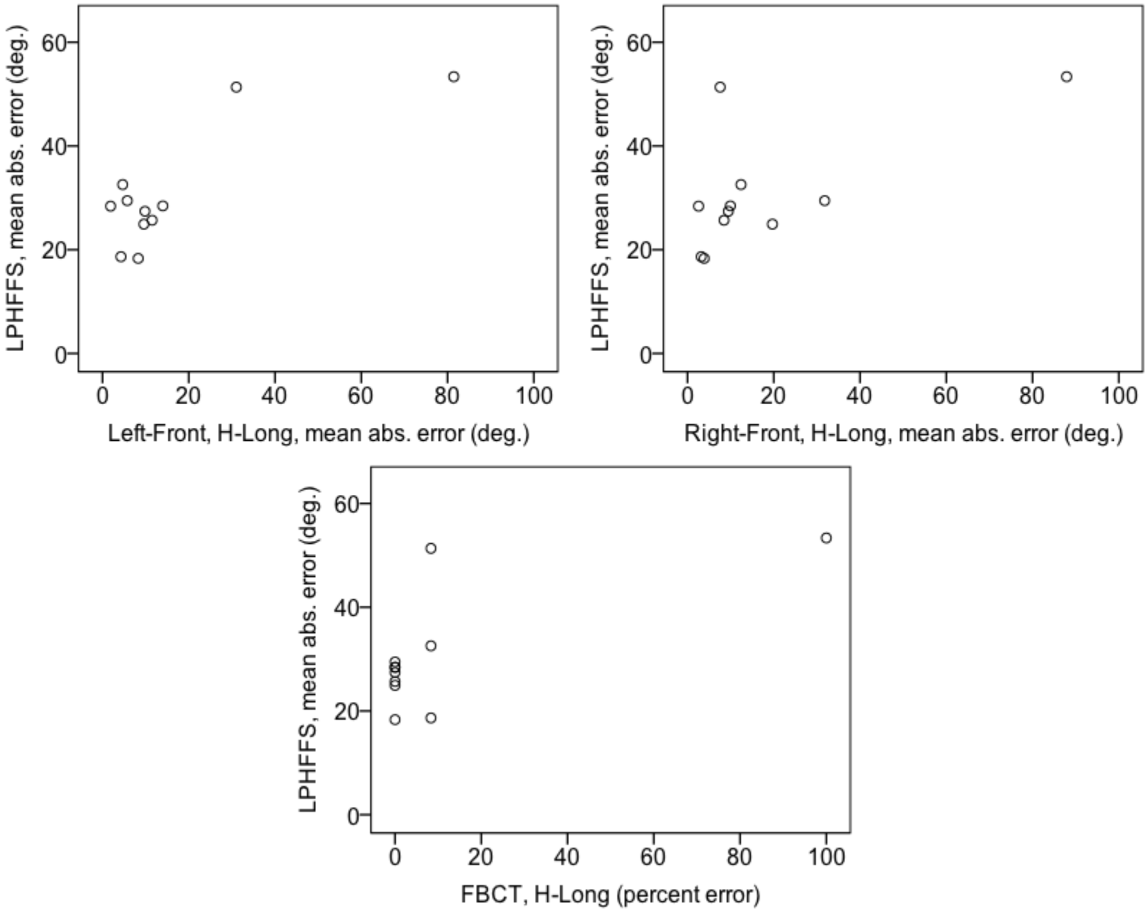


Figure 52. Over-the-ear (Com-Tac II), H-Long correlation between LPHFFS and 30/60 Accuracy (Left-Front & Right-Front) quadrants, and the FBCT.

The H-Short stimuli significantly predicted open-ear localization performance in the FBCT, *F* (1, 9) = 46.83, *p* < 0.001. The FBCT measure explained 82.1% of the variability (adjusted R^2) in over-the-ear localization performance. No significant outliers were found (± 3 Std.Dev.). Independence of Errors was verified with the Durbin-Watson statistic (1.28), showing no autocorrelation. Error Variance appeared to show negative heteroscedasticity with a potential for Type II errors. The Koenker test for Heteroscedasticity was not significant ($X^2(1) = 0.090$, *p* = 0.296). Normality of Error was verified with a histogram showing a mean near zero and SD near one for all AFFD measures. The preceding assumptions, required for this statistical analysis to be considered valid, appear to have been met.

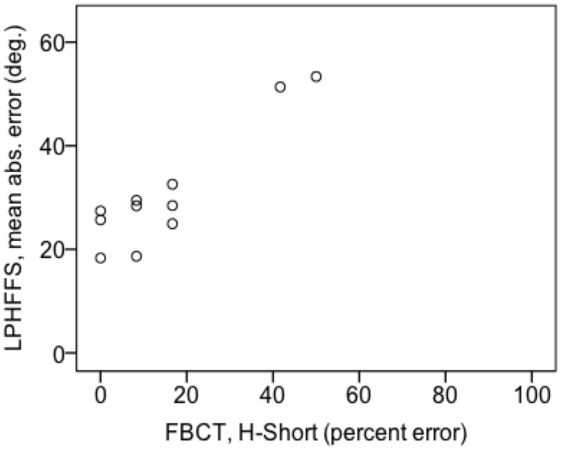


Figure 53. Over-the-ear (Com-Tac II), H-Short correlation between LPHFFS and FBCT.

The L-Long stimuli significantly predicted over-the-ear HPED localization performance in the Left-Rear, *F* (1, 9) = 8.02, *p* = 0.020 and Right-Rear, *F* (1, 9) = 9.74, *p* = 0.012, quadrants. The Left-Rear and Right-Rear measures explained 42.1% and 46.6% of the variability (adjusted R^2) in over-the-ear HPED localization performance, respectively. No significant outliers were found (± 3 Std.Dev.). Independence of Errors was verified with the Durbin-Watson statistic (1.72 and 2.07, respectively), showing no autocorrelation. Error Variance appeared to show negative heteroscedasticity, with a potential for Type II errors, for Left-Rear and positive heteroscedasticity, with a potential for Type I errors for the Right-Rear quadrants. The Koenker test for Heteroscedasticity was not significant for the Left-Rear ($X^2(1) = 0.257$, $p = 0.612$) and was significant for the Right-Rear ($X^2(1) = 5.546$, $p = 0.019$). Normality of Error was verified with a histogram showing a mean near zero and SD near one for all AFFD measures. The preceding assumptions, required for this statistical analysis to be considered valid, appear to have been met. However, the potential of a Type I error exists, in the Right-Rear quadrant, due to positive heteroscedasticity.

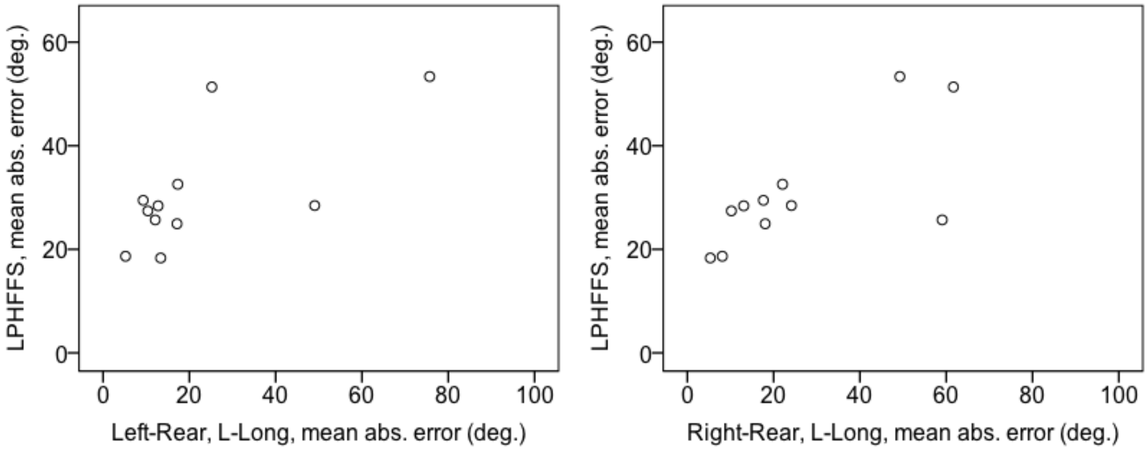


Figure 54. Over-the-ear (Com-Tac II), L-Long correlation between LPHFFS and 30/60 Accuracy (Left-Rear & Right-Rear) quadrants.

Over-the-ear HPED Stepwise Regression

A Stepwise Linear Regression was performed to predict OTE Localization Performance from all Quadrant-Stimuli combinations. Left and Right side quadrant-stimuli combinations and FBCT stimuli combinations were tested separately. Analysis of the Left side combinations showed that the Left-Front H-Long and Left-Front L-Long quadrant-stimuli combinations statistically significantly predicted Localization Performance, F (2, 8) = 17.589, p = 0.001, adjusted R^2 = 0.768 (Table 27). Analysis of the Right side combinations showed that the Right-Rear L-Short quadrant-stimuli combination statistically significantly predicted Localization Performance, F (1, 9) = 11.014, p = 0.009, adjusted R^2 = 0.500 (Table 28). Analysis of the FBCT combinations showed that the H-Short stimulus statistically significantly predicted Localization

Performance, F (1, 9) = 46.833, $p < 0.001$, adjusted $R^2 = 0.821$ (Table 29). All variables added statistically significantly to the prediction, $p < 0.05$.

Table 27. ANOVA for Localization Performance and stepwise regression predictors in the over-the-ear listening condition using left hemisphere quadrant-stimuli combinations.

Model	*df*	MS	*F*	*p*
Regression	2	538.452	17.589	0.001
Residual	8	30.613		
Total	10			

Predictors: Left-Front H-Long, Left-Front L-Long

Table 28. ANOVA for Localization Performance and stepwise regression predictors in the over-the-ear listening condition using right hemisphere quadrant-stimuli combinations.

Model	*df*	MS	*F*	*p*
Regression	1	727.407	11.014	0.009
Residual	9	66.045		
Total	10			

Predictor: Right-Rear L - Short

Table 29. ANOVA for Localization Performance and stepwise regression predictors in the over-the-ear listening condition using FBCT-stimuli combinations.

Model	*df*	MS	*F*	*p*
Regression	1	1108.741	46.833	<0.001
Residual	9	23.674		
Total	10			

Predictor: H-Short

Assumptions Overview Concerning the Current Performance Data

Normality - The Shapiro-Wilk test of Normality found non-normal distributions in 10 of 21 open-ear conditions 14 of 21 ITE conditions and 16 of 21 OTE conditions. However, it must be considered that the data used in these analyses were first transformed from a raw error score to a mean absolute error. When taking the absolute value of the raw error, the negative distribution tail has essentially been folded onto the positive tail. This will create skewed data and can result in a non-normal finding in the normality test. The raw data also included cone of confusion error. Furthermore, cone of confusion error will add a positive tail to data presented to the front and a negative tail to data presented to the rear. Cone of confusion errors are real, and expected to occur and often increase when a device is worn. Cone of confusion errors also result in skewed raw data for a given quadrant. This skew in raw data will also be seen when the data is transformed into a mean of its absolute value. While this may be concerning, the resulting regression analysis found residuals to be normally distributed for all tested conditions.

Correlation Significance – All significant correlations also had a strong R^2 value (≥ 0.6) and were considered strong enough for further analysis. The statistical significance of a correlation indicates the likelihood that the correlation could have been obtained by chance. The stimulus/test conditions selected for regression analysis were felt to be of practical significance due to their high correlation value (R^2) and high significance, with a relatively small sample size.

Heteroscedasticity – Of the 18 linear regressions performed, five showed significant positive heteroscedasticity with the Koenker test. Of these, four were low frequency sounds and either in the rear hemisphere (3) or the FBCT (1). Only one included a high frequency sound and was in the front hemisphere. When heteroscedasticity is positive it increases the likelihood of a Type I error. Negative heteroscedasticity results in a likelihood of increased Type II error.

The *F*-test in the linear regression model tested if a linear relationship between the AFFD and the LPHFFS existed and if it was a better model than the simple mean of the correlation. Quadratic and nonparametric regression analyses were not performed.

Results: Auditory Learning

The following analysis of variance testing and post-hoc comparisons were performed to determine if training with a given HPED would allow for auditory learning, and if auditory learning would crossover to a non-training HPED. Data used in these analyses were obtained from LPHFFS testing during Phase I and III. Data were grouped and analyzed to find auditory learning effects in both the training and non-training HPED for each training group. LPHFFS results consisted of the mean absolute error composite of all stimuli. LPHFFS HPED and OE results were compared pre- and post-training to identify any interactions or main effects. Open-ear data were also used as a baseline to test for training effects.

Training HPED - All Groups

The two-way, mixed factor ANOVA for mean absolute error of LPHFFS showed a significant interaction between test day and listening condition $F(1,9) = 10.71$, $p = 0.010$, and a main effect of test day, $F(1, 9) = 29.76$, $p < 0.001$, and listening condition, $F(1, 9) = 31.59$, $p < 0.001$ (Table 30). Post-hoc comparisons, using a paired samples *t*-test, with Bonferroni correction ($\alpha = 0.0125$), for each day showed a significant difference in mean absolute error between listening conditions pre-training, and no significant difference post-training (Figures 55 & 56). This interaction indicates that auditory learning occurs, and that one can expect improved performance with a device when given sufficient experience and performance feedback. It is important to note that not only can device performance improve, but also that device performance can match that of the open-ear. There were five outliers in the data, as assessed by inspection of a boxplot. Values greater than 1.5 box-lengths from the edge of the box were considered to be outliers, with rationale as described earlier. One outlier was contained in each of the following group combinations: Pre-Training OE and Post-Training OE. Three outliers (two above and one below) were contained in the Pre-Training Device group. Mean absolute error was normally distributed for three of the four group combinations as assessed by Shapiro-Wilk's test ($p < 0.05$). The Pre-Training OE group was not normally distributed.

Table 30. ANOVA for LPHFFS Improvement with Training Device for both Training Groups

Source	*df*	MS	*F*	*p*
Test Day (D)	1	2197.86	29.76	<0.001*
Test Day x Group (G)	1	2.16	0.03	0.8679
Error (D)	9	73.86		
Condition (C)	1	518.81	31.59	<0.001*
C x G	1	27.30	1.66	0.229
Error (C)	9	16.42		
D x C	1	183.82	10.71	0.010*
D x C x G	1	21.84	1.27	0.288
Error (D x C)	9	17.16		

* indicates statistically-significant result (p<0.05)

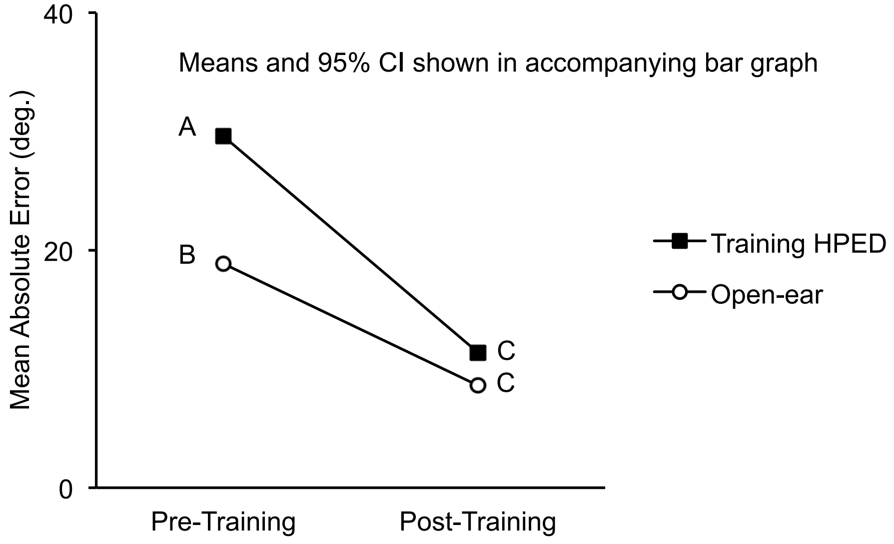


Figure 55. Combined training groups localization performance (LPHFFS) for open-ear and training HPED. Within pairs of means, both across Training Day (horizontal) and across Listening Condition (vertical), means with the same letter are not significantly different at *p*<0.05 using a paired samples *t*-test with Bonferroni correction (*α*=0.0125). There was no comparison made between the two Listening Conditions across Training Days.

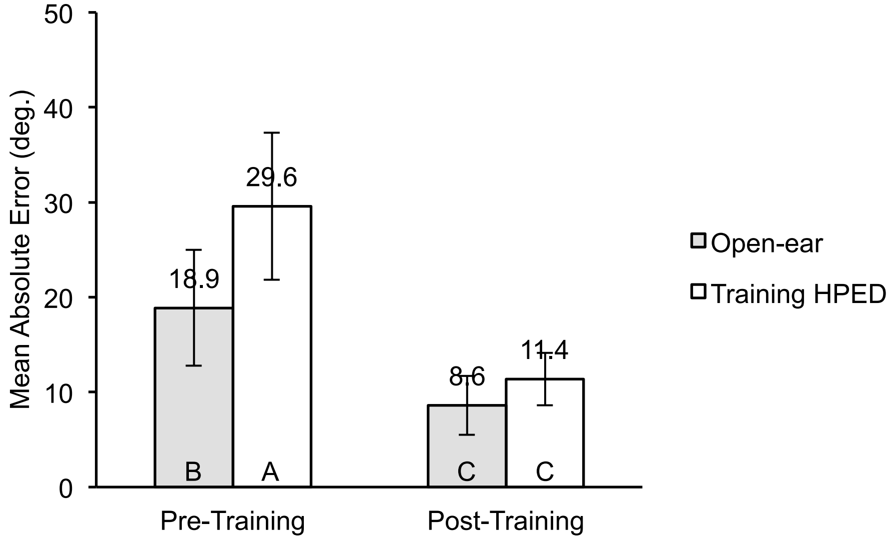


Figure 56. Combined training groups localization performance (LPHFFS) for open-ear and training HPED; means and 95% CI shown. Means with the same letter are not significantly different at *p*<0.05 using a paired samples *t*-test with Bonferroni correction (*α*=0.0125).

Training HPED: ITE Group

The two-way within-subjects ANOVA for mean absolute error of LPHFFS showed a near significant interaction between test day and listening condition *F* (1,5) = 4.49, *p* = 0.088, and a main effect of test day, *F* (1, 5) = 16.04, *p* = 0.010, and listening condition, *F* (1, 5) = 23.95, *p* = 0.005 (Table 31). Post-hoc comparisons, using a paired samples *t*-test, with Bonferroni correction (α = 0.0125), for each training day showed a significant difference in mean absolute error between listening conditions on pre-training and no significant difference on post-training (Figures 57 & 58). There were three outliers in the data, as assessed by inspection of a boxplot. Values greater than 1.5 box-lengths from the edge of the box were considered to be outliers. One outlier was contained in each of the following group combinations Pre-Training OE, Pre-Training ITE, and Post-Training OE. Mean absolute error was normally distributed for two of the four group combinations as assessed by Shapiro-Wilk test (*p* < 0.05). The two OE groups were not normally distributed.

Table 31. ANOVA for LPHFFS Improvement with Training Device in ITE (EB15) Training Group

Source	*df*	MS	*F*	*p*
Test Day (D)	1	1285.85	16.04	0.010*
Error (D)	5	80.18		
Condition (C)	1	169.44	23.95	0.005*
Error (C)	5	7.07		
D x C	1	43.41	4.49	0.088
Error (D x C)	5	9.66		

* indicates statistically-significant result (p<0.05)

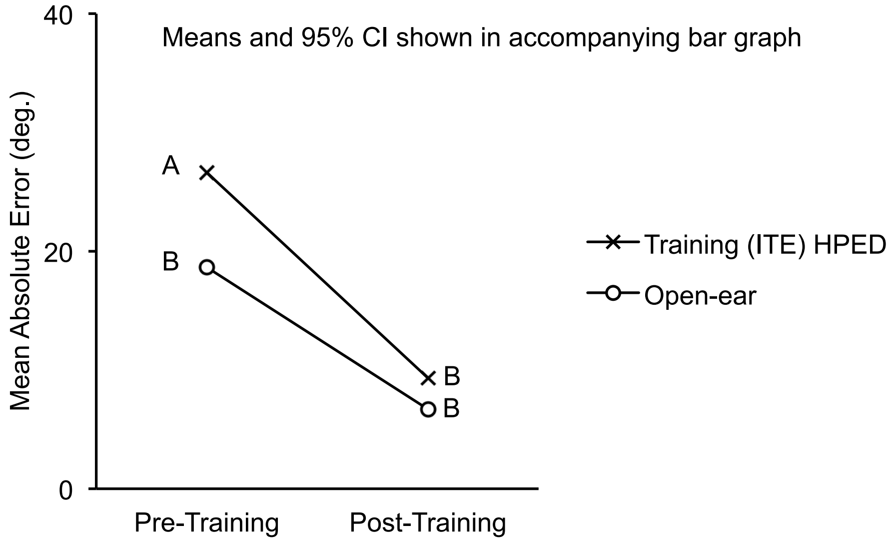


Figure 57. ITE training group localization performance (LPHFFS) for open-ear and training HPED. Within pairs of means, both across Training Day (horizontal) and across Listening Condition (vertical), means with the same letter are not significantly different at *p*<0.05 using a paired samples *t*-test with Bonferroni correction (*α*=0.0125). There was no comparison made between the two Listening Conditions across Training Days.

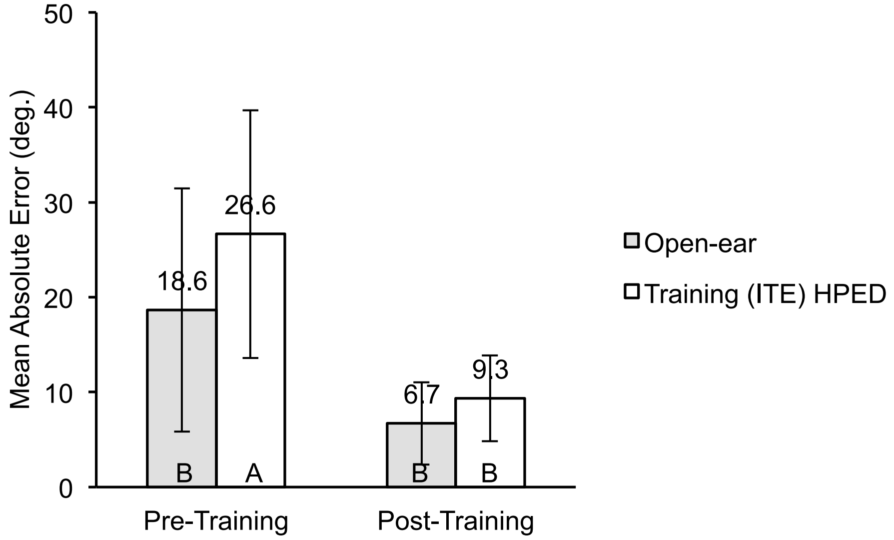


Figure 58. ITE (EB15) training group localization performance (LPHFFS) for open-ear and training HPED; means and 95% CI shown. Means with the same letter are not significantly different at *p*<0.05 using a paired samples *t*-test with Bonferroni correction (*α*=0.0125).

Training HPED - OTE Group

The two-way, within subjects ANOVA for mean absolute error of LPHFFS showed a near significant interaction between test day and listening condition *F* (1,4) = 5.74, *p* = 0.075, and a main effect of test day, *F* (1, 4) = 14.33, *p* = 0.019, and listening condition, *F* (1, 4) = 12.79, *p* = 0.023 (Table 32). Post-hoc comparisons, using a paired samples *t*-test, with Bonferroni correction (α = 0.0125), for each day showed a significant difference in mean absolute error between listening conditions on pre-training, and no significant difference on post-training (Figures 59 & 60). There were two outliers in the data, as assessed by inspection of a boxplot. Values greater than 1.5 box-lengths from the edge of the box were considered to be outliers. One outlier was contained in each of the following group combinations Pre-Training OTE and Post-Training OE. Mean absolute error was normally distributed for three of the four group combinations as assessed by Shapiro-Wilk test (*p* < 0.05). The Post-Training OE group was not normally distributed.

Table 32. ANOVA for LPHFFS Improvement with Training Device in OTE (Com-Tac II) Training Group

Source	*df*	MS	*F*	*p*
Test Day (D)	1	945.14	14.33	0.019*
Error (D)	4	65.96		
Condition (C)	1	359.40	12.79	0.023*
Error (C)	4	28.10		
D x C	1	152.34	5.74	0.075
Error (D x C)	4	26.53		

* indicates statistically-significant result (p<0.05)

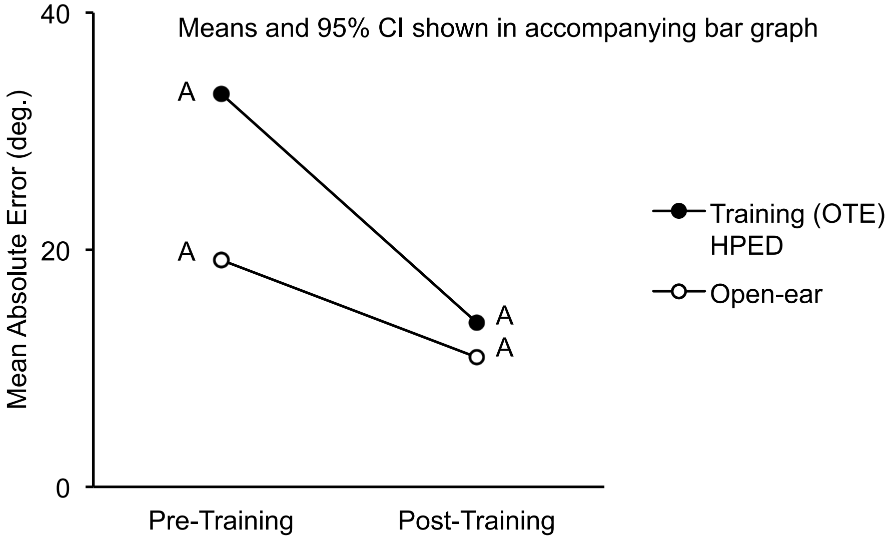


Figure 59. OTE (Com-Tac II) training group localization performance (LPHFFS) for open-ear and training HPED. Within pairs of means, both across Training Day (horizontal) and across Listening Condition (vertical), means with the same letter are not significantly different at $p<0.05$ using a paired samples t-test with Bonferroni correction ($\alpha=0.0125$). There was no comparison made between the two Listening Conditions across Training Days.

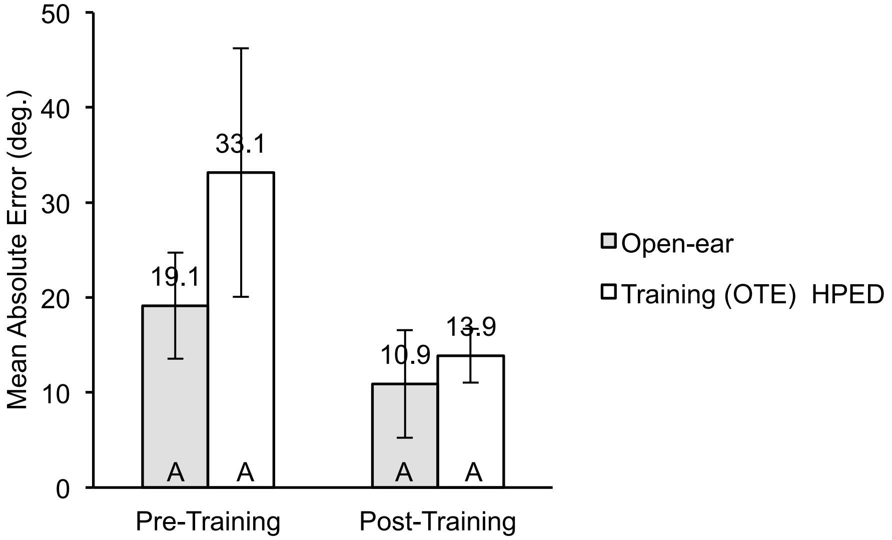


Figure 60. OTE (Com-Tac II) training group localization performance (LPHFFS) for open-ear and training HPED; means and 95% CI shown. Means with the same letter are not significantly different at $p<0.05$ using a paired samples t-test with Bonferroni correction ($\alpha=0.0125$).

Non-Training HPED (Crossover) - All Groups

The two-way, within subjects ANOVA for mean absolute error of LPHFFS showed no significant interaction between test day and listening condition F (1,9) = 0.40, $p = 0.542$, and a significant main effect of test day, F (1,9) = 16.80, $p = 0.003$, and listening condition, F (1,9) = 48.21, $p < 0.001$ (Table 33). Post-hoc comparisons of main effects, using a paired samples *t*-test showed that the open-ear listening condition had less error than the device listening condition, and that error decreased from pre-training to post-training (Figures 61 & 62). The improvement in performance (decreased error) between pre and post-training is most likely from a practice effect of taking the LPHFFS test multiple times. The fact that no interaction was present indicates that crossover of auditory learning did not occur for the non-test device. There were four outliers in the data, as assessed by inspection of a boxplot. Values greater than 1.5 box-lengths from the edge of the box were considered to be outliers. Two outliers were contained in the Pre-Training Device group with one outlier in the Pre-Training OE and Post-Training OE groups. Mean absolute error was normally distributed for two of the four group combinations as assessed by Shapiro-Wilk test ($p < 0.05$). The Pre-Training OE and Pre-Training Device groups were not normally distributed.

Table 33. ANOVA for LPHFFS Crossover with Non-Training Device for both Training Groups

Source	*df*	MS	*F*	*p*
Test Day (D)	1	1253.70	16.80	0.003*
Test Day x Group (G)	1	78.03	1.05	0.333
Error (D)	9	74.63		
Condition (C)	1	1057.58	48.21	<0.001*
C x G	1	13.70	0.62	0.450
Error (C)	9	21.94		
D x C	1	4.34	0.40	0.542
D x C x G	1	7.23	0.67	0.434
Error (D x C)	9	10.79		

* indicates statistically-significant result (p<0.05)

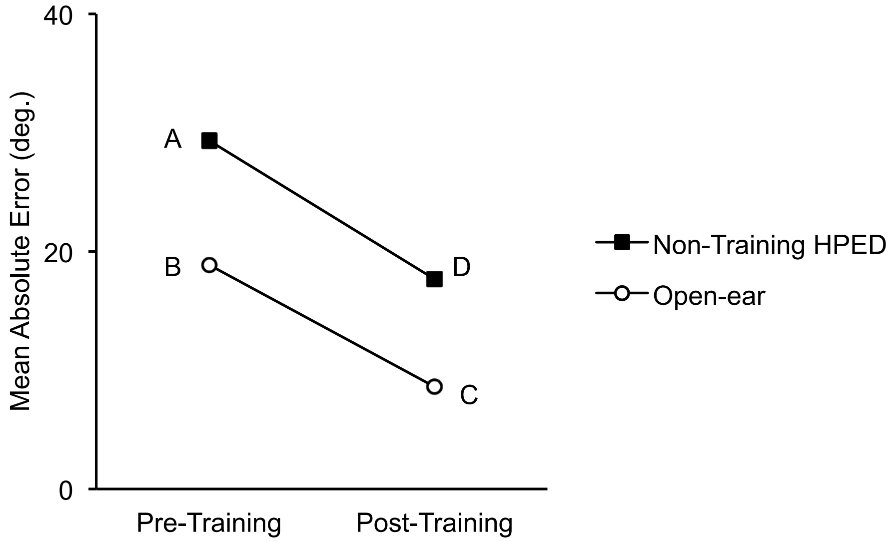


Figure 61. Combined training groups localization performance (LPHFFS) for open-ear and non-training HPED. Within pairs of means, both across Training Day (horizontal) and across Listening Condition (vertical), means with the same letter are not significantly different at *p*<0.05 using a paired samples *t*-test with Bonferroni correction (*α*=0.0125). There was no comparison made between the two Listening Conditions across Training Days.

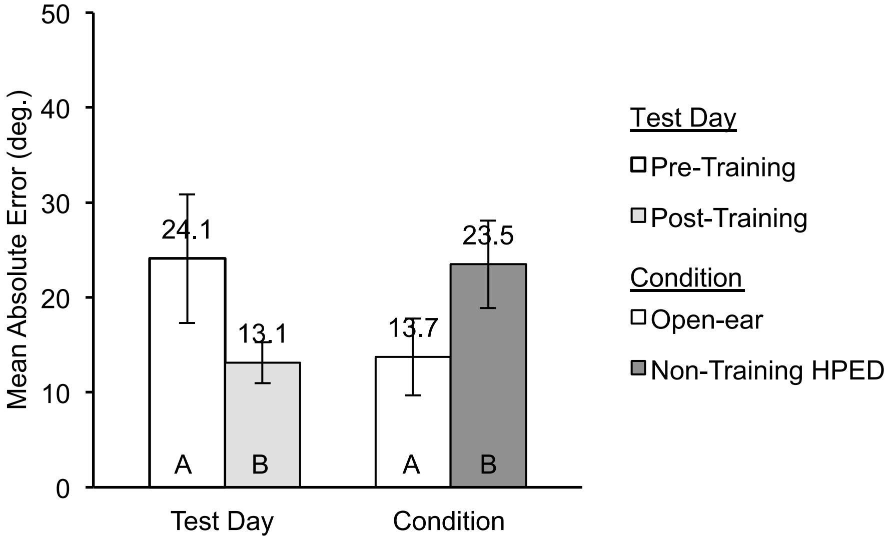


Figure 62. Combined training groups localization performance (LPHFFS) for open-ear and non-training HPED, showing a main effects of test day and listening condition; means and 95% CI shown. Grouped means with the same letter are not significantly different at *p*<0.05 using a paired samples *t*-test.

Non-Training HPED (Crossover) - ITE Group

The two-way, within subjects ANOVA for mean absolute error of LPHFFS showed no significant interaction between test day and listening condition *F* (1,5) = 1.63, *p*=0.258, and a significant main effect of test day, *F* (1,5) = 11.67, *p*=0.019, and listening condition, *F* (1,5) = 39.13, *p*=0.002 (Table 34). Post-hoc comparisons of main effects, using a paired samples *t*-test showed that the open-ear listening condition had less error than the device listening condition, and that error decreased from pre-training to post-training (Figures 63 & 64). The improvement in performance (decreased error) between pre and post-training is most likely from a practice effect of taking the LPHFFS test multiple times. The fact that no interaction was present indicates that crossover of auditory learning did not occur for the OTE (non-test) device. There were three outliers in the data, as assessed by inspection of a boxplot. Values greater than 1.5 box-lengths from the edge of the box were considered to be outliers. One outlier was contained in each of the following group combinations: Pre-Training OTE, Pre-Training OE, and Post-Training OE. Mean absolute error was normally distributed for two of the four group combinations as assessed by Shapiro-Wilk test ($p < 0.05$). The Pre-Training OE and Post-Training OE groups were not normally distributed.

Table 34. ANOVA for LPHFFS Crossover with Non-Training Device in ITE (EB15) Training Group

Source	*df*	MS	*F*	*p*
Test Day (D)	1	1076.50	11.67	0.019*
Error (D)	5	92.24		
Condition (C)	1	456.81	39.13	0.002*
Error (C)	5	11.67		
D x C	1	12.53	1.63	0.258
Error (D x C)	5	7.69		

* indicates statistically-significant result (p<0.05)

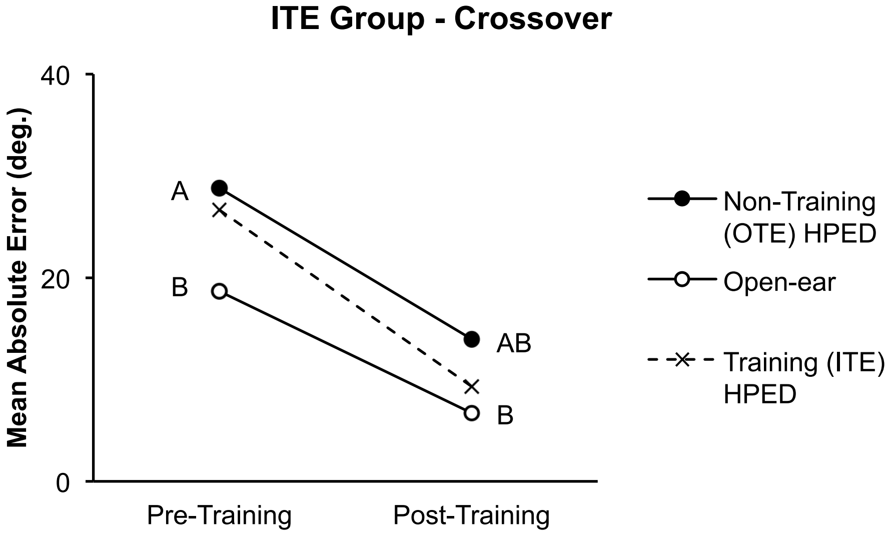


Figure 63. ITE (EB15) training group localization performance (LPHFFS) for open-ear and non-training HPED (training HPED shown for comparison). Within pairs of means, both across Training Day (horizontal) and across Listening Condition (vertical), means with the same letter are not significantly different at p<0.05 using a paired samples *t*-test with Bonferroni correction (α=0.0125). There was no comparison made between the two Listening Conditions across Training Days.

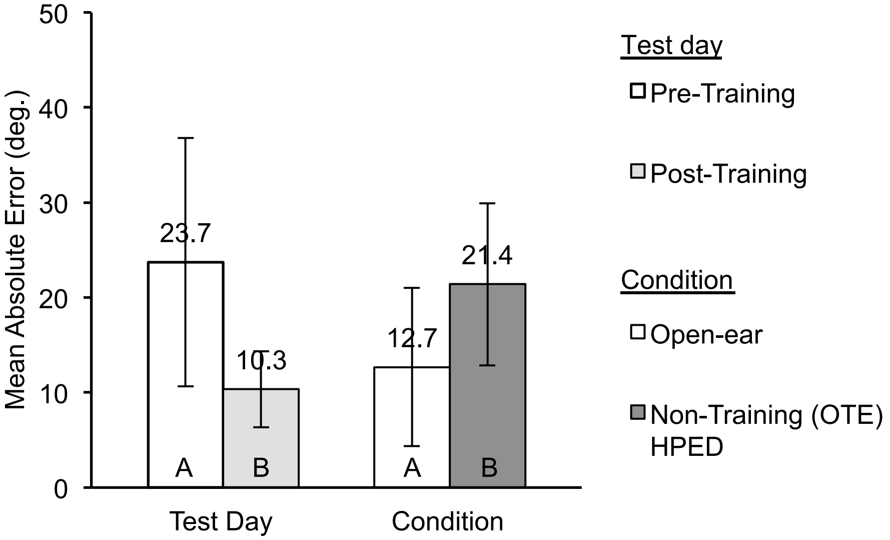


Figure 64. ITE (EB15) training group localization performance (LPHFFS) for open-ear and non-training HPED, showing a main effects of test day and listening condition; means and 95% CI shown. Grouped means with the same letter are not significantly different at *p*<0.05 using a paired samples *t*-test.

Non-Training HPED (Crossover) - OTE Group

The two-way within subjects ANOVA for mean absolute error of LPHFFS showed no significant interaction between test day and listening condition *F* (1,4) = 0.01, *p* = 0.92, a near significant main effect of test day, *F* (1,4) = 6.15, *p* = 0.068, and a significant main effect of listening condition, *F* (1,4) = 17.29, *p* = 0.014 (Table 35). Post-hoc comparisons of main effects, using a paired samples *t*-test, showed that the open-ear listening condition had less error than the device listening condition (Figures 65 & 66). However, a comparison of the means suggested a trend of reduced error from pre to post-training. The improvement in performance (decreased error) between pre and post-training is most likely from a practice effect of taking the LPHFFS test multiple times. The fact that no interaction was present indicated that crossover of auditory learning did not occur for the ITE (non-test) device. There were four outliers in the data, as assessed by inspection of a boxplot. Values greater than 1.5 box-lengths from the edge of the box were considered to be outliers. One outlier was contained in each of the following group combinations Pre-Training ITE and Post-Training OE. Two outliers were contained in the Post-Training ITE group (one in either direction). Mean absolute error was normally distributed for three of the four group combinations as assessed by Shapiro-Wilk test ($p < 0.05$). The Post-Training OE group was not normally distributed.

Table 35. ANOVA for LPHFFS Crossover with Non-Training Device in OTE (Com-Tac II) Training Group

Source	*df*	MS	*F*	*p*
Test Day (D)	1	323.67	6.15	0.068
Error (D)	4	52.62		
Condition (C)	1	601.33	17.29	0.014*
Error (C)	4	34.77		
D x C	1	0.17	0.01	0.920
Error (D x C)	4	14.66		

* indicates statistically-significant result (p<0.05)

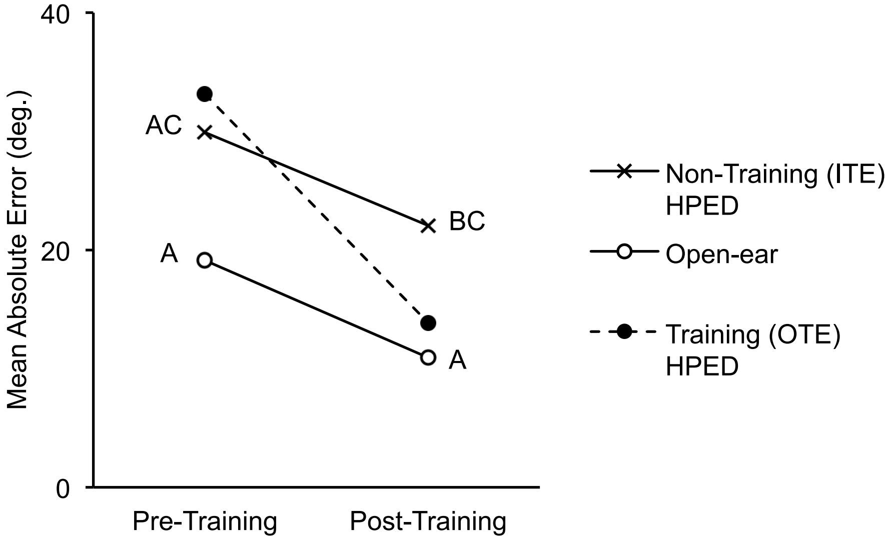


Figure 65. OTE (Com-Tac II) training group localization performance (LPHFFS) for open-ear and non-training HPED (training HPED shown for comparison). Within pairs of means, both across Training Day (horizontal) and across Listening Condition (vertical), means with the same letter are not significantly different at *p*<0.05 using a paired samples *t*-test with Bonferroni correction (*α*=0.0125). There was no comparison made between the two Listening Conditions across Training Days.

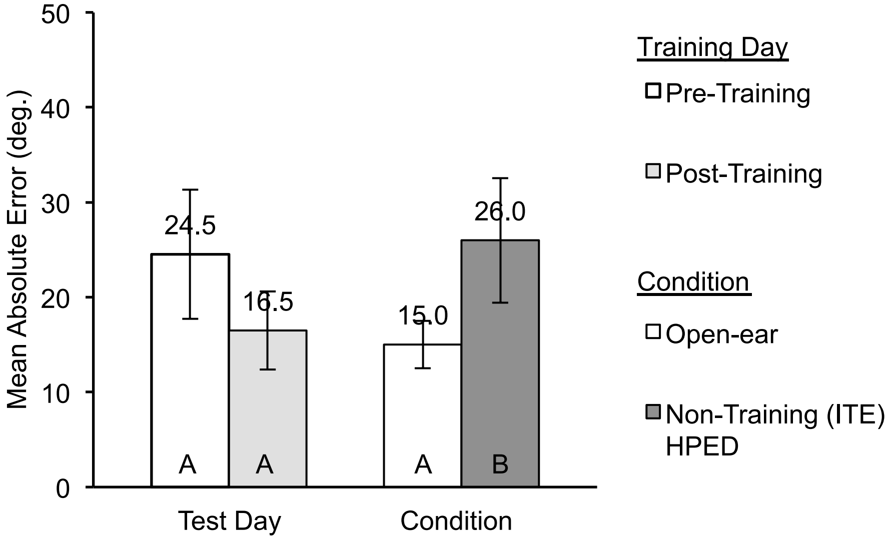


Figure 66. OTE (Com-Tac II) training group localization performance (LPHFFS) for open-ear and non-training HPED, showing a main effect of listening condition but not test day; means and 95% CI shown. Grouped means with the same letter are not significantly different at *p*<0.05 using a paired samples *t*-test.

Assumptions Overview Concerning the Auditory Learning Data

Outliers - While there were several outliers in the data, this was somewhat expected given the nature of the data being collected. Outliers are considered to be actual data points and not the result of equipment or data entry errors. It is expected that these outliers would be part of the normal data set, given a larger sample of users with varying amounts of hearing loss and localization performance.

Normality - The Shapiro-Wilk test of Normality found non-normal distributions in 4 of the 12 conditions testing for auditory learning with the training HPED and 5 of the 12 conditions testing for auditory learning with the non-training HPED. Normality errors were also expected due to the transformation of data into a mean of the absolute error as discussed previously. Results are considered valid, as ANOVA measures are rather robust to normality errors.

Results: Confidence

The following analysis and post-hoc comparisons were performed to determine how confidence ratings differed pre-training, post-training, and what changes in confidence occurred due to training. Analysis was performed for each training group separately. Data used in these analyses were obtained from the confidence rating during Phase I (pre-training) and III (post-training). Data were grouped and analyzed to identify differences in confidence between listening conditions and between pre- and post-training. Confidence data consisted of mean confidence ratings for each listening condition and pre/post-training combination.

ITE Group

A Friedman non-parametric test was performed on the pre- and post-training mean confidence of each listening condition for the ITE Group. There was a statistically significant difference in the perceived confidence in localization accuracy for the various listening condition (open-ear, ITE, OTE) and test day (pre-training & post-training) combinations, $\chi^2(2) = 25.104$, $p < 0.001$ (Table 36). Post-hoc analysis with Wilcoxon signed-rank tests was conducted to determine 1) differences in confidence between pre and post-training for each listening condition (Figure 67), 2) differences in pre-training confidence for each listening condition (Figure 68), and 3) differences in post-training confidence for each listening condition (Figure 69).

Table 36. Chi-square for Pre- and Post-Training Confidence in the ITE Group.

X^2	n	*df*	Asymp. Sig.
25.104	6	5	<0.001

There were statistically-significant differences in confidence between pre and post-training in the OTE pre-training (Mdn = 4) compared to post-training (Mdn = 3), $z = -2.121$, $p = 0.03$ showing a decrease in confidence, with no significant differences in the open-ear pre-training (Mdn = 6) compared to post-training (Mdn = 6), $z = 0.000$, $p = 1.000$, and ITE pre-training (Mdn = 4) compared to post-training (Mdn = 5), $z = 1.667$, $p = 0.096$.

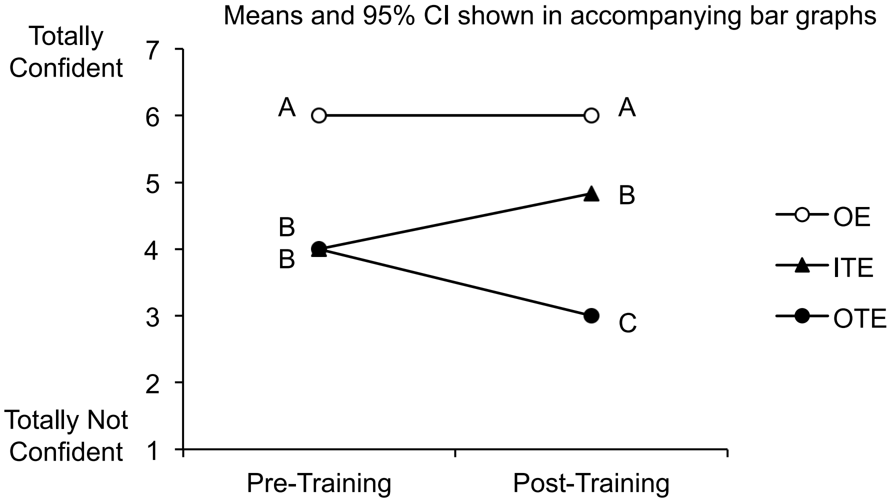


Figure 67. ITE (EB15) training group mean confidence. Within pairs of means, both across Training Day (horizontal) and across Listening Condition (vertical), means with the same letter are not significantly different at $p<0.05$ using a Wilcoxon signed-rank test. There was no comparison made between the Listening Conditions across Training Days.

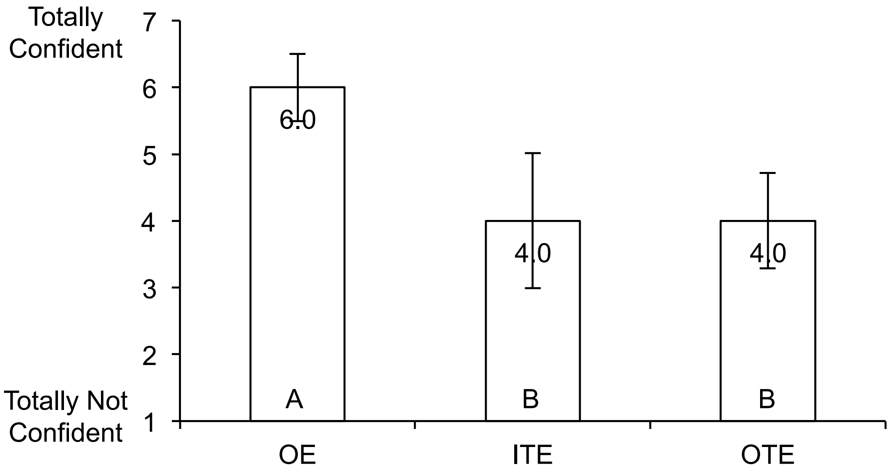


Figure 68. ITE (EB15) training group pre-training confidence; means and 95% CI shown. Means with the same letter are not significantly different at $p<0.05$ using a Wilcoxon signed-rank tests.

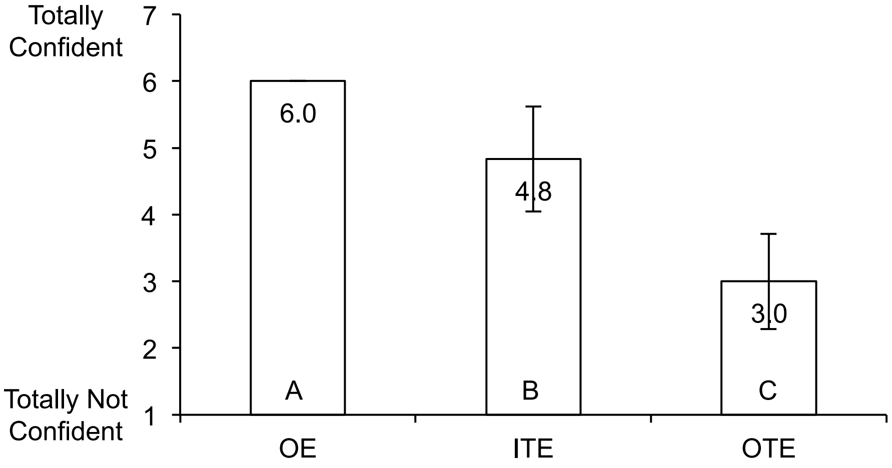


Figure 69. ITE (EB15) training group post-training confidence; means and 95% CI shown. Means with the same letter are not significantly different at *p*<0.05 using a Wilcoxon signed-rank tests.

There were statistically-significant differences in pre-training confidence for the open-ear (Mdn = 6) compared to ITE (Mdn = 4), *z* = 2.232, *p* = 0.026, and open-ear (Mdn = 6) compared to OTE (Mdn = 4), *z* = 2.251, *p* = 0.024, with no significant difference in the ITE (Mdn = 4) compared to OTE (Mdn = 4), *z* = 0.000, *p* = 1.000.

There were statistically-significant differences in post-training confidence for the open-ear (Mdn = 6) compared to ITE (Mdn = 5), *z* = 2.121, *p* = 0.034, open-ear (Mdn = 6) compared to OTE (Mdn = 3), *z* = 2.220, *p* = 0.026, and ITE (Mdn = 5) compared to OTE (Mdn = 3), *z* = 2.232, *p* = 0.026.

OTE Group

A Friedman non-parametric test was performed on the pre- and post-training mean confidence of each listening condition for the ITE Group. There was a statistically significant difference in the perceived confidence in localization accuracy for the various listening condition (open-ear, ITE, OTE) and test day (pre-training & post-training) combinations, $\chi^2(2) = 15.906$, $p = 0.007$ (Table 37). Confidence was higher post-training for all three listening conditions. Post-hoc analysis with Wilcoxon signed-rank tests was conducted to determine 1) differences in confidence between pre and post-training for each listening condition (Figure 70), 2) differences in pre-training confidence for each listening condition (Figure 71), and 3) differences in post-training confidence for each listening condition (Figure 72).

Table 37. Chi-square for Pre- and Post-Training Confidence in the OTE Group.

X^2	n	*df*	Asymp. Sig.
15.906	5	5	0.007

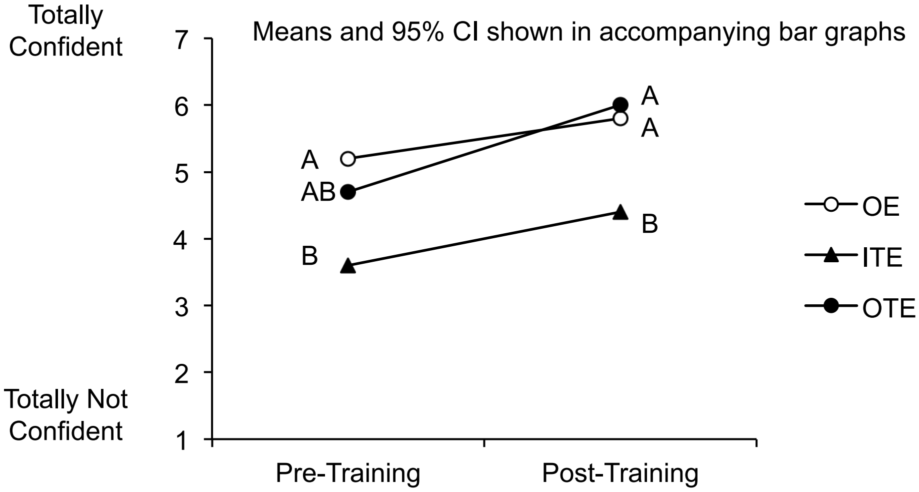


Figure 70. OTE (Com-Tac II) training group mean confidence. Within pairs of means, both across Training Day (horizontal) and across Listening Condition (vertical), means with the same letter are not significantly different at $p<0.05$ using a Wilcoxon signed-rank test. There was no comparison made between the Listening Conditions across Training Days.

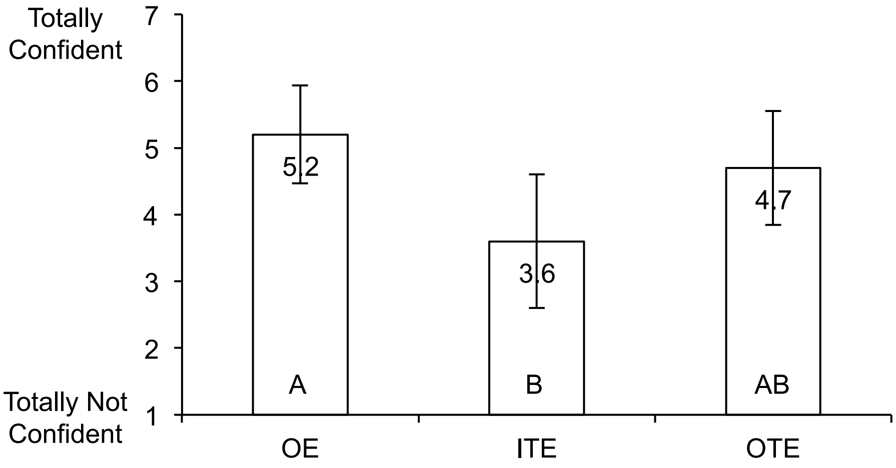


Figure 71. OTE (Com-Tac II) training group pre-training confidence; means and 95% CI shown. Means with the same letter are not significantly different at $p<0.05$ using a Wilcoxon signed-rank tests.

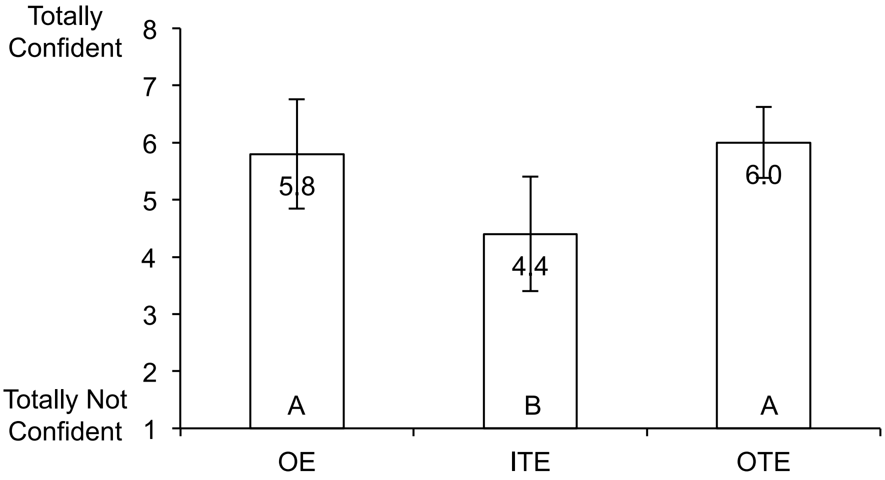


Figure 72. OTE training group post-training confidence; means and 95% CI shown. Means with the same letter are not significantly different at $p<0.05$ using a Wilcoxon signed-rank tests.

There were no statistically-significant differences in confidence between pre and post-training for each listening condition: open-ear pre-training (Mdn = 5) compared to post-training (Mdn = 6), *z* = 1.134, *p* = 0.257, ITE pre-training (Mdn = 4) compared to post-training (Mdn = 4), *z* = 1.300, *p* = 0.194, and OTE pre-training (Mdn = 5) compared to post-training (Mdn = 6), *z* = 1.841, *p* = 0.066.

There was a statistically-significant difference in pre-training confidence for the open-ear (Mdn = 5) compared to ITE (Mdn = 4), *z* = 2.060, *p* = 0.039, with no significant differences in the open-ear (Mdn = 5) compared to OTE (Mdn = 5), *z* = 0.962, *p* = 0.336 and ITE (Mdn = 4) compared to OTE (Mdn = 5), *z* = 1.084, *p* = 0.279.

There were statistically-significant differences in post-training confidence for the open-ear (Mdn = 6) compared to ITE (Mdn = 4), *z* = 2.070, *p* = 0.038 and ITE (Mdn = 4) compared to OTE (Mdn = 6), *z* = 2.070, *p* = 0.038, with no significant difference in the open-ear (Mdn = 6) compared to OTE (Mdn = 6), *z* = 1.000, *p* = 0.317.

Assumptions Overview Concerning the Confidence Data

Normality – The Shapiro-Wilk test of Normality found a non-normal distribution in one of the 12 conditions tested (6 in each test group). The ITE post-training condition, in the ITE group, was not normally distributed (*p* = 0.031). However, the skewness (*z* = -1.70, *SE* = 0.845) and kurtosis (*z* = 2.07, *SE* = 1.741) values were normal for this condition.

Results: Response Time

The following analysis of variance testing was performed to determine if differences in response times existed pre- and post-training for the open-ear, training HPED, and non-training HPED listening conditions. Data used in these analyses were obtained from LPHFFS Phase I and III testing. Data were grouped and analyzed to identify differences in response time in the open-ear, training HPED, and non-training HPED listening conditions for each training group. Response time data consisted of the mean response time, in seconds, for each listening condition and training-day combination.

The two-way mixed design ANOVA for mean response time for pre- and post-training with the open-ear, training HPED, and non-training HPED, for both training groups, showed no interactions or main effects (Table 38, Figure 73). There were four outliers in the data, as assessed by inspection of a boxplot. Values greater than 1.5 box-lengths from the edge of the box were considered to be outliers with rationale as described earlier. One outlier was contained in each of the following conditions pre-training with the training HPED, post-training with the open-ear, training HPED, and non-training HPED. Mean response time was normally distributed for the pre-training conditions, but not for the post-training conditions as assessed by Shapiro-Wilk test ($p < 0.05$).

Table 38. Mauchly’s Test of Sphericity and ANOVA for Response Time in the open-ear and Training HPED Listening Conditions for both Training Groups.

Mauchly’s Test of Sphericity					Epsilon (ε)	
Variables	Mauchly’s Criterion	Chi-Square	*df*	*p*	Greenhouse-Geisser	Huynh-Feldt
Test Day	1.000	0.000	0	NA	1.000	1.000
Condition	0.673	3.167	2	0.205	0.754	0.973
Test Day x Condition	0.795	1.836	2	0.399	0.830	1.000

ANOVA for Response Time in the open-ear and Training HPED Listening Conditions for both Training Groups.

Source	*df*	MS	*F*	*p*	Greenhouse-Geisser
Test Day (D)	1	0.217	0.534	0.484	0.484
Test Day x Group (G)	1	0.153	0.376	0.555	0.555
Error (D)	9	0.407			
Condition (C)	1	0.079	1.018	0.381	0.365
C x G	1	0.097	1.248	0.311	0.306
Error (C)	9	0.078			
D x C	1	0.036	0.406	0.672	0.636
D x C x G	1	0.088	0.978	0.395	0.384
Error (D x C)	9	0.090			

* indicates statistically-significant result ($p<0.05$)

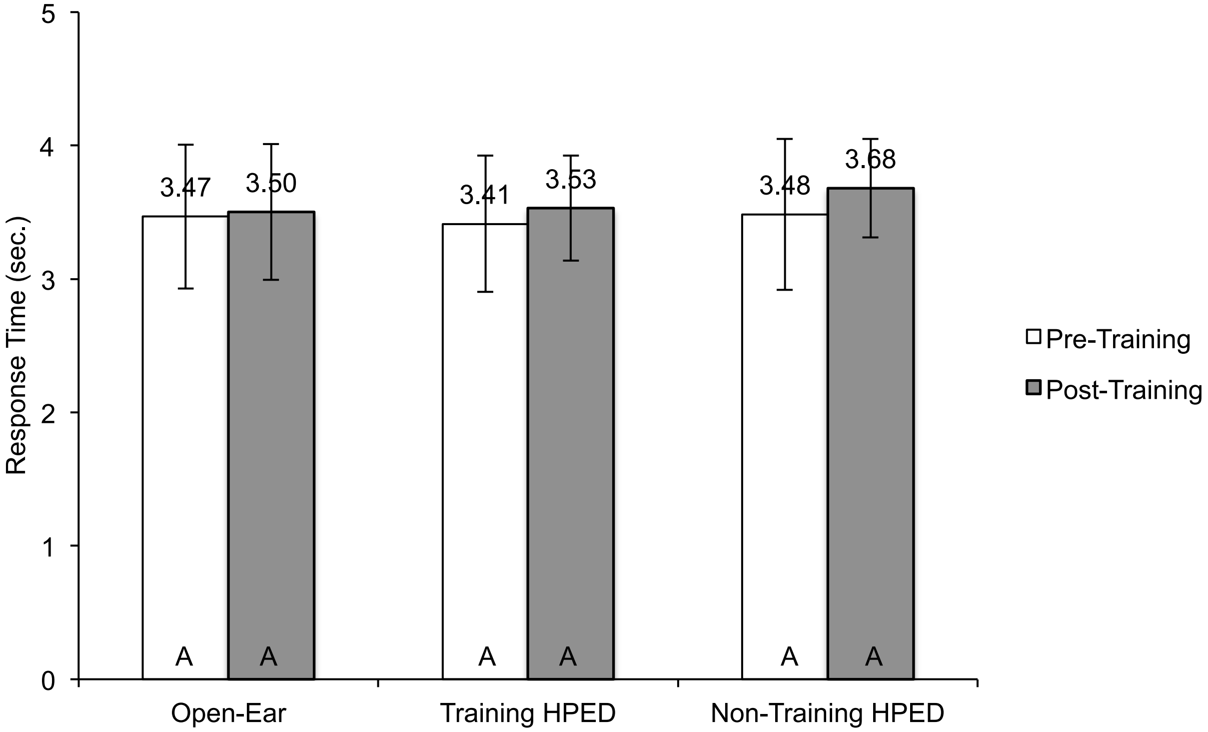


Figure 73. Combined training groups LPHFFS response time; means and 95% CI shown. Means with the same letter are not significantly different at *p*<0.05.

Assumptions Overview Concerning the Response Time Data

Outliers - While there were several (four) outliers in the data, this was somewhat expected given the nature of the data being collected. A closer look at the data indicates that all outliers were from one participant. This participant simply took longer to respond than the other participants. These outliers were considered to be actual data points and not the result of equipment or data entry errors. It is expected that these outliers would be part of the normal data set, given a larger sample of users with varying amounts of hearing loss and localization performance.

Normality - The Shapiro-Wilk test of Normality showed non-normal distributions in three of the six conditions testing response time. All non-normal distributions were in the post-training conditions. A closer look at the data indicated that the same participant responsible for outliers was also responsible for the non-normal distributions. It is interesting to note that the 95% confidence intervals decreased for all post-training conditions. However, the mean response times for this participant actually increased in all post-training conditions. Because this participant's response times were greater in the post-training condition, and the variation of the overall mean response time decreased, the distribution of the responses showed both a positive skewness and positive Kurtosis. This can account for the non-normal distributions in the post-training conditions. These results are considered valid, as ANOVA measures are rather robust to normality errors.

Results: Predicting Post-Training Performance

The following analysis was performed to determine if pre-training AFFD measures were predictive of overall localization performance post-training. Each training group was analyzed separately. Data used in these analyses were obtained from AFFD Phase I (pre-training) testing and LPHFFS Phase III (post-training) testing. AFFD tests included the IACT and the FBDT. AFFD results consisted of the percent correct for each IACT/stimulus and FBDT/stimulus combinations. LPHFFS results consisted of the mean absolute error composite for all stimuli. Data were grouped and analyzed by HPED listening condition. AFFD results were then compared to LPHFFS results to determine which AFFD/stimulus combinations could predict overall LPHFFS performance. The level of the LPHFFS pre-training was not considered. Therefore, a correlation does not indicate how much more auditory learning is possible. It is, however, *predictive* of

LPHFFS after training has occurred. Thus, if performance is predicted to be low, little or no auditory learning can be expected.

ITE Group

A Pearson product-moment correlation coefficient was computed to assess the relationship between the post-training LPHFFS and three pre-training AFFD measures (IACT-R, IACT-L, & FBDT) for each of the four stimuli (Table 39). The LPHFFS measured mean absolute error while the AFFD measured percent correct. Because error is being compared with percent correct, the expected relationship will be negative. Analysis showed a linear relationship between LPHFFS and AFFD tasks, with some tasks having no apparent relationship. However, not all localization tasks were normally distributed, as assessed by Shapiro-Wilk's test ($p < 0.05$). Strong negative correlations (< -0.6) were found between LPHFFS and the IACT-L AFFD with both H-Long ($r(4) = -0.652$, $p = 0.161$) and H-Short ($r(4) = -0.813$, $p = 0.049$) stimuli, and the IACT-R AFFD with both H-Long ($r(4) = -0.818$, $p = 0.046$) and H-Short ($r(4) = -0.713$, $p = 0.112$) stimuli. Not all correlations were found to be significant, meaning that there was a chance that they could have occurred at random.

Table 39. In-the-ear HPED (EB15) correlation of post-training LPHFFS with pre-training AFFD measures.

	Stimulus		IACT-L	IACT-R	FBDT
LPHFFS	H-Long	Pearson Correlation	-0.652	-.818*	0.283
		Sig. (2-tailed)	0.161	0.046	0.587
		n	6	6	6
	H-Short	Pearson Correlation	-.813*	-0.713	0.298
		Sig. (2-tailed)	0.049	0.112	0.566
		n	6	6	6
	L-Long	Pearson Correlation	-0.014	-0.386	0.567
		Sig. (2-tailed)	0.98	0.45	0.24
		n	6	6	6
	L-Short	Pearson Correlation	-0.238	-0.435	-0.266
		Sig. (2-tailed)	0.649	0.388	0.61
		n	6	6	6

* indicates statistically-significant result ($p<0.05$)

While strong correlations were found, a practical correlation with the IACT would include both left and right side tests. Practical correlations were found in the IACT with the H-Long and H-Short stimuli (Figure 74). A linear regression was performed to establish if each stimulus-test pair could predict in-the-ear HPED localization performance. The H-Long stimuli in the IACT-L and IACT-R measures explained 28.1% and 58.7% of the variability (adjusted R^2) in the in-the-ear localization performance, respectively. These findings were not significant for the IACT-L, F (1, 4) = 2.96, p = 0.161, but were significant for the IACT-R, F (1, 4) = 8.11, p = 0.046. The non-significant finding in the IACT-L indicated that using the mean LPHFFS value was just as good a predictor of localization performance. No significant outliers were found (± 3 Std.Dev.). Independence of Errors was verified with the Durbin-Watson statistic (1.282 and 1.064 respectively) showing no autocorrelation. The Koenker test for Heteroscedasticity was not significant for the IACT-L ($X^2(1) = 1.245$, p = 0.264) or IACT-R ($X^2(1) = 3.121$, p =

0.077). Normality of Error was verified with a histogram showing a mean near zero and SD near one for all AFFD measures. The preceding assumptions, required for this statistical analysis to be considered valid, appear to have been met.

The H-Short stimuli in the IACT-L and IACT-R measures explained 57.7% and 38.6% of the variability (adjusted R^2) in the in-the-ear localization performance, respectively. These findings were significant for the IACT-L, F (1, 9) = 7.81, p = 0.049, but not significant for the IACT-R, F (1, 4) = 4.14, p = 0.112. No significant outliers were found (± 3 Std.Dev.). Independence of Errors was verified with the Durbin-Watson statistic (1.897 and 1.848 respectively) showing no autocorrelation. The Koenker test for Heteroscedasticity was not significant for the IACT-L ($X^2(1) = 0.039$, p = 0.844) or IACT-R ($X^2(1) = 0.254$, p = 0.614). Normality of Error was verified with a histogram showing a mean near zero and SD near one for all AFFD measures. The preceding assumptions, required for this statistical analysis to be considered valid, appear to have been met.

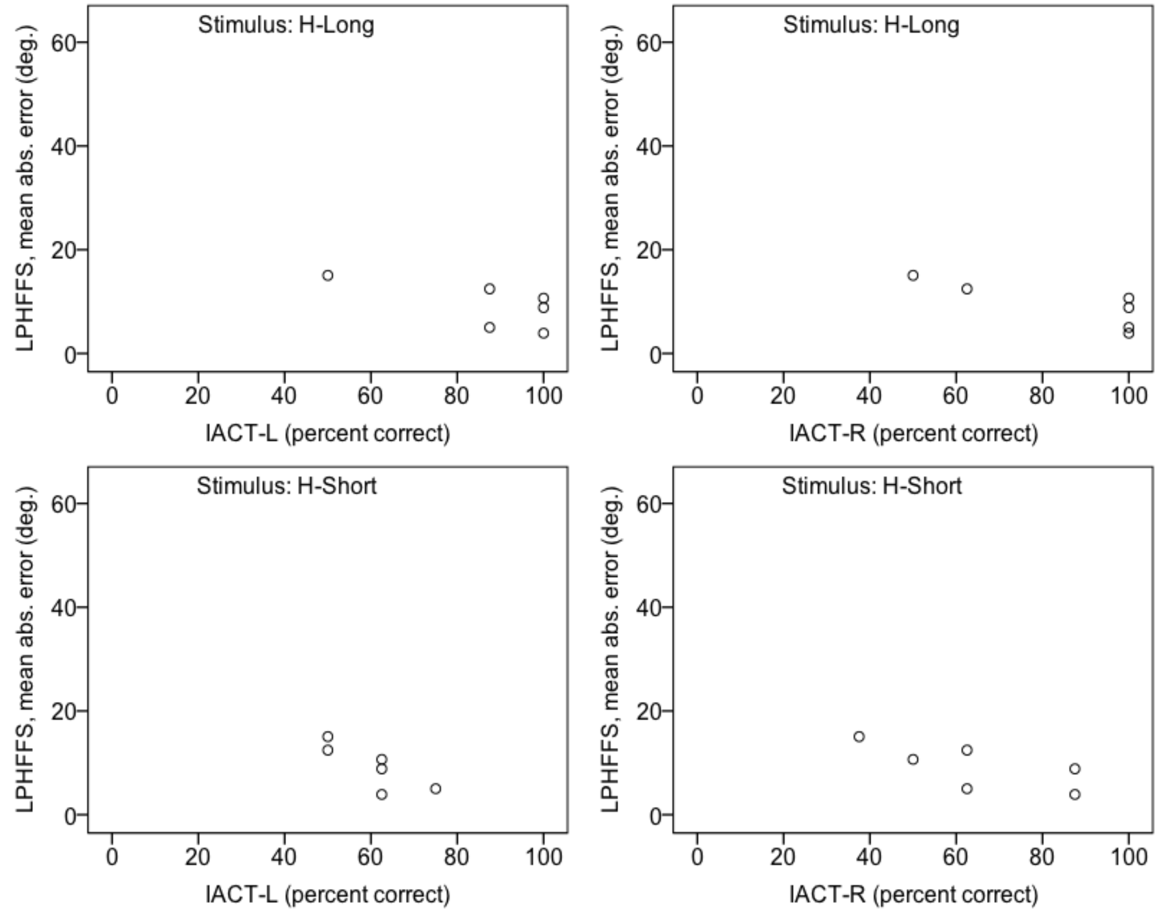


Figure 74. In-the-ear HPED (EB15) correlation between post-training LPHFFS and pre-training AFFD measures.

OTE Group

A Pearson product-moment correlation coefficient was computed to assess the relationship between the LPHFFS (Post-Training) and three AFFD measures (IACT-R, IACT-L, & FBDT) for each of the four stimuli (Table 40). The LPHFFS measured mean absolute error while the AFFD measured percent correct. Because error is being compared with percent correct, the expected relationship will be negative. Analysis showed a linear relationship between OTE LP and AFFD tasks, with some tasks having no apparent relationship. However, not all localization tasks were normally distributed, as assessed by Shapiro-Wilk's test ($p < 0.05$). Strong negative correlations (< -0.6) were found with the L-Long stimuli in the FBCT ($r(3) = -0.874$, $p = 0.053$) and the L-Short stimuli in the IACT-R ($r(3) = -0.738$, $p = 0.154$). No correlations were found to be significant, meaning that there is a chance that these correlations could have occurred due to chance.

Table 40. Over-the-ear HPED (Com-Tac II) correlation of post-training LPHFFS with pre-training AFFD measures.

	Stimulus		IACT-L	IACT-R	FBDT
LPHFFS	H-Long	Pearson Correlation	0.74	-0.357	0.383
		Sig. (2-tailed)	0.153	0.556	0.524
		n	5	5	5
	H-Short	Pearson Correlation	0.267	-0.39	0.168
		Sig. (2-tailed)	0.664	0.516	0.788
		n	5	5	5
	L-Long	Pearson Correlation	0.207	-0.157	-0.874
		Sig. (2-tailed)	0.739	0.801	0.053
		n	5	5	5
	L-Short	Pearson Correlation	-0.051	-0.738	-0.455
		Sig. (2-tailed)	0.936	0.154	0.441
		n	5	5	5

* Correlation is significant at the 0.05 level (2-tailed).

While strong (but non-significant) correlations were found, a practical correlation with the IACT would include both left and right side tests. Practical correlations were found only in FBDT with the L-Long stimuli (Figure 75). A linear regression was performed to establish if the L-Long/FBDT stimulus-test pair could predict over-the-ear HPED localization performance. The L-Long stimuli in the FBDT explained 68.5% of the variability (adjusted R^2) in the over-the-ear localization performance. This finding was not significant, $F(1, 3) = 9.69$, $p = 0.053$, but was very close given the small sample size. No significant outliers were found (± 3 Std.Dev.). Independence of Errors was verified with the Durbin-Watson statistic (2.498) showing no autocorrelation. The Koenker test for Heteroscedasticity was significant, ($X^2(1) = 4.404$, $p = 0.036$), indicating the potential for Type II errors. Normality of Error was verified with a histogram showing a mean near zero and SD near one for all AFFD measures. The preceding assumptions, required for this statistical analysis to be considered valid, appear to have been met.

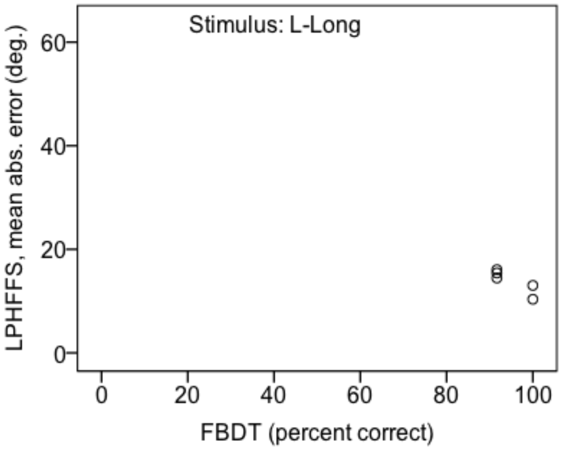


Figure 75. Over-the-ear HPED (Com-Tac II) correlation between post-training LPHFFS and pre-training AFFD measures.

Assumptions Overview Concerning the Post-Training Performance Data

Normality – The Shapiro-Wilk test of Normality found a non-normal distribution in 4 of the 12 in-the-ear HPED measures and 6 of the 12 over-the-ear HPED measures. However, measures of skewness and kurtosis were normal for all in-the-ear (Table 41) and over-the-ear (Table 42) conditions.

Table 41. Tests of Normality for in-the-ear (EB15) conditions.

			Shapiro-Wilk		Skewness		Kurtosis	
Stimulus	Measure	*df*	Statistic	*p*	*z*	SE	*z*	SE
H-Long	IACT-L	6	0.721	0.01*	-2.291	0.845	2.273	1.741
	IACT-R	6	0.692	0.005*	-1.296	0.845	-0.640	1.741
	FBDT	6	0.831	0.110	1.053	0.845	-0.447	1.741
	LPHFFS	6	0.958	0.802	-0.082	0.845	-0.796	1.741
H-Short	IACT-L	6	0.866	0.212	0.370	0.845	-0.060	1.741
	IACT-R	6	0.908	0.425	0.049	0.845	-0.753	1.741
	FBDT	6	0.940	0.659	0.941	0.845	0.039	1.741
	LPHFFS	6	0.958	0.802	-0.082	0.845	-0.796	1.741
L-Long	IACT-L	6	0.822	0.091	-1.014	0.845	-0.172	1.741
	IACT-R	6	0.683	0.004*	0.000	0.845	-1.914	1.741
	FBDT	6	0.921	0.514	-0.520	0.845	0.765	1.741
	LPHFFS	6	0.958	0.802	-0.082	0.845	-0.796	1.741
L-Short	IACT-L	6	0.775	0.035*	0.540	0.845	-1.373	1.741
	IACT-R	6	0.801	0.060	-1.521	0.845	0.782	1.741
	FBDT	6	0.866	0.211	-1.503	0.845	0.881	1.741
	LPHFFS	6	0.958	0.802	-0.082	0.845	-0.796	1.741

* Indicates significance for non-normal distribution

Table 42. Tests of Normality for over-the-ear (Com-Tac II) conditions.

			Shapiro-Wilk		Skewness		Kurtosis	
Stimulus	Measure	*df*	Statistic	*p*	*z*	SE	*z*	SE
H-Long	IACT-L	5	0.961	0.814	-0.444	0.913	-0.089	2.000
	IACT-R	5	0.774	0.048*	-1.184	0.913	-0.326	2.000
	FBDT	5	0.552	0.000*	2.449	0.913	2.500	2.000
	LPHFFS	5	0.927	0.578	-1.133	0.913	0.262	2.000
H-Short	IACT-L	5	0.871	0.272	-0.076	0.913	-0.912	2.000
	IACT-R	5	0.828	0.135	1.416	0.913	1.459	2.000
	FBDT	5	0.961	0.814	0.444	0.913	-0.090	2.000
	LPHFFS	5	0.927	0.578	-1.133	0.913	0.262	2.000
L-Long	IACT-L	5	0.552	0.000*	-2.449	0.913	2.500	2.000
	IACT-R	5	0.833	0.146	-1.491	0.913	1.000	2.000
	FBDT	5	0.684	0.006*	0.667	0.913	-1.667	2.000
	LPHFFS	5	0.927	0.578	-1.133	0.913	0.262	2.000
L-Short	IACT-L	5	0.684	0.006*	0.667	0.913	-1.667	2.000
	IACT-R	5	0.881	0.314	-1.193	0.913	0.268	2.000
	FBDT	5	0.771	0.046*	-1.379	0.913	0.159	2.000
	LPHFFS	5	0.927	0.578	-1.133	0.913	0.262	2.000

* Indicates significance for non-normal distribution

Correlation Significance – Correlations with an R^2 value of 0.6 or greater were considered strong enough for further analysis. However, not all of the correlations were found to be significant ($\alpha = 0.05$). The statistical significance of a correlation indicates the likelihood that the correlation could have been obtained by chance. The stimulus/test conditions selected for regression analysis were felt to be of practical significance due to their high correlation value (R^2) regardless of their significance.

Heteroscedasticity – Of the five linear regressions performed, one showed significant negative heteroscedasticity with the Koenker test. The over-the-ear FBDT with the L-Long stimuli showed negative heteroscedasticity. Negative heteroscedasticity results in a likelihood of increased Type II error. Given the near significance (*p* = 0.053) of the over-the-ear FBDT with the L-Long stimuli, the finding of negative heteroscedasticity, and the relatively small sample size, it is possible that this stimulus/test pair was significant.

Discussion

Predicting Current Performance

Overviews of the AFFD test/stimulus combinations that were of practical significance and showed a good predictive value are shown in Table 43. The H-Long stimuli was highly correlated and showed a high predictive value for all three listening conditions, when presented in the front left and right quadrants of the 30°/60° Accuracy and FBCT AFFD measure. Only one of these test-stimulus conditions (ITE Right-Front) showed potential Type I error (finding significance when there is none), due to positive heteroscedasticity. No other AFFD test/stimulus combinations showed both practical significance and good predictive value for all three listening conditions.

All other test/stimuli combinations were either not consistent across listening conditions, not found meaningful due to significance on only one side (e.g. left but not right), or simply did not show a correlation. It is possible that other test/stimulus combinations are appropriate for a given listening condition but not all combinations.

Table 43. Overview of Practical Correlations found in each listening condition.

		OE		ITE		OTE	
		Left	Right	Left	Right	Left	Right
Front Hemisphere (30°/60° Accuracy)	H-Long	X	X	X	X*	X	X
	H-Short	X	X	-	-	-	-
	L-Long	-	-	-	-	-	-
	L-Short	-	-	-	-	-	-
Rear Hemisphere (30°/60° Accuracy)	H-Long	-	-	-	-	-	-
	H-Short	-	-	-	-	-	-
	L-Long	-	-	-	-	X	X*
	L-Short	X*	X*	-	-	-	-
FBCT	H-Long	X		X		X	
	H-Short	X		-		X	
	L-Long	X*		-		-	
	L-Short	-		-		-	

* Potential Type I Error due to positive heteroscedasticity (Koenker).

The H-Long stimulus appeared to be an appropriate test measure due to its predictive value for normal hearing individuals in all listening conditions. While not tested directly in individuals with hearing loss, the H-Long stimulus includes frequencies between 3-6k Hz, and is expected to be sensitive to changes in localization performance in individuals with high frequency (noise-induced) hearing loss. High-frequency noise-induced hearing loss is commonly seen in the military and is a primary concern for readiness issues (Department of the Army, 2008).

Composite results of the stepwise regression from all listening conditions are shown in Table 44. While this method identified the optimal stimulus combination for each listening condition it did not identify any stimulus combinations that were consistent between all listening conditions. The H-Long stimulus, however, was found to be a significant predictor in more listening conditions and quadrant-stimuli combinations than any other stimuli.

Table 44. Composite results showing quadrant-stimulus combinations (shown as an X) that best predicted localization performance based on a stepwise regression for each listening condition.

		OE		ITE		OTE	
		Left	Right	Left	Right	Left	Right
Front Hemisphere	H-Long	-	-	X	X	X	-
(30°/60° Accuracy)	H-Short	X	-	-	-	-	-
	L-Long	-	-	-	-	X	-
	L-Short	-	X	-	-	-	-
Rear Hemisphere	H-Long	-	-	-	-	-	-
(30°/60° Accuracy)	H-Short	-	-	X	-	-	-
	L-Long	-	X	-	-	-	-
	L-Short	-	-	-	-	-	X
FBCT	H-Long	X		X		-	
	H-Short	X		-		X	
	L-Long	-		-		-	
	L-Short	-		-		-	

The 30°/60° Accuracy and FBCT AFFD measures, when combined with the H-Long stimulus, were found to have practical significance and a good predictive value as seen in Table 43. While it appears that either test can be used to provide localization performance information, this may only be applicable to individuals with normal hearing in both ears. Since the FBCT does not directly measure performance in the left and right hemispheres, it may be possible for an individual with one normal hearing ear and one damaged ear to perform well on the FBCT. It is expected that such an individual, however, would not perform equally well in the 30°/60° Accuracy test when tested on both the left and right sides. There may be an appropriate use for the FBCT as an annual screener for individuals with no change in hearing thresholds, who previously passed a more comprehensive performance task. An advantage of using the FBCT is its relatively small footprint and short test duration when compared to the 30°/60° Accuracy test, which must be tested on both the left and right sides. However, because the FBCT cannot identify a unilateral deficit, it should not be used for initial assessment, assessment after a change in hearing thresholds, or a return to duty assessment after an auditory insult.

The 30°/60° Accuracy test, while only testing one quadrant at a time must provide for an expectation of potential cone of confusion errors. As such, it must present potential speaker locations both to the front and back of the individual for a given hemisphere. This creates a larger equipment footprint required for testing. It should be possible, however, to reduce the distance of the speakers from the listener location, which would help to reduce the overall equipment footprint required for either test.

Using the 30°/60° Accuracy AFFD measure provides the clinician with a mean absolute error value. It must be remembered that this value is a composite of three types of error: blur, cone of confusion, and other error. Cone of confusion error is arguably the most influential error type, due to its frequency and its relative strength in affecting the overall mean absolute error. When interpreting the results of this AFFD measure, one should not determine the results to simply represent localization blur, unless it can be confirmed that no cone of confusion errors were present. Because cone of confusion error can strongly influence the mean absolute error, this AFFD measure is rather sensitive to cone of confusion errors. This is important because visual search techniques can compensate well for simple blur errors, but the magnitude of cone of confusion errors can mislead and delay visual acquisition of a target.

Auditory Learning

The overall improvement in AFFD localization performance from pre-training to post-training can be attributed to both a practice effect as well as auditory learning. The overall improvement in the open-ear condition from pre-training to post-training can only be attributed to a practice effect due to the controls in this experiment. Because humans are constantly using and refining their open-ear performance, here it can be considered to have plateaued in its performance, except where an auditory insult has occurred or the shape of the pinna has changed. The open-ear performance is therefore used as a baseline, and can be thought of as a gold standard or maximum expected performance for a given individual or group of individuals. The open-ear performance is, however, subject to practice effects for particular stimuli. Indeed, herein see the practice effect is evident by the improved open-ear performance from pre-training to post-training. A similar performance improvement, due to practice, is expected in the AFFD listening conditions as well. However, if the performance improvement in the AFFD listening conditions is greater than that of the open-ear condition, that improvement is attributed to a learning effect. This interaction of performance with training indicates auditory learning has occurred.

Interactions were evident within each training group (ITE and OTE) with their respective training HPED. This interaction was stronger when tested with composite data from both training groups. This was probably due to a higher number of samples, which increased the power in the analysis. Not only was the interaction present, but the results also indicated that the post-training performance did not differ, statistically, between the open-ear and HPED listening condition. This is an important finding and can have a significant impact on studies that are designed to compare and contrast HPEDs with each other and/or with open-ear performance. These studies often find that open-ear performance is superior to HPED performance, and that HPEDs differ in their performance levels. This study suggests, that with continued use, these performance differences may diminish or become nonexistent. Consequently, caution should be taken when rating HPEDs where the data are based solely on performance of novice HPED users.

While it was evident that auditory learning occurred for the training HPED, there appeared to be no crossover of auditory learning to the non-test HPED. That is, no interactions were found for the non-training HPED. This does not mean that auditory learning cannot occur for a non-training HPED, but only that it was not found in this study, with these particular HPEDs. Due to the magnitude of physical and dynamic differences in the two HPEDs used in this study (ITE vs. OTE), this finding is not surprising. It may be possible for some crossover to occur for HPEDs that are more similar to each other. For example, devices that have similar electronic auditory processors, frequency response, microphone placement, or physical size/shape may enable crossover to occur.

Confidence

The pre-training confidence data, for the ITE group, showed greater confidence in the open-ear condition than either of the HPED conditions. Pre-training confidence data, for the OTE group, showed greater confidence in the open-ear condition than for the ITE listening condition but not the OTE listening condition. While it is expected for open-ear confidence to be greater than HPED confidence initially, there is no apparent reason for OTE confidence to be better than ITE confidence other than random variation.

The change in confidence from pre- to post-training showed a near significant increase for the training HPED in each training group. This finding supports the previous finding of increased performance from auditory learning for each training HPED. However, the non-training HPED results are mixed. In the ITE group the non-training (OTE) HPED showed a significant decrease in confidence, while in the OTE group the non-training (ITE) HPED showed no significant change. This finding is not readily understood as the reason for the decrease in confidence seen in the ITE group is not apparent.

Post-training results in the ITE group continued to show significantly greater confidence in the open-ear condition than either HPED condition. While both HPED conditions were statistically the same pre-training, the training (ITE) HPED showed significantly greater confidence than the non-training (OTE) HPED post-training. This separation is a result of a near significant increased in confidence in the training HPED and a significant decrease in confidence in the non-training HPED. Post-training results in the OTE group were interesting, while there was no significant change in confidence within a listening condition, the near significant increase in the OTE confidence allowed for a significant difference between the ITE and OTE conditions. This resulted in the open-ear and OTE conditions showing no statistical difference from each other and both showing statistically greater confidence that the ITE condition.

Overall, there was no change in open-ear confidence, the training HPED showed near significant increase in confidence for both training groups and non-training HPED results were mixed. These findings were consistent with overall localization performance (LPHFFS) tested both pre- and post-training. While these findings are interesting, it is not suggested that they be used as a predictor of localization performance. They do show, however, that confidence in an HPED can increase with training/use.

Response Time

Measures of response time were generally unremarkable. There was no difference between pre- and post-training response times in either training group or as a whole. Interestingly, post-training response times appeared to increase (become longer), while variation (seen in the width of the confidence intervals) decreased. However, this difference was not statistically-significant and is thought to be the result of normal participant variation with a relatively small sample size.

Predicting Post-Training Performance

The pre-training AFFD test/stimulus combinations that best predicted post-training localization performance were different between the two HPED training groups. In the in-the-ear HPED training group, the H-Long and H-Short stimuli were good predictors of localization performance when used with the IACT-L and IACT-R AFFD measures. However, not all of these correlations were found to be significant and could have occurred from chance. In the over-the-ear HPED training group, the L-Long stimuli was a good predictor of localization performance when used with the FBDT AFFD measure. A significant limitation of this analysis was the supremacy of the HPEDs used. This resulted in (LPHFFS and AFFD) data that were concentrated in the high performance (low error) extreme of the potential response range. Data, concentrated in one extreme of the potential response region, can obscure correlations that would otherwise be seen with more disperse data sets. The inclusion of HPEDs that do not afford auditory learning would help disperse the data and may uncover AFFD test/stimulus combinations that are significant and show strong correlations for both in-the-ear and over-the-ear listening conditions. Because this analysis lacked a range of HPEDs (specifically HPEDs that do not allow for auditory learning), it was limited in its ability to establish an appropriate correlation. It is possible that a more disperse data set will show significant and strong correlations between these AFFD test/stimulus combinations.

Conclusions

Predicting Current Performance

When measuring horizontal localization performance, there are various types of error that can be considered. The errors seen in this study included localization blur, cone of confusion, and other (unspecified) error. The data from AFFD measures and the LPHFFS contained a combination of these errors, which were easily discerned when viewing the raw data. However, assigning a specific response to a given error type was not practical, as the types of error often overlapped. Other AFFD measures, or methods of data analysis, may be able to better define and isolate these types of error for use as a performance predictor.

The H-Long stimuli, when used with the 30/60 Accuracy (Left and Right-Front quadrant) AFFD measure, provided the best AFFD test/stimulus combination for predicting localization performance. This AFFD test/stimulus combination was the only combination that predicted performance for all listening conditions. While no low frequency stimuli were shown to be good predictors, the use of a high-frequency stimulus was desirable. The high prevalence of high-frequency hearing loss in the military suggests that localization difficulty should be more problematic for high-frequency sounds. Monaural horizontal localization and elevation cues also rely on heavily on higher frequencies. The use of a high-frequency AFFD stimulus should be more sensitive to these types of hearing deficits.

Auditory Learning

It is clear from this study that auditory learning occurred for the HPED in which training was performed. While pre-training performance with an HPED was worse than open-ear performance, post-training performance showed near equal performance between the open-ear and training HPED. This improvement in overall localization performance is attributed to auditory learning. Table 45 shows the difference in mean error between the open-ear and HPED in pre-training and post-training as well as the percent improvement. While the percent improvement in the OTE HPED is greater than the ITE HPED it is important to realize that its pre-training difference was much worse than the ITE HPED. There is no practical post-training difference between the HPED devices.

Table 45. Difference in mean error between open-ear and HPED condition for pre-training, post-training and percent improvement.

Listening Condition	Pre-Training	Post-Training	% Improvement
ITE HPED	8°	2.6°	67.5%
OTE HPED	14°	3°	78.6%
Composite Training HPED	10.7°	2.8°	73.4%

The training duration used to achieve this level of performance was relatively short, with no more than 12 hours of HPED use in a two-week period. This amount and duration of training was similar to previous studies of auditory learning. The importance of environmental feedback gained through an active, and possibly passive, training task is most evident when comparing the current results with those of Russell (1977). Russell studied the effects of partial (correct vs. incorrect) and total feedback (correct, and actual location if incorrect) on horizontal localization with earmuffs use over the course of three days. While his results indicate that “feedback facilitates performance” (p 219), the effect was not significant. He then postulated that increased practice may facilitate improved performance and conducted localization training for five days. Surprisingly, however, this training was conducted without feedback. He found that accuracy improved from 50% to 70% but concluded that “listeners cannot adapt”. It appears that longer duration training periods and feedback that identifies the location of the source, as in the present study, will afford auditory learning. It also appears that training conducted over several days may be necessary for cortical plasticity to be most effective. While some studies found auditory learning to begin within minutes (Canon, 1971; Freedman, Wilson, and Rekosh, 1967) the time required to obtain near complete auditory learning are much longer and are on the order of weeks (Van Wanrooij and Van Opstal, 2005; Hofman et al., 1998). It is be expected that frequent and consistent use of an HPED (as demonstrated in this and other studies) is needed to facilitate near complete recovery of localization performance in the time frame reported. While not studied directly, auditory learning may be incomplete or delayed with HPED use that is infrequent or not consistent. Auditory learning cannot be expected to occur when wearing a HPED that completely removes localization cues or distorts them to a point that will not afford auditory learning.

The performance improvements seen in the training HPED were not realized in the non-training HPED. This lack of crossover of auditory learning between HPEDs may be the result of differences in their auditory processors, microphone and speaker characteristics, and physical placement. While not tested, crossover of auditory learning may still be possible for HPEDs that are more similar.

Confidence and response time were also measured as indicators of auditory learning. User confidence in localization accuracy for the training HPED increased post-training. However, confidence in the non-training HPED showed mixed results. Increased confidence that coincides with increased performance is important, as it will help ensure HPED use by individuals working in noise hazardous environments that also require good localization skills. While confidence improved with auditory learning, measures of response time showed no change between training groups. There were no differences in response time between listening conditions or as a result of training with a HPED.

Since auditory learning can improve HPED performance to levels at or near open-ear performance, the effects of auditory learning should be considered when rating or ranking HPEDs. Studies or measures that rate or rank HPED performance and do not consider the effects of auditory learning may inadvertently prejudice HPEDs that would otherwise provide superior performance.

Predicting Post-Training Performance

This study did not answer well the question of which AFFD test/stimulus best predicted post-training localization performance. Possible reasons for this may be attributed to potentially flawed AFFD measure, HPEDs that did not represent the broad range of potential HPEDs, a limited number of participants, or other unforeseen factors. While some AFFD test/stimulus combinations were found for each HPED type, there was no common combination between HPED types. It is possible that with a greater range of HPEDs, to include those that do not afford auditory learning, an appropriate AFFD test/stimulus combination could be found.

Study Limitations

This study attempted to find an AFFD test/stimulus combination that would predict current and post-training localization performance. However, all participants in this study had normal hearing thresholds and was not intended to represent the wide variety of hearing thresholds found in the military or other industries. Using participants with hearing loss of varying degrees would be required to validate the AFFD test/stimulus combinations found in this study.

The sole use of high quality/performing HPEDs, that afforded auditory learning, was also a limitation. Since there were no HPEDs, in this study, that did not afford auditory learning, correlations either found or not-found were unremarkable. It is possible that strong and significant correlations would be found if the full performance spectrum of HPEDs was studied.

The initial concept of the various AFFD measures was to separate the various types of error. The FBCT was used to measure cone of confusion error and the 30°/60° Accuracy was to measure localization blur. However, cone of confusion error was used prevalent in the 30°/60° Accuracy AFFD. This might have been corrected by writing more specific test instructions to indicate in which quadrant the stimuli and responses were expected. Limiting the responses of tests would allow for specific, separate measurement of blur and cone of confusion. These measures could then be combined to provide a measure of overall performance, or used separately to determine which measure was the best predictor of performance.

The LPHFFS was used as the gold standard of overall localization performance. However, there may be other more appropriate measures of performance that are more veridical. The fact that the participants were seated, had a response screen in front of them, and knew that there were a limited number of fixed location speakers at ear level may have influenced how they responded. While they were instructed that they could move their head, some were observed to keep their head in a fixed position. This may have resulted in increased cone of confusion errors for long duration stimuli where head movements would quickly reveal such errors. Participant responses may have also been different in a more dynamic environment, such as walking through an urban environment or through heavy vegetation. These more realistic environments might encourage more head movement, introduce vertical localization errors, or increase attentiveness throughout the test. More realistic environments might also require more attentional resources for other tasks, which could affect localization performance in various ways.

Recommendations for AFFD and HPED Localization Tests based on this Research

Given that this dissertation was an initial experiment with attendant limitations, recommendations can be made, with caution, for development of an efficient psychophysical test method based on its results.

AFFD – Current Localization Performance

The following recommendations are designed to test the current ability of a Soldier to perform horizontal localization (Table 46), with either open ears or with an ITE/OTE hearing protector (and may include any type of headgear e.g., helmet, protective mask, etc.). This would comprise a basic measure of auditory fitness for duty, but the criterion score would depend upon the particular missions and jobs to be performed in duty.

The recommended test protocol is similar to that of the 30°/60° Accuracy test outlined previously. Testing will be conducted in the Left-Front and Right-Front quadrant and will use only one stimulus (detailed later). Two speakers, placed in each quadrant, will present the stimulus. The stimulus will be presented from each speaker three times for a total of six stimulus presentations in each quadrant. Using the front center of the listener as a reference for 0°, speaker locations will include 30° and 60° for the Right-Front quadrant and 300° and 330° for the Left-Front quadrant (Figure 76). Speakers will be covered in a manner that does not allow the listener to know the exact location or number of speakers. The speaker covering should extend to the rear of the listener. This will allow the listener to reasonably expect stimuli to be presented from the rear, allowing for cone of confusion errors to be measured.

Table 46. Elements Recommended for an Efficient Psychophysical AFFD-HPED Localization Test

Equipment and Test Room	• Stimulus presentation equipment capable of routing signal automatically to one of two speakers e.g., audiometer, compact disk player, or computer • 4-Speakers • Speaker structure and cover • Listener response dial • Software or hardware to capture, record, and score listener response • Room suitable for equipment setup and quiet enough for testing (Table 15)
Instrumentation and Layout	• Speaker structure/cover to conceal actual and potential speaker locations from 0° to 180° on side testing is being conducted (Figure 77) • Listener aligned with response dial and target placed at an azimuth of 0° • Speakers placed to minimize reflections from hard surfaces • Speakers placed to ensure listener is not in the near field
Presentation Protocol	• 30/60 Accuracy Test conducted in the Left-Front and Right-Front quadrants • Stimulus presented from each speaker three times for each quadrant test.
Dependent Measures	• Mean absolute error (in degrees) • Cone of confusion error reported separately as either a count or percent of total possible.
Stimulus	• Filtered pink-noise • Frequency range: 3000-6000 Hz • Duration: 3 sec • Intensity: 60-70 dB

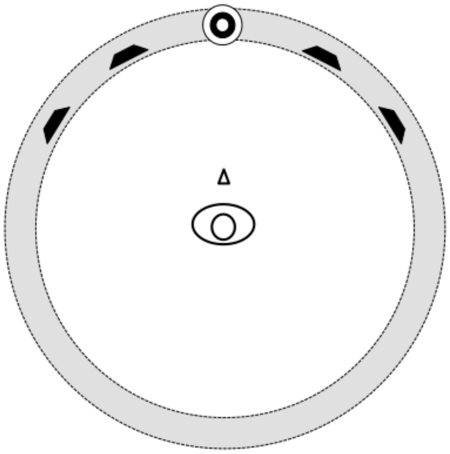


Figure 76. Listener position (center), visual target (bull's-eye), and speaker locations for Left-Front and Right-Front quadrant testing.

The test stimuli should consist of a filtered pink-noise with a frequency range of 3000-6000 Hz. This frequency range will be sensitive to changes in hearing affected by noise-induced hearing loss and frequencies that aid in sound localization. Stimulus duration should allow for head movement, but should not be so long as to prolong the test. A stimulus of approximately 3 sec duration is appropriate and recommended, based on the results of this research. Stimulus intensity should be easily heard above the background noise, but not so intense as to cause a startle response. A stimulus intensity of 60-70 dB was found to be appropriate in this study, but the actual stimulus level will depend upon the ambient background noise in the test room. Table 15 provides maximum permissible ambient noise levels for a 60 dB stimulus to be easily heard. The stimulus should be created and recorded such that unwanted distortions, including harmonic distortions which effectively change the frequency range or intensity, are not present.

Dependent measures should include the mean absolute error (in degrees) for stimuli presented in both the Left-Front and Right-Front quadrants. Because cone of confusion errors can have a large effect on this measure, it is recommended that responses identified as a cone of confusion error not be included in this calculation. To account for cone of confusion errors, they should be counted and reported separate from the mean absolute error as either a total count or as a percentage of the total number of stimuli presented. This will allow for a more accurate measure of localization, while still accounting for cone of confusion errors. The acceptable score, i.e., criterion, or range of scores, was not determined in this research, and may vary depending on the occupational specialty of the listener.

The reverberation characteristics of the test room may also have an impact on the criterion score. It is expected that testing may be conducted in a clinical audiometric sound booth, large office, or small classroom type space. While this study was performed in a room with a relatively short reverberation time, it is not expected that all testing facilities can achieve such short reverberations times. Furthermore, using such short reverberation times may also not accurately reflect localization performance in the expected real world environments. Reverberation time changes from 150 ms to 600 ms at 4000 Hz can result in a 10-15% decrease in horizontal localization accuracy (Giguere & Abel, 1993). Scharine (2009) showed that horizontal localization improved when increasing the mean reverberation time (RT60) from 240 ms to 340 ms. This same increase in reverberation time showed a decrease in horizontal localization performance when the listener was wearing a helmet that either partially or completely covered the pinna. The reader is cautioned that the effects of various reverberation times on the outcomes of this AFFD Test have not been studied. Recommended RT60 is no more than 600 ms at 2000 Hz and above.

Equipment requirements for this AFFD test include 1) a computer, compact disk player, or audiometer capable of playing and routing a signal automatically to one of two speaker locations, 2) 4 speakers with accompanying speaker structure, and 3) a listener response dial (hardware or software), 4) a method of capturing and scoring the response. The listener response dial should allow the listener to easily orient and accurately indicate the azimuth, along a continuum of degrees, of the stimuli as perceived by the listener. Capturing and scoring the response is best done automatically within a software program.

The equipment layout can take many different forms depending on the constraints of the room. The distance the speakers are placed from the listener can be adjusted to fit the constraints of the room. However, speakers should not be placed too close to a reflecting surface (e.g., hard wall or desk) or such that the listener is within the near field of the speaker. The actual distance of these constraints will depend on the speakers and the speaker housing selected. Two potential speaker arrangements are shown in Figure 77. The layout on the left shows an optimal setup with potential speaker locations surrounding the listener. If space does not permit such a setup, the layout on the right may be used. Other layouts are also possible. In the layout on the right, the listener is set to receive testing in the Right-Front quadrant. To test the Left-Front quadrant, the listener must turn 180° and face the opposite direction. This layout still allows for cone of confusion error, as speakers are located both in front, to the rear, and on the same side of the listener.

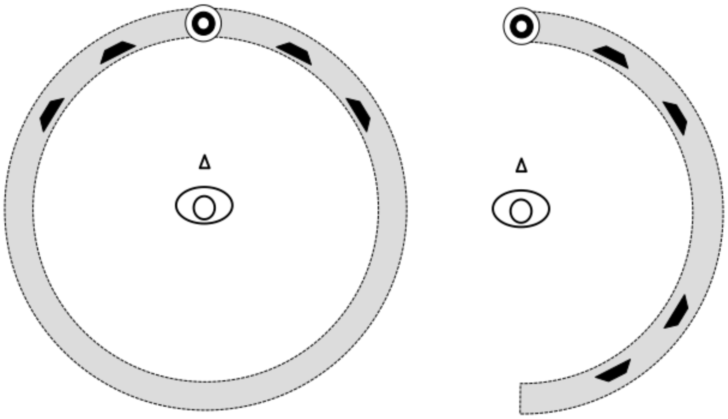


Figure 77. Top down view of two example layouts of a recommended AFFD test of horizontal localization. Left and Right panels show the participant location (center), active speaker (solid black) positions, speaker structure and covering (grey circle/semi-circle), and participant orientation target (bull's-eye).

It is expected that multiple listening conditions (open-ear or device) can be tested in one clinical session. However, to avoid practice effects, it is not recommended that the same listening condition be tested more than once. If testing multiple HPED/TCAPS, one should consider the possible practice effects of performing such tests all within one session. These practice effects may, however, be unavoidable, even if conducted over multiple sessions. It is recommended that the listener be given a few practice stimulus-response trials prior to beginning the actual AFFD test. The projected test administration time is approximately 5 min per listening condition (3 min test administration for each condition + 2 min to score).

Auditory Learning

Because the intent of this study was not to quantify the rate of auditory learning, it is difficult to say how much use/training of a HPED/TCAPS is needed to acquire optimal or near optimal performance. Furthermore, this study was unable to recommend an appropriate AFFD test that would indicate whether HPED/TCAPS afford auditory learning or measure performance level of an experienced HPED/TCAPS user. However, with a minimal amount of training/use, the current AFFD test recommendations could demonstrate the effects of auditory learning, and allow for a more informed judgment of performance in an experienced user. It is recommended that an individual use a HPED/TCAPS for at least ten nearly consecutive days, with at least one hour of daily use in horizontal localization activities which include immediate sound source feedback. After such use/training, it is reasonable to expect localization performance with an HPED/TCAPS to have improved enough to allow for subsequent AFFD testing. AFFD testing after use/training indicate more accurately the expected performance of an experienced user.

Recommendations for Future Research

The results of this study indicated AFFD test/stimulus combinations that predicted open-earn and HPED performance in individuals with normal hearing thresholds. It is strongly recommended that similar studies include participants with hearing loss to determine if the AFFD test/stimulus combinations would hold true for them as well. This is especially important for the military and other industries that have a high prevalence of personnel with hearing loss. Studies of auditory learning stratified by hearing loss would also be beneficial to determine the limits of auditory learning as a result of auditory damage.

This study was limited to localization in the horizontal plane. Studies of vertical localization and distance estimation will also be beneficial. Military personnel experience threats from all locations in both urban and rural battlefields. Assessing open-ear and HPED localization performance in the horizontal plane, vertical plane, and at various distances is important for pre-placement and return-to-duty evaluations.

It was shown that auditory learning occurred after providing a limited but reasonable amount of HPED training with controlled training tasks. However, military personnel may not have the luxury of such training. Future studies should explore the rate of auditory learning for various types of training tasks. Such training tasks may include the passive (worn for normal daily activities) use of an HPED under various conditions. Users of a HPED would then know how long a HPED should be used before an appropriate level of auditory learning could be expected. Other studies could assess activities that increase either the rate or magnitude of auditory learning and the effect of multiple HPED or passive HPDs on auditory learning.

This study also attempted to find an AFFD test/stimulus that could predict which HPEDs would afford auditory learning. However, the use of a narrow range of HPEDs did not allow for conclusive results. Future studies should include a wide range of HPEDs that do and do not afford auditory learning. Findings from such studies can provide HPED users with guidance on which HPED will allow for auditory learning. It may also be an appropriate metric for rating, ranking, or classifying HPEDs in general.

Appendix A. Human Subjects IRB Documents

Virginia Tech IRB Approval Letter #11-047

Investigators IRB Human Subjects Training Certificate

Informed Consent Form for Proposed Experiment

VirginiaTech

Office of Research Compliance
Institutational Review Board
2000 Kraft Drive, Suite 2000 (0497)
Blacksburg, VA 24060
540/231-4606 Fax 540/231-0959
email irb@vt.edu
website http://www.irb.vt.edu

MEMORANDUM

DATE: October 4, 2012

TO: John Casali, Jay Evan Clasing, Martin B Robinette

FROM: Virginia Tech Institutional Review Board (FWA00000572, expires May 31, 2014)

PROTOCOL TITLE: In-Field Human Factors Evaluation of the Effects of Augmented Hearing Protection/Enhancement Devices (HPEDs) on Auditory Detection and Identification with Relevance to Situation Awareness for the U.S. Marines

IRB NUMBER: **11-047**

Effective October 4, 2012, the Virginia Tech Institution Review Board (IRB) Chair, David M Moore, approved the Amendment request for the above-mentioned research protocol.

This approval provides permission to begin the human subject activities outlined in the IRB-approved protocol and supporting documents.

Plans to deviate from the approved protocol and/or supporting documents must be submitted to the IRB as an amendment request and approved by the IRB prior to the implementation of any changes, regardless of how minor, except where necessary to eliminate apparent immediate hazards to the subjects. Report within 5 business days to the IRB any injuries or other unanticipated or adverse events involving risks or harms to human research subjects or others.

All investigators (listed above) are required to comply with the researcher requirements outlined at:

http://www.irb.vt.edu/pages/responsibilities.htm

(Please review responsibilities before the commencement of your research.)

PROTOCOL INFORMATION:

Approved As: **Expedited, under 45 CFR 46.110 category(ies) 4,7**
Protocol Approval Date: **January 20, 2012**
Protocol Expiration Date: **January 19, 2013**
Continuing Review Due Date*: **January 5, 2013**

*Date a Continuing Review application is due to the IRB office if human subject activities covered under this protocol, including data analysis, are to continue beyond the Protocol Expiration Date.

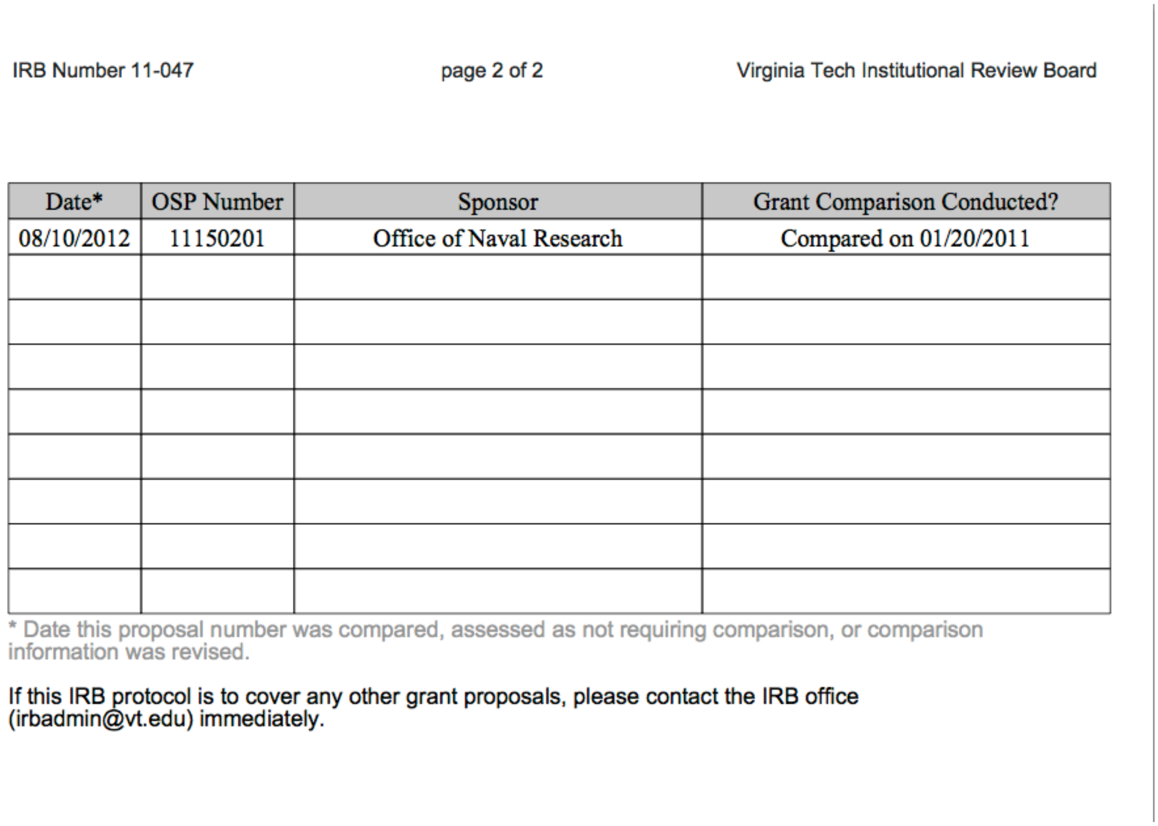
FEDERALLY FUNDED RESEARCH REQUIREMENTS:

Per federal regulations, 45 CFR 46.103(f), the IRB is required to compare all federally funded grant proposals/work statements to the IRB protocol(s) which cover the human research activities included in the proposal / work statement before funds are released. Note that this requirement does not apply to Exempt and Interim IRB protocols, or grants for which VT is not the primary awardee.

The table on the following page indicates whether grant proposals are related to this IRB protocol, and which of the listed proposals, if any, have been compared to this IRB protocol, if required.

Invent the Future

VIRGINIA POLYTECHNIC INSTITUTE AND STATE UNIVERSITY
An equal opportunity, affirmative action institution



IRB Number 11-047 page 2 of 2 Virginia Tech Institutional Review Board

Date*	OSP Number	Sponsor	Grant Comparison Conducted?
08/10/2012	11150201	Office of Naval Research	Compared on 01/20/2011

* Date this proposal number was compared, assessed as not requiring comparison, or comparison information was revised.

If this IRB protocol is to cover any other grant proposals, please contact the IRB office (irbadmin@vt.edu) immediately.

Certificate of Completion

This certifies that

John Casali

Has completed

Training in Human Subjects Protection

On the following topics:

Historical Basis for Regulating Human Subjects Research

The Belmont Report

Federal and Virginia Tech Regulatory Entities, Policies and Procedures

on

May 2, 2006

David Moore, IRB Chair

Certificate of Completion

This certifies that

Martin B Robinette

Has completed

Training in Human Subjects Protection

On the following topics:

Historical Basis for Regulating Human Subjects Research

The Belmont Report

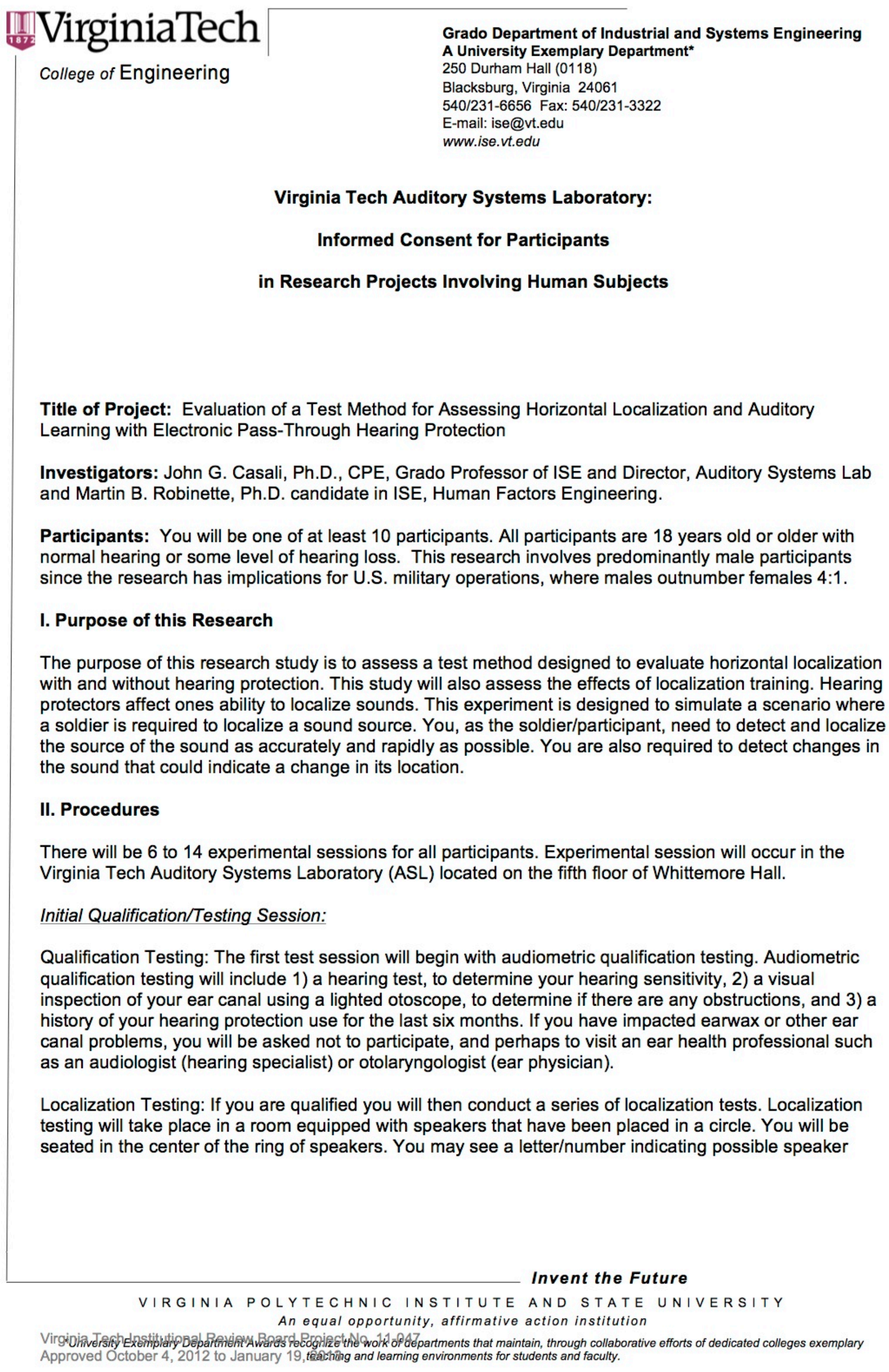
Federal and Virginia Tech Regulatory Entities, Policies and Procedures

on

August 25, 2010

David Moore, IRB Chair

NOTE: This Informed Consent was approved by the VT IRB on 4 October 2012 under IRB #11-047.



VirginiaTech
College of Engineering

Grado Department of Industrial and Systems Engineering
A University Exemplary Department*
250 Durham Hall (0118)
Blacksburg, Virginia 24061
540/231-6656 Fax: 540/231-3322
E-mail: ise@vt.edu
www.ise.vt.edu

Virginia Tech Auditory Systems Laboratory:

Informed Consent for Participants

in Research Projects Involving Human Subjects

Title of Project: Evaluation of a Test Method for Assessing Horizontal Localization and Auditory Learning with Electronic Pass-Through Hearing Protection

Investigators: John G. Casali, Ph.D., CPE, Grado Professor of ISE and Director, Auditory Systems Lab and Martin B. Robinette, Ph.D. candidate in ISE, Human Factors Engineering.

Participants: You will be one of at least 10 participants. All participants are 18 years old or older with normal hearing or some level of hearing loss. This research involves predominantly male participants since the research has implications for U.S. military operations, where males outnumber females 4:1.

I. Purpose of this Research

The purpose of this research study is to assess a test method designed to evaluate horizontal localization with and without hearing protection. This study will also assess the effects of localization training. Hearing protectors affect ones ability to localize sounds. This experiment is designed to simulate a scenario where a soldier is required to localize a sound source. You, as the soldier/participant, need to detect and localize the source of the sound as accurately and rapidly as possible. You are also required to detect changes in the sound that could indicate a change in its location.

II. Procedures

There will be 6 to 14 experimental sessions for all participants. Experimental session will occur in the Virginia Tech Auditory Systems Laboratory (ASL) located on the fifth floor of Whittemore Hall.

Initial Qualification/Testing Session:

Qualification Testing: The first test session will begin with audiometric qualification testing. Audiometric qualification testing will include 1) a hearing test, to determine your hearing sensitivity, 2) a visual inspection of your ear canal using a lighted otoscope, to determine if there are any obstructions, and 3) a history of your hearing protection use for the last six months. If you have impacted earwax or other ear canal problems, you will be asked not to participate, and perhaps to visit an ear health professional such as an audiologist (hearing specialist) or otolaryngologist (ear physician).

Localization Testing: If you are qualified you will then conduct a series of localization tests. Localization testing will take place in a room equipped with speakers that have been placed in a circle. You will be seated in the center of the ring of speakers. You may see a letter/number indicating possible speaker

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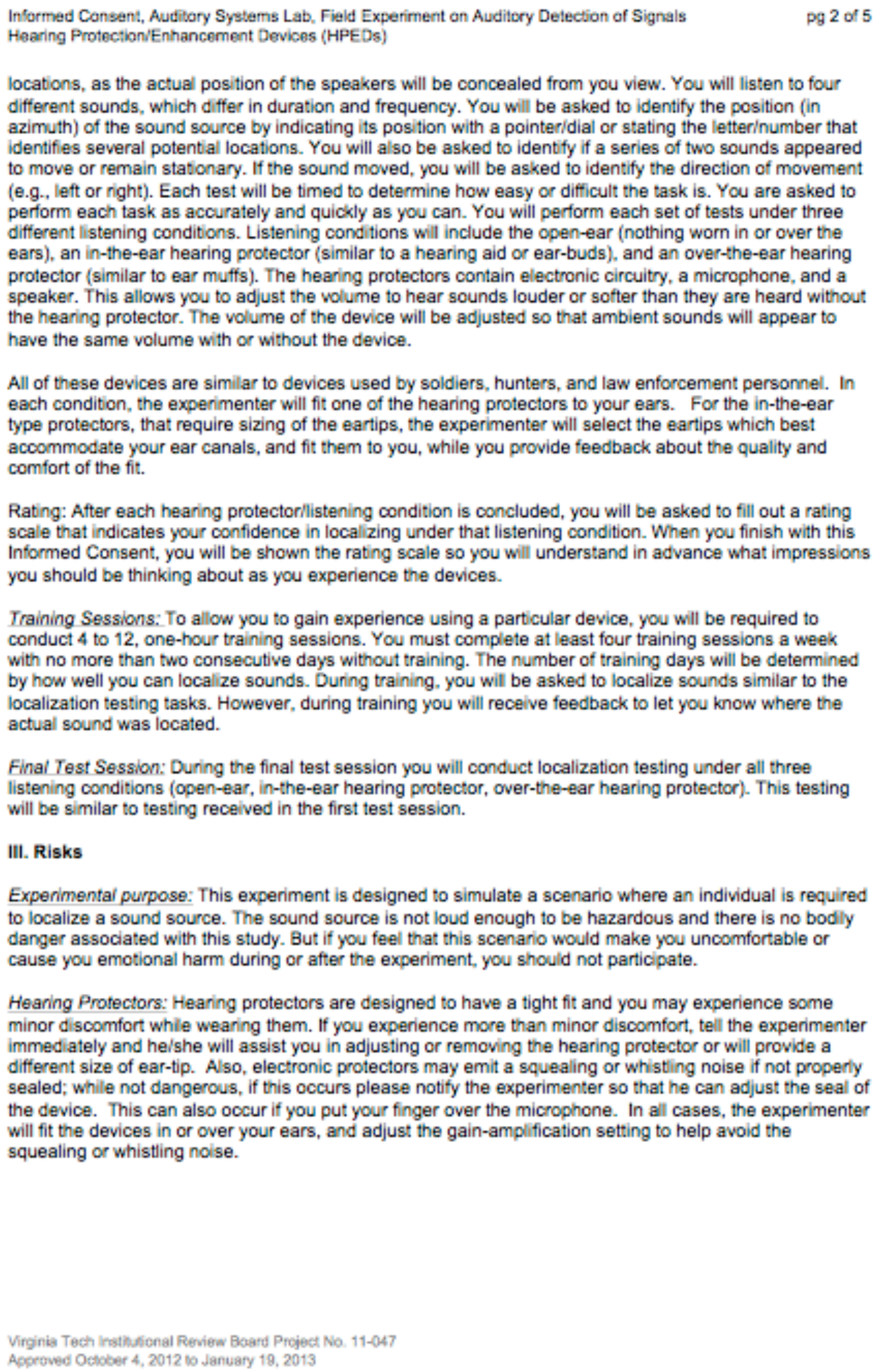

Informed Consent, Auditory Systems Lab, Field Experiment on Auditory Detection of Signals pg 2 of 5
Hearing Protection/Enhancement Devices (HPEDs)

locations, as the actual position of the speakers will be concealed from you view. You will listen to four different sounds, which differ in duration and frequency. You will be asked to identify the position (in azimuth) of the sound source by indicating its position with a pointer/dial or stating the letter/number that identifies several potential locations. You will also be asked to identify if a series of two sounds appeared to move or remain stationary. If the sound moved, you will be asked to identify the direction of movement (e.g., left or right). Each test will be timed to determine how easy or difficult the task is. You are asked to perform each task as accurately and quickly as you can. You will perform each set of tests under three different listening conditions. Listening conditions will include the open-ear (nothing worn in or over the ears), an in-the-ear hearing protector (similar to a hearing aid or ear-buds), and an over-the-ear hearing protector (similar to ear muffs). The hearing protectors contain electronic circuitry, a microphone, and a speaker. This allows you to adjust the volume to hear sounds louder or softer than they are heard without the hearing protector. The volume of the device will be adjusted so that ambient sounds will appear to have the same volume with or without the device.

All of these devices are similar to devices used by soldiers, hunters, and law enforcement personnel. In each condition, the experimenter will fit one of the hearing protectors to your ears. For the in-the-ear type protectors, that require sizing of the eartips, the experimenter will select the eartips which best accommodate your ear canals, and fit them to you, while you provide feedback about the quality and comfort of the fit.

Rating: After each hearing protector/listening condition is concluded, you will be asked to fill out a rating scale that indicates your confidence in localizing under that listening condition. When you finish with this Informed Consent, you will be shown the rating scale so you will understand in advance what impressions you should be thinking about as you experience the devices.

Training Sessions: To allow you to gain experience using a particular device, you will be required to conduct 4 to 12, one-hour training sessions. You must complete at least four training sessions a week with no more than two consecutive days without training. The number of training days will be determined by how well you can localize sounds. During training, you will be asked to localize sounds similar to the localization testing tasks. However, during training you will receive feedback to let you know where the actual sound was located.

Final Test Session: During the final test session you will conduct localization testing under all three listening conditions (open-ear, in-the-ear hearing protector, over-the-ear hearing protector). This testing will be similar to testing received in the first test session.

III. Risks

Experimental purpose: This experiment is designed to simulate a scenario where an individual is required to localize a sound source. The sound source is not loud enough to be hazardous and there is no bodily danger associated with this study. But if you feel that this scenario would make you uncomfortable or cause you emotional harm during or after the experiment, you should not participate.

Hearing Protectors: Hearing protectors are designed to have a tight fit and you may experience some minor discomfort while wearing them. If you experience more than minor discomfort, tell the experimenter immediately and he/she will assist you in adjusting or removing the hearing protector or will provide a different size of ear-tip. Also, electronic protectors may emit a squealing or whistling noise if not properly sealed; while not dangerous, if this occurs please notify the experimenter so that he can adjust the seal of the device. This can also occur if you put your finger over the microphone. In all cases, the experimenter will fit the devices in or over your ears, and adjust the gain-amplification setting to help avoid the squealing or whistling noise.

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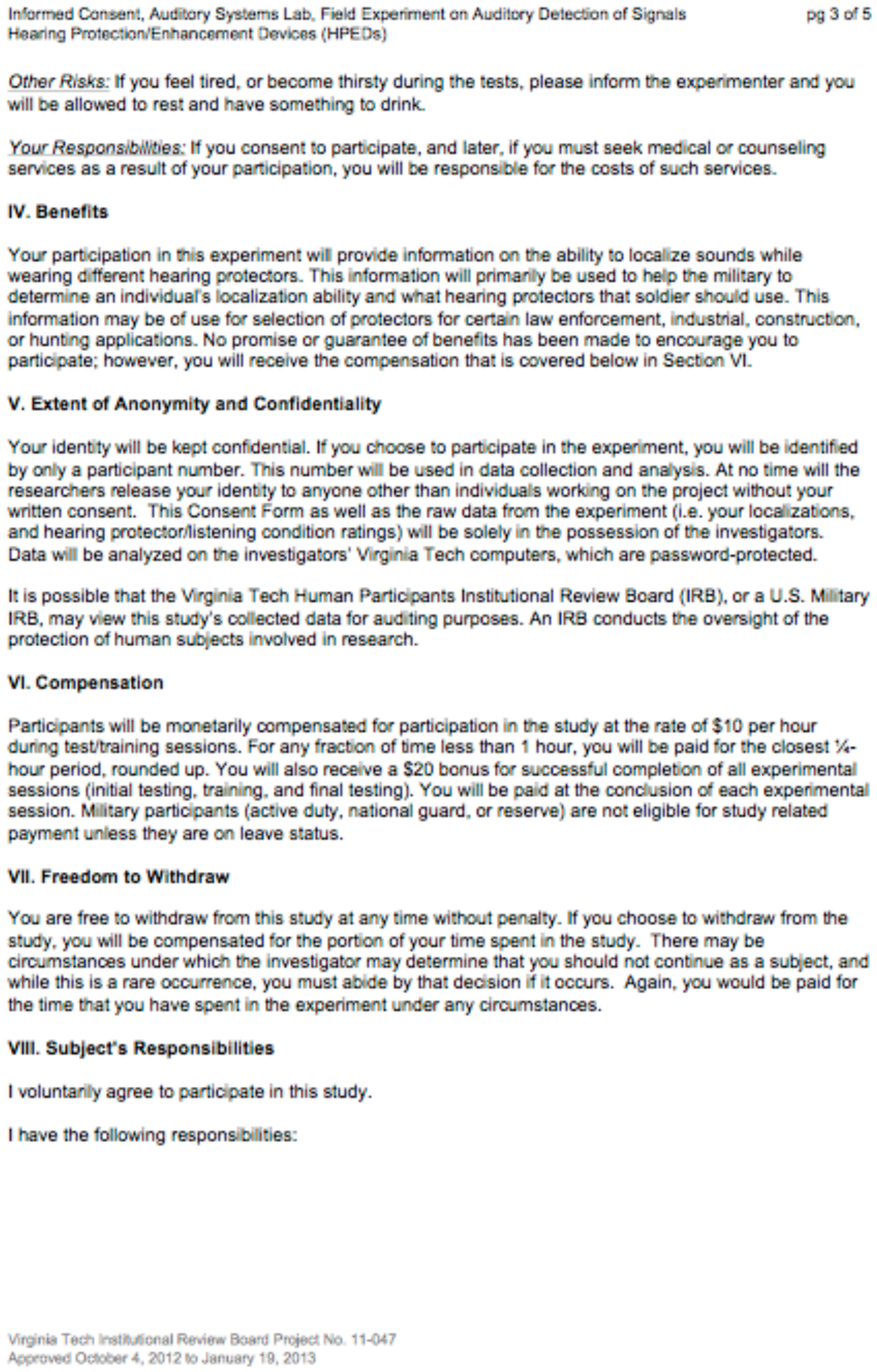


Other Risks: If you feel tired, or become thirsty during the tests, please inform the experimenter and you will be allowed to rest and have something to drink.

Your Responsibilities: If you consent to participate, and later, if you must seek medical or counseling services as a result of your participation, you will be responsible for the costs of such services.

IV. Benefits

Your participation in this experiment will provide information on the ability to localize sounds while wearing different hearing protectors. This information will primarily be used to help the military to determine an individual's localization ability and what hearing protectors that soldier should use. This information may be of use for selection of protectors for certain law enforcement, industrial, construction, or hunting applications. No promise or guarantee of benefits has been made to encourage you to participate; however, you will receive the compensation that is covered below in Section VI.

V. Extent of Anonymity and Confidentiality

Your identity will be kept confidential. If you choose to participate in the experiment, you will be identified by only a participant number. This number will be used in data collection and analysis. At no time will the researchers release your identity to anyone other than individuals working on the project without your written consent. This Consent Form as well as the raw data from the experiment (i.e. your localizations, and hearing protector/listening condition ratings) will be solely in the possession of the investigators. Data will be analyzed on the investigators' Virginia Tech computers, which are password-protected.

It is possible that the Virginia Tech Human Participants Institutional Review Board (IRB), or a U.S. Military IRB, may view this study's collected data for auditing purposes. An IRB conducts the oversight of the protection of human subjects involved in research.

VI. Compensation

Participants will be monetarily compensated for participation in the study at the rate of $10 per hour during test/training sessions. For any fraction of time less than 1 hour, you will be paid for the closest ¼-hour period, rounded up. You will also receive a $20 bonus for successful completion of all experimental sessions (initial testing, training, and final testing). You will be paid at the conclusion of each experimental session. Military participants (active duty, national guard, or reserve) are not eligible for study related payment unless they are on leave status.

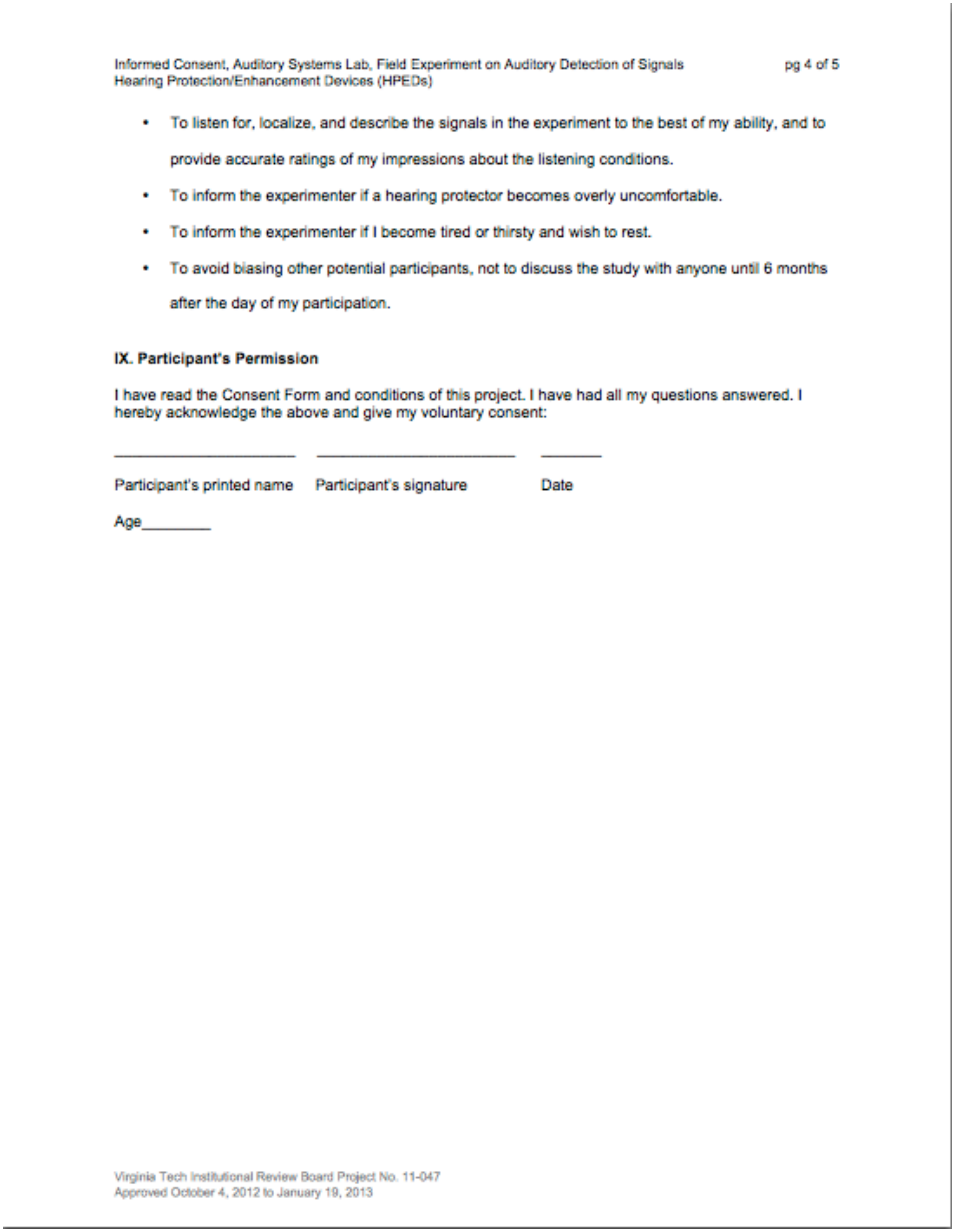
VII. Freedom to Withdraw

You are free to withdraw from this study at any time without penalty. If you choose to withdraw from the study, you will be compensated for the portion of your time spent in the study. There may be circumstances under which the investigator may determine that you should not continue as a subject, and while this is a rare occurrence, you must abide by that decision if it occurs. Again, you would be paid for the time that you have spent in the experiment under any circumstances.

VIII. Subject's Responsibilities

I voluntarily agree to participate in this study.

I have the following responsibilities:



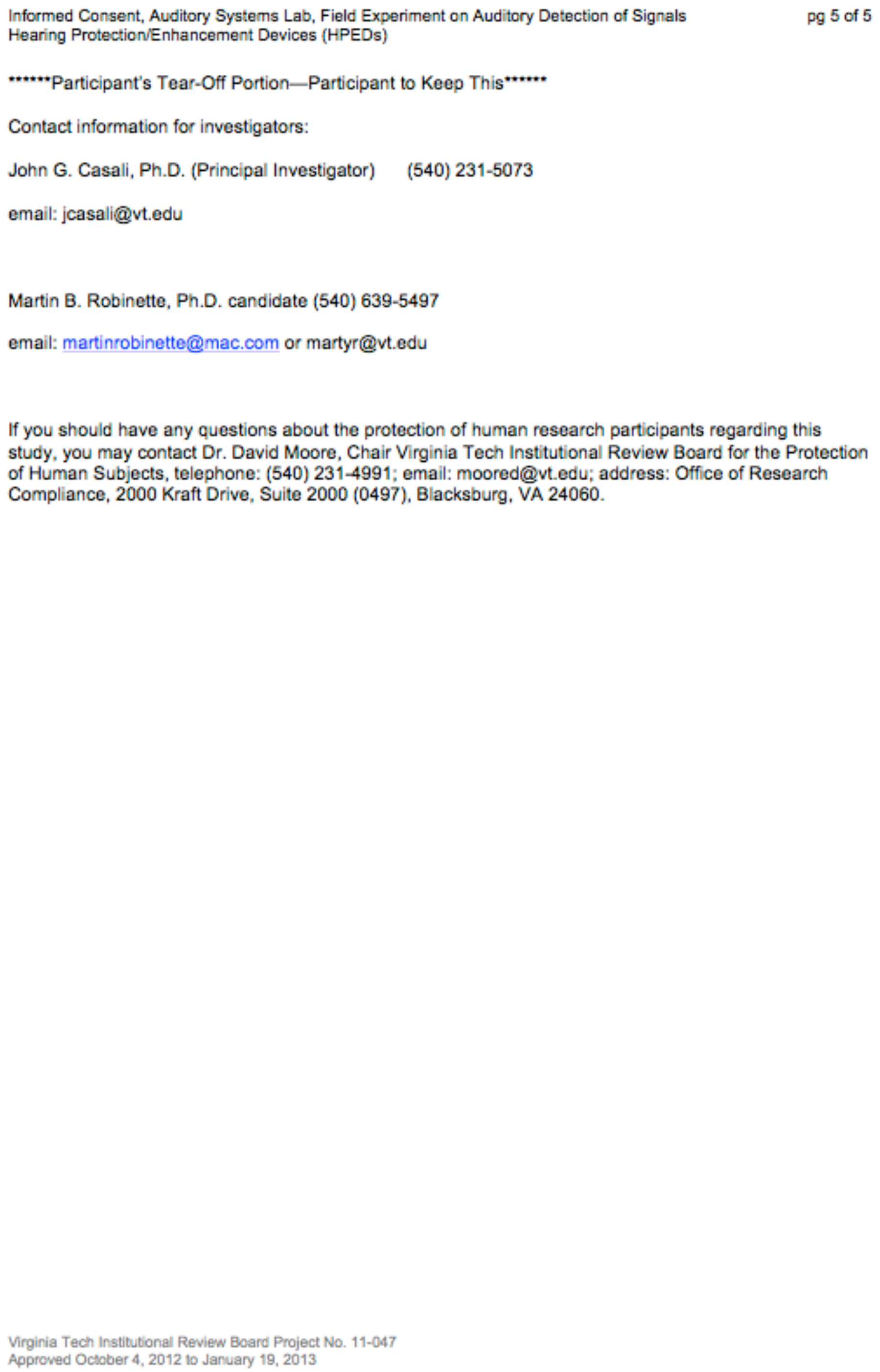
- To listen for, localize, and describe the signals in the experiment to the best of my ability, and to provide accurate ratings of my impressions about the listening conditions.
- To inform the experimenter if a hearing protector becomes overly uncomfortable.
- To inform the experimenter if I become tired or thirsty and wish to rest.
- To avoid biasing other potential participants, not to discuss the study with anyone until 6 months after the day of my participation.

IX. Participant's Permission

I have read the Consent Form and conditions of this project. I have had all my questions answered. I hereby acknowledge the above and give my voluntary consent:

______________________	________________________	_______
Participant's printed name	Participant's signature	Date

Age________



******Participant's Tear-Off Portion—Participant to Keep This******

Contact information for investigators:

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Martin B. Robinette, Ph.D. candidate (540) 639-5497

email: martinrobinette@mac.com or martyr@vt.edu

If you should have any questions about the protection of human research participants regarding this study, you may contact Dr. David Moore, Chair Virginia Tech Institutional Review Board for the Protection of Human Subjects, telephone: (540) 231-4991; email: moored@vt.edu; address: Office of Research Compliance, 2000 Kraft Drive, Suite 2000 (0497), Blacksburg, VA 24060.

Appendix B. Demographic Information Form

Demographic Information **Participant #**

Contact Information

Last, First Name

Age (18-45)

Gender

Address

Phone Number

City

State

Zip

HPED Use History

Type/Model Dates of use (range) Hours per day (average)

Type/Model Dates of use (range) Hours per day (average)

Type/Model Dates of use (range) Hours per day (average)

HPED use ≤ 5 hrs/mo in last 6 mo.

Otoscopy Findings

Occluded Y N

Pathology Y N

Acceptable Y N

Audiogram

Date ______________ Acceptable Y N

	500	1000	2000	3000	4000	6000
Left	35	35	35		55	
Right	35	35	35		55	

Appendix C. Listening Condition Rating scale

Listening Condition Rating scale **Participant #** ______

Please rate how confident you were at accurately identifying the azimuth, direction (front-back), and movement as a whole for each listening condition. Use a rating scale of 1 to 7 with 1 being Totally Not Confident and 7 being Totally Confident.

↔

Totally Not Confident 1 2 3 4 5 6 7 Totally Confident

Listening Condition:

Open Ear ______________

In-The-Ear ______________

Over-The-Ear ______________

References

Abel, S. M. (2008). Barriers to hearing conservation programs in combat arms occupations. *Aviation, Space, and Environmental Medicine, 79*(6), 591-598.

Abel, S. M., Boyne, Stephen, & Roesler-Mulroney, Heidi. (2009). Sound localization with an army helmet worn in combination with an in-ear advanced communications system. *Noise and Health, 11*(45), 199-205.

Abel, S. M., & Lam, K. (2008). Impact of unilater hearing loss on sound localization. *Applied Acoustics, 69*(9), 804-811.

Abel, Sharon M., & Hay, Valerie H. (1996). Sound Localization the Interaction of Aging, Hearing Loss and Hearing Protection. *Scandinavian Audiology, 25*(1), 3-12.

Abel, Sharon M., Tsang, Suzanne, & Boyne, Stephen. (2007). Sound localization with communications headsets: Comparison of passive and active systems. *Noise and Health, 9*(37), 101-107.

Abouchacra, K., & Letowski, T. (2001). *Localization accuracy of speech in the presence of non-directional and directional noise maskers.* Paper presented at the Paper presented at the 17th International Congress on Acoustics, , Rome, Italy.

Abouchacra, K. S., Emanuel, D. C., Blood, I. M., & Letowski, T. R. (1998). Spatial perception of speech in various signal to noise ratios. *Ear and Hearing, 19*(4), 298-309.

accurateshooter.com. (2011). Remington Introduces $20 Custom-Molded Ear Protection Kit. Retrieved 10 May, 2012, from http://bulletin.accurateshooter.com/2011/10/remington-introduces-20-custom-molded-ear-protection-kit/

Aearo. (2005). Peltor COM-TAC II military & special ops headset. http://www.aearo.com/pdf/comm/comtac2_full.pdf Retrieved 10 May 2012, 2012, from http://www.aearo.com/pdf/comm/comtac2_full.pdf

Ahroon, William A., Gordon, Elmaree, & Ostler, Dale A. (2002). Noise Protection of the HGU-56/P Aircrew Integrated Helmet System Worn with Eyeglasses (pp. 46). Fort Rucker, AL: Army Aeromedical Research Lab.

Alali, Khaled A., & Casali, John G. (2011). The challenge of localizing vehicle backup alarms: Effects of passive and electronic hearing protectors, ambient noise level, and backup alarm spectral content. *Noise and Health, 13*(51), 99-112.

Altman, J. A., & Viskov, O. V. (1977). discrimination of perceived movement velocity for fused auditory image in dichotic stimulation. *Journal of the Acoustical Society of America, 61*(3), 816-819.

Altshuler, M.W., & Comalli, P.E. (1975). Effects of stimulus intensity and frequency on median horizontal plane sound localization. *Journal of Auditory Research, 15*, 262-265.

Atherley, G. R. C., & Noble, W. G. (1970). Effect of ear-defenders (ear-muffs) on the localization of sound. *British Journal of Industrial Medicine, 27*(3), 260-265.

Batteau, D. W. (1963). Localization of sound: A new theory of human audition. Final Report Contract N123-(60530) 302083A. China Lake, Calif.: U.S. Naval Ordinance Test Station.

Bekesy, G. (1960). *Experiments in Hearing* (E. G. Weaver, Trans. E. G. Weaver Ed.). New York: McGraw-Hill.

Berger, E. H. (2000). Hearing Protection Devices. In E. H. Berger, L. H. Royster, J. D. Royster, D. P. Driscoll & M. Layne (Eds.), *The Noise Manual* (Fifth ed.). Fairfax, VA: American Industrial Hygiene Association.

Blamey, Peter, Arndt, Patti, Bergeron, François, Bredberg, Göran, Brimacombe, Judy, Facer, George, . . . Whitford, Leslie. (1996). Factors Affecting Auditory Performance of Postlinguistically Deaf Adults Using Cochlear Implants. *Audiology and Neuro-Otology, 1*(5), 293-306.

Blauert, Jens. (1997). *Spatial Hearing The Psychophysics of Human Sound Localization* (Revised ed.). Cambridge: The MIT Press.

Bolia, Robert S., D'Angelo, William R., Mishler, Pamela J., & Morris, Linda J. (2001). Effects of Hearing Protectors on Auditory Localization in Azimuth and Elevation. *Human Factors: The Journal of the Human Factors and Ergonomics Society, 43*(1), 122-128.

Borg, Erik, Bergkvist, Christina, & Bagger-Sjoback, Dan. (2008). Effect on Directional Hearing in Hunters Using Amplifying (Level Dependent) Hearing Protectors. *Otology & Neurotology, 29*, 579-585.

Bradley, John S., & Gover, Bradford N. (2004). Speech and Noise Levels Associated with Meeting Rooms: National Research Council Canada.

Brungart, Hobbs, B. W., & Hamil, J. T. (2007). *A Comparsion of Acoustic and Psychoacoustic Measurements of Pass-Through Hearing Protection Devices*. Paper presented at the IEEE Workshop on Applications of Signal Procesing to Audio and Acoustics, New Paltz, NY.

Brungart, Douglas S., Eades, Cynthia S., & Simpson, Brian D. (2006). *The Effect of Microphone Placement on Localization Accuracy with Electronic Pass-through Earplugs.* Paper presented at the IEEE Workshop on Applications of Signal Processing to Audio and Acoustics, New Paltz, NY.

Brungart, Douglas S., Kordik, Alexander J., & Simpson, Brian D. (2004). The effects of single and double hearing protection on the localization and segregation of spatially-separated speech signals (L). *Journal of the Acoustical Society of America, 116*(4), 1897-1900.

Brungart, Douglas S., Kordik, Alexander J., Simpson, Brian D., & McKinley, Richard L. (2003). Auditory Localization in the Horiziontal Plane with Single and Double Hearing Protecion. *Aviation, Space, and Environmental Medicine, 74*(9), 937-946.

Brungart, Douglas S., Simpson, Brian D., & McKinley, Richard L. (2003). Auditory localization in the horizontal plane with singe and double hearing protection. *Aviation, Space, and Environmental Medicine, 74*(9), 937-946.

Buser, Pierre, & Imbert, Michel. (1992). *Audition* (R. H. Kay, Trans.). Cambridge: The MIT Press.

Butler, Robert A. (1986). The bandwidth effect on monaural and binaural localization. *Hearing Research, 21*(1), 67-73.

Canon, L. K. (1971). Directed attention and maladaptive "adaptation" to displaement of the visual field. *Journal of Experimental Psychology, 88*, 403-408.

Casali. (2010a). Passive Augmentations in Hearing Protection Technology Circa 2010 including Flat-Attenuation, Passive Level-Dependent, Passive Wave Resonance, Passive Adjustable Attenuation, and Adjustable-Fit Devices: Review of Design, Testing, and Research. *International Journal of Acoustics and Vibration, 15*(4).

Casali. (2010b). Powered Electronic Augmentations in Hearing Protection Technology Cira 2010 including Active Noise Reduction, Electronically-Modulated Sound Transmission, and Tactical Communications Devices: Review of Design, Testing, and Research. *International Journal of Acoustics and Vibration, 15*(4).

Casali, Keady, J. P., Killion, M. C., & Talcott, K. A. (2011). *Military Hearing Protection-Enhancement Devices (HPEDs): Protective, but Can the Soldier Locate the Shooter?* Paper presented at the PowerPoint Presentation at the National Hearing Conservation Association, February 24-26, 2011, Mesa, AZ.

Casali, J.G. (2011). Human Factors Issues in Auditory Warning Signal Design -- the Basics (slides from course ISE 5644: Human Audition and Noise).

Casali, John G. , Ahroon, William A., & Lancaster, Jeff A. . (2009). A field investigation of hearing protection and hearing enhancement in one device: For soldiers whose ears and lives depend upon it. *Noise and Health, 11*(42), 69-90.

Chandler, David W. (2006). Blast-Related Ear Injury in Current U.S. Military Operations. *The ASHA Leader, 11 July 2006*.

Chandler, David W., & Grantham, D. Wesley. (1992). Minimum audible movement angle in the horizontal plane as a function of stimulus frequency and bandwidth, source azimuth, and velocity. *Journal of the Acoustical Society of America, 91*(3), 1624-1636.

Chau, William, & Duda, Richard O. (1996). Combined Monaural and binaural Localization of Sound Sources. *Proceedings of ASILOMAR-29*, 1281-1285.

Chung, King, Neuman, Arlene C., & Higgins, Michael. (2008). Effects of in-the-ear microphone directionality onsound direction identification. *Journal of the Acoustical Society of America, 123*(4), 2264-2275.

Clasing, J. (2012). *The Effects of Augmented Hearing Protection/Enhancement Devices on Situation Awareness.* (Ph.D. (in preparation)), Virginia Polytechnic Institute and State University, Blacksburg, VA.

Clifton, R. K., Clarkson, M. G., Gwiazda, J., Bauer, J. A, & Held, Richard. (1988). Growth in head size during infancy: Implications for sound localization. *Developmental Psychology, 24*, 477-483.

Coleman, Paul D. (1963). An Analysis of Cues to Auditory Depth Perception in Free Space. *Psychological bulletin, 60*(3), 302-315.

Comalli, P.E., & Altshuler, M.W. (1976). Effect of stimulus intensity frequency, and unilateral hearing loss on sound localization. *Journal of Auditory Research, 16*, 275-279.

Davis, J.R., & Stephens, S.D.G. (1974). The effect of intensity on localization of different acoustical stimuli in the vertical plane. *Journal of Sound and Vibration, 35*, 223-229.

Medical Standards for Appointment, Enlistment, or Induction in the Armed Forces (DoD Instruction No. 6130.4) (2005).

Department of Defense. (2012). Auditory Fitness for Duty (Draft ed., pp. White Paper - Draft): Hearing Center of Excellence.

Medical Examinations and Standards Volume 4 - Special Standards and Requirements (Air Force Instruction N. 48-123) (2006).

Military Police: The Army Civilian Police and Security Guard Program (Army Regulation No. 190-56) (2006a).

Department of the Army. (2006b). *Technical Guide (TG 41) Personal Hearing Protective Devices - Their Fitting, Care and Use*. (TG 41).

Department of the Army. (2008). *ST 4-02.501 Army Hearing Program*. (ST 4-02.501). Fort Sam Houston, TX: United States army Medical Department Center and School.

Department of the Army. (2009). *Soldier's Manual of Common Tasks: Warrior Skills Level 1,* : Department of the Army.

Standards of Medical fitness (2010).

Physical examinations and standards for enlistment, commission, and special duty. In: Manual of the Medical Department (NAVMED P-117) (2005).

Department of Veterans Affairs. (2010). Annual Benefits Report Fiscal Year 2010.

Deutsch, Lawrence J., & Richards, Alan M. (1979). *Elementary Hearing Science*. Baltimore: University Park Press.

Devor, M., & Wall, P. D. (1978). Reorganisation of spinal cord sensory map after peripheral nerve injury. *Nature 276*, 75-76.

Devor, Marshall, & Wall, Patrick D. (1981). Effect of Peripheral Nerve Injury on Receptive Fields of Cells in the Cat Spinal Cord. *Journal of Comparative Neurology, 199*, 277-291.

Dixon, W.J. (1951). Ratios Involving Extreme Values. *The Annals of Mathematical Statistics, 22*(1), 68-78.

Donahue, Amy M., & Ohlin, Doug W. (1993). Noise and the Impairment of Hearing. In D. P. Deeter & J. C. Gaydos (Eds.), *Occupational Health - The Soldier and the Industrial Base* (Vol. 2). Washington DC: Office of The Surgeon General at TMM Publications Borden Institute.

Dostrovsky, Jonathan O, Millar, Julian, & Wall, Patrick D. (1976). The Immediate Shift of Afferent Drive of dorsal Column Nucleus Cells following Deafferentation: A Comparison of Acute and Chronic Deafferentation in Gracile Nucleus and Spinal Cord. *Experimental Neurology, 52*, 480-495.

Duda, Richard O. (1997). Elevation Dependence of the Interaural Transfer Function. In R. H. Gilkey & T. R. Anderson (Eds.), *Binaural and Spatial Hearing in Real and Virtual Environments*. New York: Psychology Press.

Durlach, Nathaniel I., Shinn-Cunningham, Barbara G., & Held, Richard M. (1993). Supernormal Auditory Localization. *Presence, 2*(2), 89-103.

Durrant, John D., & Lovrinic, Jean H. (1977). *Bases of Hearing Science*. Baltimore: The Williams & Wilkins Company.

Endsley, MIca R. (1995). Toward a theory of Situation Awareness in Dynamic Systems. *Human Factors, 37*(1), 32-64.

Etymotic Research Inc.). EB15 Technical Specifications. Retrieved 3 June 2013, 2013, from http://www.etymotic.com/hp/eb15.html

Freedman, S. J., & Gardos, G. (1965). *Compensation for auditory re-arrangement and transfer to hand-eye coordination*. Paper presented at the MIT Conference on Adaptation, Cambridge, Massachusetts.

Freedman, S. J., & Stampfer, K. (1964). *Changes in auditory localization with displaced ears*. Paper presented at the Psychonomic Society, Niagra Falls, Ontario.

Freedman, S. J., Wilson, L., & Rekosh, J. H. (1967). Compensation for auditory re-arrangement in hand-ear coorination. *Perceptual and Motor Skills, 24*, 1207-1210.

Freigang, Claudia, Schmidt, Lucas, Wagner, Jan, Eckardt, Rahel, Steinhagen-Thiessen, Elisabeth, Ernst, Arne, & Rubsamen, Rudolf. (2011). Evaluation of Central Auditory Discrimination Abilities in Older Adults. *Frontiers in Aging Neuroscience, 3*(6), 1-11.

Gelfand, Stanley A. (1990). *Hearing - An Introduction to Pshchologyical and Physiological Acoustics* (Second ed.). New York: Marcel Dekker, Inc.

Giguere, Christian, & Abel, Sharon M. (1993). Sound localization: Effects of reverberation time, speaker array, stimulus frequency, and stimulus rise/decay. *Journal of the Acoustical Society of America, 94*(2), 769-776.

Grantham, D. Wesley. (1986). Detection and discrimination of simualted motion of auditory targets in the horizontal plane. *Journal of the Acoustical Society of America, 79*(6), 1939-1949.

Grantham, D. Wesley. (1997). Auditory Motion Perception: Snapshots Revisited. In R. H. Gilkey & T. R. Anderson (Eds.), *Binaural and Spatial Hearing in Real and Virtual Environments*. New York: Psychology Press.

Hajicek, Joshua J., Myrent, Noah, Li, Qi, Barker, Daniel, & Coyne, Karen M. (2010). *Protocols for Improved Understanding of Situational Awareness Effects of Head-Borne PPE*. Paper presented at the IEEE International Conference on Technologies for Homeland Security (HST), Waltham, Mass.

Hartmann, W. M. (1983). Localization of sound in rooms. *Journal of the Acoustical Society of America, 74*(5), 1380-1391.

Hartmann, W. M., & Rakerd, B. (1989). On the minimum audible angle - A decision theory approach. *Journal of the Acoustical Society of America, 85*(5), 2031-2041.

Hartmann, William Morris, & Rakerd, Brad. (1993). Auditory spectral discrimination and the localization of clicks in the sagittal plane. *Journal of the Acoustical Society of America, 94*(4), 2083-2092.

Haustein, B. G., & Schirmer, W. (1970). Messeinrichtung zur Untersuchung des Richtungslokalisationsvermogens [A measuring apparatus for the investigation of the faculty of directional localization]. *Hochfrequenztech. u. Elektroakustik, 79*, 96-101.

Hebrank, J., & Wright, D. (1975). The effect of stimulus intensity upon the localization of sound sources on the median plane. *Journal of Sound and Vibration, 38*, 498-500.

Held, Richard. (1955a). Shifts in Binaural Localization After Prolonged Exposures to Atypical Combinations of Stimuli. *The American Journal of Psychology, 68*(4), 526-548.

Held, Richard. (1955b). Shifts in binaural localizaton after prolonged exposure to atypical combinations of stimuli. *American Journal of Psychology, 68*, 526-548.

Hofman, Paul M., Riswick, Jos G.A. Van, & Opstal, A. John Van. (1998). Relearning sound localization with new ears. *Nature Neuroscience, 1*(5), 417-421.

Javer, A.R., & Schwarz, D.W. (1995). Plasticity in human directional hearing. *Journal of Otolaryngology, 24*(2), 111-117.

Johnson, Kenneth W., Walker, Willard C., & Cutnell, John D. (1977). *The Science of Hi-Fidelity* (Second ed.). Dubuque, Iowa: Kendall/Hunt Publishing Company.

Kaptein, Marurits, Nass, Clifford, & Markopoulos, Panos. (2010). *Powerful and Consistent Analysis of Likert-Type Rating Scales.* Paper presented at the CHI Conference on Human Factors in Computing Systems, Atlanta Georgia.

Key Hearing.). Retrieved 10 May, 2012, from http://www.keyhearing.com/Hearing_Protection_Ear_Buds.aspx

Killion, Mead C. (1997). SNR Loss: "I Can Hearing What People Say, but I Can't Understand Them.". *The Hearing Review, 4*(12), 8, 10, 12, &14.

King, Robert B., & Olfield, Simon R. (1997). The impact of signal bandwidth on auditory localization: implications for the design of three-dimensional audio displays. *Human Factors: The Journal of the Human Factors and Ergonomics Society, 39*(2), 287-295.

Kliegl, Reinhold, Smith, Jacqui, & Baltes, Paul B. (1989). Testing-the-limits and the study of adult age differences in cognitive plasticity of a mnemonic skill. *Developmental Psychology, 25*(2), 247-256.

Koehnke, Janet, & Besing, Joan. (1997). Binaural Performance in Listeners with Impaired hearing: Aided and Unaided Results. In R. H. Gilkey & T. R. Anderson (Eds.), *Binaural and Spatial Hearing in Real and Virtual Enbironments*. New York: Psychology Press.

Kraus, Nina, McGee, Therese, Carrell, Thomas D., King, Cynthia, Tremblay, Kelly, & Nicol, Trent. (1995). Central Auditory System Plasticity Associated with Speech Discrimination Training. *Journal of Cognitive Neuroscience, 7*(1), 25-32.

Land, Beverly C. (2010). Current Department of Defense Guidance for Total Force Fitness. *Military Medicine (Supplement), 175*(8), 3-5.

Laroche, Chantal, Giguere, Christian, Soli, Sigfrid D., & Vaillancourt, Veronique. (2008). *Establishment of fitness standards for hearing-critical jobs*. Paper presented at the Communication: 9th International Congress on Noise as a Public Health Problem (ICBEN), Foxwoods, CT.

Letowski, T., Mermagen, T., & Abouchacra, K.S. (2004). *Directional detection and localization of a bolt click sound in jungle- and pink-noise*. Paper presented at the Paper presented at the Noise-Con, , Baltimore, Maryland.

Lewald, Jorg. (2002). Rapid Adaptation to Auditory - Visual Spatial Disparity. *Learning & Memory, 9*, 268-278.

Macpherson, Ewan A., & Middlebrooks, John C. (2000). Localization of brief sounds: Effects of level and background noise. *Journal of the Acoustical Society of America, 108*(4), 1834-1849.

Makous, James C., & Middlebrooks, John C. (1990). Two-dimensional sound localization by human listeners. *Journal of the Acoustical Society of America, 87*(5), 2188-2200.

Marshall, S.L.A. (1947). *Men Against Fire: The Problem of Battle Command*. New York: William Morrow.

Martilla, John A., & Carvey, Davis W. (1975). Four Subtle Sins in Marketing Research. *Journal of Marketing, 39*(1), 8-15.

Mershon, Donald H., Ballenger, William L., Little, Alex D., McMurtry, Patrick L., & Buchanan, Judith L. (1989). Effects of room reflectance and background noise on perceived auditory distance. *Perception, 18*(3), 403-416.

Mershon, Donald H., & King, L. E. (1975). Intensity and reverberation as factors in the auditory perception of egocentric distance. *Percepton & Psychophysics, 18*(6), 409-415.

Middlebrooks, J. C., & Green, D. M. (1991). Sound localization by human listeners. *Annual Review of Psychology, 42*, 135-159.

Middlebrooks, John C. (1992). Narrow-band sound localization related to external ear acoustics. *Journal of the Acoustical Society of America, 92*(5), 2607-2624.

Middlebrooks, John C. (1997). Spectral Shape Cues for Sound Localization. In R. H. Gilkey & T. R. Anderson (Eds.), *Binaural and Spatial Hearing in Real and Virtual Environments*. New Youk: Psychology press.

Mikaelian, H. H. (1969). Adaptation to rearranged ear-hand coordination. *Perceptual and Motor Skills, 28*, 147-150.

Mills, A. W. (1958). On the Minimum Audible Angle. *The Journal of the Acoustical Society of America, 30*(4), 237-246.

Moller, H, & Pedersen, CS. (2004). Hearing at low and infrasonic frequencies. *Noise and Health, 6*(23), 37-57.

Noble, W. G., & Russell, G. (1972). Theoretical and Practical Implications of the Effects of Hearing Protection Devices on Localization Ability. *Acta Oto-laryngologica, 74*(1-6), 29-36.

Noble, William, Byrne, Denis, & Lepage, Bernadette. (1994). Effects on sound localization of configuration and type of hearing impairment. *Journal of the Acoustical Society of America, 95*(2), 992-1005.

Noble, William, Byrne, Denis, & Ter-Horst, Kim. (1997). Auditory localization, detection of spatial separateness, and speech hearing in noise by hearing impaired listeners. *Journal of the Acoustical Society of America, 102*(4), 2343-2352.

Noble, William, Murray, Narelle, & Waugh, Richard. (1990). The Effect of Various Hearing Protectors on Sound Localization in the Horizontal and Vertical Planes. *American Industrial Hygiene Association Journal, 51*(7), 370-377.

O'Connor, Francis G., Deuster, Patricia A., DeGroot, David W., & White, Duvell W. (2010). Medical and Environmental Fitness. *Military Medicine (Supplement), 175*, 57-64.

Oldfield, Simon R., & Parker, Simon P. A. (1984). Acuity of sound localisation: a topography of auditory space. I. Normal hearing conditions. *Perception 13*(5), 581-600.

Oldfield, Simon R., & Parker, Simon P. A. (1986). Acuity of sound localisation: a topography of auditory space. III. Monaural hearing conditions. *Perception, 15*(1), 67-81.

Palmer, Catherine V., Nelson, Caharles T., & Lindley, George A. (1998). The funcionally and physiologically plasatic adult auditory system. *Journal of the Acoustical Society of America, 103*(4), 105-1721.

Peltor.). Peltor Comtac II Electronic Headsets. Retrieved 11 May, 2012, from http://www.opticsplanet.net/peltor-comtact-ii-electronic-headsets-military-green-mt15h69fb-47.html?utm_source=google&utm_medium=cpc&utm_campaign=plusbox-beta&gclid=CMjwrMuvjK8CFQdN4AodVlFA9Q

Perrett, Stephen, & Noble, William. (1997). The contribution of head motion cues to localization of low-pass noise. *Perception and Psychophysics, 59*(7), 1018-1026.

Peters, Leslie J., & Garinther, Georges R. (1990). The Effects of Speech Intelligibility on Crew Performance in an M1A1 Tank Simulator. Aberdeen Proving Grounds, Maryland: U.S. Army Human Engineering Laboratory.

Petrusic, William M., & Baranski, Joseph V. (2003). Judging confidence influences decision processing in comparative judgments. *Psychonomic bulletin & Review, 10*(1), 7.

Pollin, Bernard, & Albe-Fessard, Denise. (1979). Organization of somatic thalamus in monkeys with and without section of dorsal spinal tracts. *Brain Research, 173*(3), 431-449.

Preibisch-Effenberger, R. (1966a). *Die Schallokalisationsfahigkeit des Menschen und ihre audiometrische Verwendung zur klinischen Diagnostic [The human faculty of sound localization and its audiometric application to clinical diagnostics]. Dissertation.* (Ph. D. Dissertation), Technische Universitat, Dresden.

Preibisch-Effenberger, R. (1966b). *Die Schallokalisationsfahigkeit des Menschen und ihre audiometrische Verwendung zur klinischen Diagnostik [The human faculty of sound localizaton and its audiometric application to clinical diagnostics].* (Ph.D. Dissertation), Technische Universitat, Dresden.

Price, G. Richard, & Hodge, David C. (1976). Detection of Combat Sounds by the Human Ear. Aberdeen Proving Grounds, MD: U. S. Army Human Engineering Laboratory.

Rajan, R., Irvine, D.R.F., Wise, L.Z., & Heil, P. (1993). Effect of Unilateral Partial Cochlear Lesions in Adult Cats on the Representation of Lesioned and unlesioned Cochleas in Promary Auditory Cortex. *Journal of Comparative Neurology, 338*(1), 17-49.

Rakerd, Brad, & Hartmann, W.M. (1985). Localization of sound in rooms, II: The effects of a single reflecting surface. *Journal of the Acoustical Society of America, 78*(2), 524-533.

Recanzone, G. H. (1998). Rapidly induced auditory plasticity: The ventriloquism aftereffect. *Proceedings of the National Academy of Sciences of the United States of America, 95*(3), 869-875.

Recanzone, G. H., Merzenich, M. M., & Jenkins, W. M. (1992). Frequency Discrimination Training Engaging a Restricted Skin Surface Results in an Emergence of a Cutaneous Response Zone in Cortical Area 3a. *Journal of Neurophysiology, 67*(5), 1057-1070.

Recanzone, G. H., Schreiner, C. E., & Merzenich, M. M. (1993). Plasticity in the Frequency Representation of Primary Auditory Cortex following Discrimination Training in Adult Owl Monkeys. *Journal of Neuroscience, 13*(1), 87-103.

Recanzone, Gregg H., Merzenich, Michael M., Jenkins, William M., Grajski, Kamil A., & Dinse, Humbert R. (1992). Topographic Reorganization of the Hand Representation in Cortical Area 3b of Owl Monkeys Trained in a Frequency-Discrimination Task. *Journal of Neurophysiology, 67*(5), 1031-1056.

Robertson, Donald, & Irvine, Dexter R.F. (1989). Plasticity of Frequency Organizationin Auditory Cortex of Guinea Pigs With Partial Unilateral Deafness. *Journal of Comparative Neurology, 282*(3), 456-471.

Robinette, M.B., Ahroon, William A., & Ostler, Dale A. (2003). Noise Attenuation of the HGU-56/P Aircrew Integrated Helment System When Worn with the Combat Vehicle Crewman Hood (BALACLAVA) (pp. 33). Fort Rucker, AL: Army Aeromedical Research Lab.

Robinson, G.S., & Casali, J.G. (2000). Speech Communications and Signal Detection in Noise. In E. H. Berger, L. H. Royster, J. D. Royster, D. P. Driscoll & M. Layne (Eds.), *The Noise Manual* (5th ed.). Fairfax, VA: American Industrial Hygiene Association.

Rowland, Roy C., & Tobias, Jerry V. (1967). Interaural Intensity Difference Limen: Federal Aviation Administration Office of Aviation Medicine.

Russell, Graeme. (1977). Limits to behavioral compensation for auditory localization in earmuff listening conditions. *Journal of the Acoustical Society of America, 61*(1), 219-220.

Sabin, Andrew T., Macpherson, Ewan A., & Middlebrooks, John C. (2004). Human sound localization at near-threshold levels. *Hearing Research, 199*, 124-134.

Salvi, R. J., Henderson, D., Fiorino, F., & Colletti, V. (1996). *Auditory System Plasticity and Regeneration*. New York: Thieme Medical.

Scharine, Angelique A. (2009). *Degradation of Auditory Localization Performance Due to Helmet Ear Coverage: The Effects of Normal Acoustic Reverberation*. (ARL-TR-4879). Aberdeen Proving Grounds, MD: Army Research Laboratory.

Scharine, Angelique A., Cave, Kara D., & Letowski, Thomasz R. (2009). Auditory Perception and Cognitive Performance. In C. E. Rash, M. B. Russo, T. R. Letowski & E. T. Schmeisser (Eds.), *Helmet-Mounted Displays: Sensation, Perception and Cognition Issues*. Fort Rucker, Alabama: U.S. Army Aeromedical Research Laboratory.

Scharine, Angelique A., & Letowski, Tomasz R. (2005). Factors Affecting Auditory Localization and Situational Awareness in the Urban Battlefield. Aberdeen Proving Grounds: Army Research Lab Aberdeen Proving Grounds MD Human Research and Engineering Directorate.

Schwaber, Mitchell K., Garraghty, Preston E., & Kaas, Jon H. (1993). Neuroplasticity of the adult primate auditory cortex following cochlear hearing loss. *American Journal of Otology, 14*(3), 252-258.

Shinn-Cunningham, Barbara G., Durlach, Nathaniel I., & Held, Richard M. (1998). Adapting to supernormal auditory localization cues. I. Bias and resolution. *Journal of the Acoustical Society of America, 103*(6), 3656-3666.

Simpson, Brian D., Bolia, Robert S., McKinley, Richard L., & Brungart, Douglas S. (2005). Impact of Hearing Protection on Sound Localization and Orienting Behavior. *Human Factors: The Journal of the Human Factors and Ergonomics Society, 47*(1), 188-198.

Slattery III, W.H., & Middlebrooks, J. C. (1994). Monaural sound localization: acute versus chronic unilateral impairment. *Hearing Research, 75*, 38-46.

Smith-Abouchacra, K.M. (1993). *Detection and localization of a target signal in multiple-source environments*. Unpublished Dissertation, . Pennsylvania State University. Unpublished Dissertation, University Park, PA, .

Steele, Kenneth M. (2010, 11 May 2012). Psychology 3203. from http://www1.appstate.edu/~kms/classes/psy3203/SoundLocalize/confusion.jpg

Stevens, S. S., & Newman, E. B. (1936). The Localization of actual Sources of Sound. *The American Journal of Psychology, 48*(2), 297-306.

Talavage, Thomas M., Sereno, Martin I., Melcher, Jennifer R., Ledden, Patrick J., Rosen, Bruce R., & Dale, Anders M. (2004). Tonotopic Organization in Human Auditory Cortex Revealed by Progressions of Frequency Sensitivity. *Journal of Neurophysiology, 91*, 1282-1296.

Talcott, Casali, J. G., Keady, J. P., & Killion, M. C. (2012). Azimuthal auditory localization of gunshots in a realistic field environment: Effects of open-ear versus hearing protection-enhancement devices (HPEDs), military vehicle noise, and hearing impairment. *International Journal of Audiology, 51*(S1), S20-S30.

Talcott, Kristen Alanna. (2011). *An In-Field Experiment on the Effects of Hearing Protection/Enhancement Devices and Military Vehicle Noise on Auditory Localization of a Gunshot in Azimuth (Dissertation).* (Ph.D. Dissertation), Virginia Polytechnic Institute and State University, Blacksburg, VA.

The Money Times. (2011). EB1 and EB15: High-Fidelity Electronic Blast PLG Earplugs. Retrieved 24 May, 2012, from http://www.themoneytimes.com/files/Etymotic EB1 and EB15 Earplugs.jpg

Tufts, Jennifer B., Vasil, Kristin A., & Briggs, Sarah. (2009). Auditory Fitness for Duty: A Review. *Journal of the American Academy of Audiology, 20*, 539-557.

Tukey, Johw W. (1977). *Exploratory Data Analysis*. Reading, Massachusetts: Addison-Wesley Publishing Company.

Van den Bogaert, Tim, Klasen, Thomas J., Moonen, Marc, Van Deun, Lieselot, & Wouters, Jan. (2006). Horizontal localization with bilateral hearing aids: Without is better than with. *Journal of the Acoustical Society of America, 119*(1), 515-526.

Van Wanrooij, Marc M., & Van Opstal, A. John. (2005). Relearning Sound Localization with a New Ear. *The Journal of Neuroscience, 25*(22), 5413-5424.

Vasama, Juha-Pekka, & Makela, Jyrki P. (1995). Auditory pathway plasticity in adult humans after unilateral idiopathic sudden sensorineural hearing loss. *Hearing Research, 87*, 132-140.

Vause, Nancy L., & Grantham, D. Wesley. (1999). Effects of Earplugs and Progective Headgear on Auditory Localizaiton Ability in the Horizontal Plane. *Human Factors: The Journal of the Human Factors and Ergonomics Society, 41*(2), 282-294.

Vliegen, joyce, & Opstal, A. John Van. (2004). The influence of duration and level on human sound localization. *Journal of the Acoustical Society of America, 115*(4), 1705-1713.

Wall, P. D., & Egger, M. D. (1971). Formation of New Connexions in Adlut Rat Brains after Partial Deafferentation. *Nature, 232*, 542-545.

Wallach, Hans. (1939). On Sound Localization. *Journal of the Acoustical Society of America, 10*, 270-274.

Welch, Robert B. (1978). *Perceptual Modification: Adapting to Altered Sensory Environments*. New York: Adademic Press.

Wells, M.J., & Ross, H.E. (1980). Distortion and adaptation in underwater sound localization. *Aviation, Space, and Environmental Medicine, 51*, 767-774.

Williges, Robert C. (2007). *CADRE Computer-Aided Design Reference for Experiments A Tool for Human Factors and Ergonomics Research*

Willott, J.F. (1996). Auditory system plasticity in the adult C57BL/6 mouse. In R. J. Salvi, D. Henderson, F. Fiorino & V. Colletto (Eds.), *Auditory System Plasticity and Regeneration* (pp. 297-316). New York: Thieme Medical.

Willott, James F. (1996). Anatomic and physiologic aging: A behavioral neuroscience perspective. *Journal of the American Academy of Audiology, 7*(3), 141-151.

Woodworth, R. S., & Schlosbert, H. (1954). *Experimental Psychology* (2nd ed.). London: Methuen.

Wright, Beverly A., & Zhang, Yuxuan. (2006). A review of learning with normal and altered sound-localization cues in human adults. *International Journal of Audiology, 45* (Supplement 1), S92-S98.

Zahorik, P., & Wightman, F. L. (2001). Loudness constancy with varying sound source distance. *Nature Neuroscience, 4*(1), 78-83.

Zahorik, Pavel, Brungart, Douglas S., & Bronkhorst, Adelbert W. (2005). Auditory Distance Perception in Humans: A Summary of Past and Present Research. *Acta Acustica united with Acustica, 91*(3), 409-420.

Zwiers, Marcel P., Opstal, A. John Van, & Paige, Gary D. (2003). Plasticity in human sound localization induced by compressed spatial vision. *Nature Neuroscience, 6*(2), 175-181.