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INTRODUCTION

1. Hearing Protection and Auditory Situation Awareness: Brief Background

Combat warfighters and other non-combat service members must utilize their auditory sense for multiple tasks, many of which have personnel safety and/or tactical mission implications. Protection and preservation of the soldiers' hearing is imperative; therefore, the use of hearing protection in many military environments, including those with gunfire and other ordnance, is critical. However, *conventional* passive hearing protection is well-known to degrade auditory aspects of task performance in many situations (e.g., see Casali, 2010b & Casali, 2012). Thus, in the past decade, considerable engineering design effort has been devoted to "augmentation" of hearing protection devices (HPDs), by incorporating special features that are intended to maintain or even enhance the warfighters' hearing, inclusive of hearing and localizing signals of interest as well as enabling communications. An exhaustive classification scheme that covers all types of HPD augmentations, including both dynamic passive and active (powered electronic) features, appears in Casali (2010a,b), with nine different classes of device as of that date. However, for most combat and non-combat ground applications in today's military, the two most common HPD augmentations include either: 1) a passive acoustic "valve" (dynamically-controlled vent "pass-through" system) in a non-electronic, passive HPD, or 2) an electronically-modulated sound transmission "pass-through" circuit in a battery-powered HPD. The first is exemplified by the commonly deployed 3M Combat Arms™ earplug (and its variants), which provides a "hear-through" vent with limited resistance when incident dB levels are low to enable sounds to pass-through the plug with low impedance, but which sharply increases its impedance, and thus its protective capability, during gunfire of high dB levels.

Alternatively to the passive, level-dependent approach, there is the general technique of an electronically-modulated sound transmission circuit, exemplified in various designs in such devices as the Peltor ComTac III™ earmuff and Nacre-Honeywell Quiet Pro+™ insert-type TCAPS (Tactical Communications and Protective Systems). These active battery-powered designs include a dynamic response sound transmission circuit, in which the salient "pass-through" feature comprises a microphone mounted on or near the protector's external surface, an output-limiting amplifier, and small loudspeakers mounted within the earcups of a muff, or internal to an earplug's body located within a sound port facing the eardrum. The sound transmission characteristic is achieved by electronics that are typically designed to pass through the HPD and boost only a certain frequency range of sounds, such as the critical speech bandwidth, critical warning signal frequencies, or even combat-relevant sounds; thus, the sound transmission circuit overcomes or bypasses the passive attenuation of the muff or earplugs and transmits the external sounds to the user's ears. While there are many differences among sound transmission devices, typically the limiting amplifier maintains a predetermined (and in most examples, user-adjustable) gain, and a limiter on the amplified earphone output to preset A-weighted noise levels (sometimes about 85 dBA, which is typical for civilian devices), until the ambient noise reaches a certain cutoff sound level (typically 110 dBA–120 dBA), at which point the electronics cease to function, wherein the device essentially reverts to a passive HPD. When these types of electronic sound-transmission HPDs further incorporate a radio communications capability, they are typically termed Tactical Communications and Protective Systems (TCAPS).

The intended benefits, as compared to conventional passive HPDs, of passive augmented HPDs as well as electronic augmented HPDs and TCAPS, include more natural hearing for the user, improved speech communications and signal detection, reduced noise-induced annoyance, improved military tactical advantage, protection from loud gunfire, and in some cases, provision of protection that is somewhat tailored for the user's needs, noise exposure, and/or job requirements. In actuality, military experience with these products in the field, as well as a very limited number of controlled in-situ human factors experiments involving either military or civilian construction work applications, has demonstrated that while some of the intended benefits of augmented HPDs and TCAPS may be realized in practice, others are indeed not (e.g., see brief review in Casali & Clasing, 2013; see individual experiments in Casali, Ahroon & Lancaster, 2009 [in-field ground warfare maneuvers]; Alali & Casali, 2011 and 2012 [construction warning signal detection/localization]; Talcott, Casali, Keady & Killion, 2012 [in-field azimuthal gunshot localization in-field]; Clasing & Casali, 2014 [in-field military signal detection and identification], and Casali & Robinette, 2014 [military azimuthal localization of signals and user training]). Of particular concern in military settings is the scenario wherein a warfighter's auditory sensing and perceptual abilities are compromised, usually as compared to their unoccluded ears, when using these augmented HPDs or TCAPS. Any impairment, impediment, or distortion of normal hearing is of serious concern here, whether it consists of not detecting, not correctly identifying, recognizing or localizing a threat, not hearing a hazard warning signal or approaching vehicle, or not adequately hearing and understanding communications from other personnel -- all part and parcel of maintaining a sense of auditory situation awareness. In part because TCAPS and augmented HPDs are specifically designed (and often advertised) to maintain or even enhance one's auditory capabilities as compared to the open ear, it is even more important that they provide adequate hearing of signals and speech in ambient environments ranging from quiet to very noisy, and that the warfighter can rely not only on the device's protective performance but also on its provision of auditory situation awareness cues that are of crucial importance to the warfighter's safety, survivability, and lethality.

However, in spite of the importance of auditory situation awareness in hazardous or hostile environments, it is a fact that historically in the evaluation of hearing protector adequacy, much more emphasis had long been placed on the capability of the HPD to provide sufficient protection from continuous and impulsive noise exposures. This resulted in well-developed, and in some cases, standardized measurement techniques (e.g., ANSI S12.6-2008) and metrics of attenuation such as the Noise Reduction Rating (NRR) and 1/3-octave band spectral attenuation mean values for continuous noise, and special sound pressure level-vs-time measurements for impulsive noise. But in parallel, there was little if any research attention given to objective measurements of the effects of HPDs and TCAPS on the wearer's ability to hear and process important acoustical signals and speech communications. Recognizing this, in 2013 at the National Hearing Conservation Association Conference, Casali presented a framework, shown in Figure 1, for the concept of human auditory situation awareness with its major sub-elements or individual hearing-critical task components. At the upper left of the flow diagram, the *detection* subtask is shown as the initial task and is the most fundamental requisite component, since if a signal is not detected (i.e., "heard"), nothing else can be achieved by the auditory system in regard to that signal. Other auditory subtasks involved in situation awareness follow detection, per the diagram.

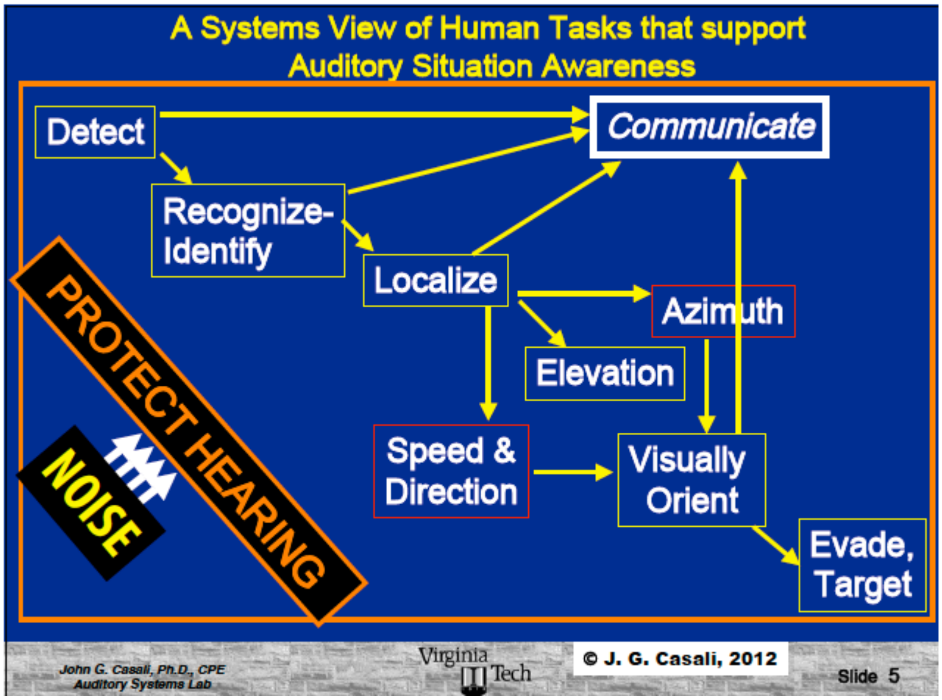

Figure 1. Network diagram of the human hearing subtasks (elements) involved in achieving and maintaining auditory situation awareness. (adapted from Casali & Clasing, 2013).

The auditory situation awareness conceptual framework of Figure 1 was spawned by the aforementioned in-field research experiments at Virginia Tech which demonstrated that certain HPDs and TCAPS indeed had deleterious effects on gunshot localization and detection/identification of various military-relevant signals, some of which were substantial when compared to the listener's much better open-ear performance on the same tasks (Casali et al., 2009; Talcott et al., 2012; Clasing & Casali, 2014). As such, at the 2013 NHCA meeting, Casali also made a first plea for consideration about the concept of an "Auditory Situation Awareness Factor" performance rating, with an emphasis on the multi-subtask components, each of which was proposed to receive an individual score -- this is depicted in Figure 2. That is to say as shown in the Figure, it was proposed that for quantifying the auditory situation awareness effects of any hearing-related device, the subtask elements of **D**etection, **R**ecognition/**I**dentification, **L**ocalization, and **COM**munications, or in short, "DRILCOM" should be included in a multi-factor measurement objective. It is to this end that this research program described herein was thereafter undertaken on request from the U.S. Department of Defense Hearing Center of Excellence, motivated in part by the Virginia Tech Auditory Systems Lab's (VT-ASL) line of research on hearing protection effects on military situation awareness that preceded it. *The overall objective was that an objective test battery be developed to properly and objectively test, and quantify, the situation awareness effects of augmented HPDs and TCAPS as measured on four major elements of the auditory task.*

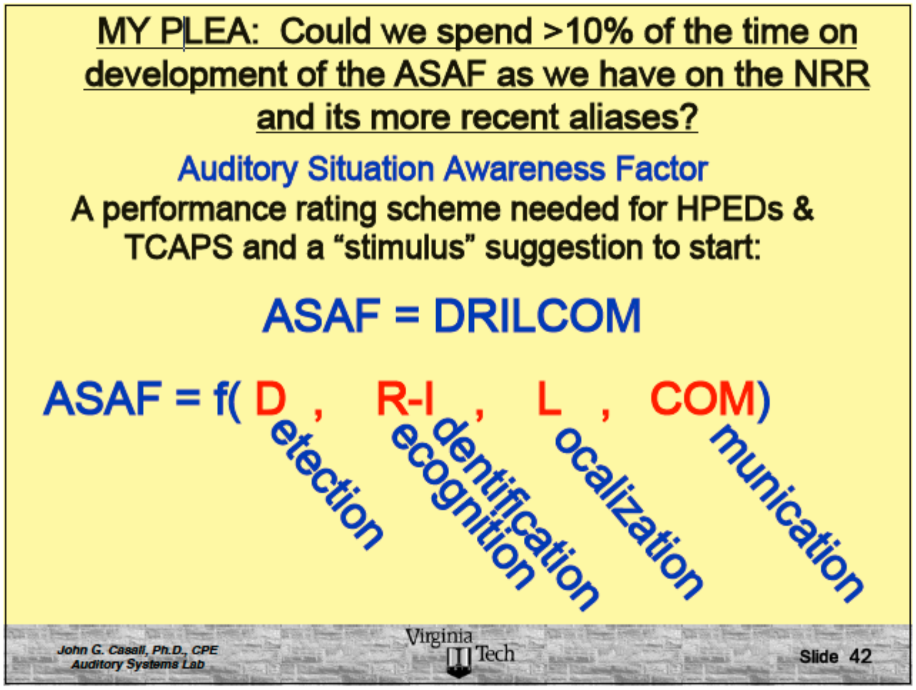

Figure 2. First offering of a concept for measurement of auditory situation awareness effects, as measured on four distinct subtask elements comprising "DRILCOM." (adapted from Casali & Clasing, 2013).

1.1. Definition of TCAPS and Augmented HPDs for this Research

Hereafter, and solely for the purposes of this research, Tactical Communications and Protective Systems (TCAPS) will exclusively refer to augmented hearing protectors inclusive of a sound transmission (pass-through) feature, and which also specifically incorporates both radio-based as well as pass-through communications features, while augmented Hearing Protection Devices (HPDs) will exclusively refer to any type of augmented HPD, passive or electronic, which does *not* incorporate radio-based communications features and which may or may not have a sound transmission (pass-through) feature.

2. Research Objectives and Fundamental Anticipated Usage of the Test Battery

As mentioned above, this Virginia Tech Auditory Systems Laboratory (ASL) research effort for the DoD Hearing Center of Excellence was aimed at the development of an efficient, in-laboratory implementable test battery for auditory situation awareness (ASA) that will objectively quantify the ASA performance afforded by various Tactical Communications and Protection Systems (hereafter, TCAPS) and augmented/advanced Hearing Protection Devices (hereafter, HPDs) used by the U.S. military. Specifically, each of the fundamental ASA task elements of **D**etection, **R**ecognition/**I**dentification, **L**ocalization, and **COM**munications, hereafter termed "DRILCOM" ASA elements (Casali & Clasing, 2013), is measured in the psychophysical test battery that is the primary deliverable from the research. The individual ASA elements' scores from the test battery were kept separate so that performance on each element of ASA could be ascertained, and via statistical analysis, the individual elements' sets of scores were applied to determine the DRILCOM test battery's effectiveness in measuring ASA afforded by each TCAPS or augmented HPD. (This aspect was preferred by the Subject Matter Expert (SME) team, which is discussed next.) The intent was that the test battery would ultimately be deployable in a military audiology clinical or other similar laboratory setting, and applicable to a wide variety of TCAPS as well as passive and augmented HPDs (Casali, 2010a,b).

The fundamental foreseen application of the DRILCOM test battery is that it would serve as one of several available measures of HPD or TCAPS performance, others of which would likely include protective capability (continuous and impulse attenuation), physical parameters such as durability and battery life, individual sizing requirements, etc. Such a battery of measures can then be used as a rather comprehensive means of assessing the performance of an advanced HPD or TCAPS prior to deployment, and for predicting its suitability for use in certain military scenarios or Military Operational Specialties (MOS) which are known to invoke task elements of the DRILCOM test battery model. It could also be applied to gauge whether a particular device is advisable for use by a particular individual who may or may not have some hearing impairment, in advance of deploying that individual with the device, and furthermore, perhaps could be adapted to the training process for that individual. Beyond those contemplated applications, more formally, the test battery and its associated scoring metric could possibly be applied for military qualification/acquisition of TCAPS and HPDs, or for developing a "qualified list" of devices based in part on DRILCOM ASA scoring, in addition to the attenuation data that is now readily available. However, this latter use is not intended as a recommendation of the VT research team, as such a formal criteria-based decision requirement and the performance criteria levels for achieving "qualification" would be a military decision; prior to such a decision, there would need to be an assessment of the criterion levels of ASA performance required for given MOS's or mission scenarios, and this would be a significant undertaking. Furthermore, this application of DRILCOM may require some type of field validation of the laboratory experiment results discussed herein from this research contract. Again, the contract was strictly was aimed at test battery development and a proof-of-concept experiment which applied the test battery to a variety of advanced HPDs and TCAPS.

Based upon the results of a DoD meeting held on September 9, 2013 at Virginia Tech, in which Dr. Casali (the Principal Investigator herein) was asked to provide an overview of his prior in-field experiments on TCAPS and HPD effects on situation awareness, the objectives of this research were sharpened. In particular, they continued to align with the PWS dated 12 July, 2013 with the four fundamental DRILCOM ASA elements; however, the primary change was that the communications tasks that were evaluated were for the sound transmission (i.e., pass-through) communications channel of the TCAPS, and *not* for radio communications which, according to the military hearing representatives at the meeting, are already evaluated under different standards (referenced later herein) for radio communications systems.

2.1. Military Subject Matter Expert (SME) Team

Recognizing the importance of military relevance of the DRILCOM test battery and its various component tasks, the VT research team requested from HCE and received permission to recruit a Subject Matter Expert (SME) team of four current or retired military officers and one military civilian employee for advice and guidance. Collectively, these five individuals spanned expertise in military audiology, military headsets and hearing protection, testing and selection of military devices, and certain aspects of military combat operations. All of them had experience with advanced HPDs and TCAPS used by various branches of the U.S. military. The SME team consisted of the following individuals:

LTC Kristen Casto, Ph.D., AuD, US Army
Audiology Consultant to The Surgeon General, Health & Wellness Directorate, G-3/5/7, Office of the Surgeon General

MAJ Ernesto Perez, U.S. Army
Assistant Product Manager, TCAPS Program, PM SWAR, PEO Soldier, Fort Belvoir

Mark Richter, U.S. Marines "Gruntworks"
Director, Marine Expeditionary Rifle Squad - SIAT, MCSC Enhanced Company Operations and Coordinator, Marine Corps Systems Command. Quantico VA 22134

MAJ Brandon Tourtillot, Ph.D., US Air Force
Program Manager, BATMAN-II, Battlespace Acoustics Branch, Air Force Research Laboratory Wright-Patterson AFB

Collin C. Drennen, (Civilian)
U.S. Army Soldier Systems Center (SSC), Program Executive Office (PEO) Soldier, PM Soldier Warrior TCAPS Program, System Engineering

Primarily, the SME team was enlisted early to help form the research process behind the development of DRILCOM. They assisted in the general development of the DRILCOM subtasks to be used in testing, reviewed examples of test stimuli for DRILCOM subtasks, helped select the group of advanced HPDs and TCAPS for the proof-of-concept experiment, and commented on subject selection and training issues. After discussions with the SME team, all final decisions on these issues were made by the VT research team. The SME team also helped contemplate the potential applications of the DRILCOM test battery, and gave limited foresight as to how it might be used appropriately for their individual needs.

BODY

3. Technical Approach

3.1 Overview of DRILCOM Test Design

The DRILCOM auditory situation awareness (ASA) test battery is composed of four tests that are designed to objectively measure specific auditory task performance of a user with either a TCAPS, advanced HPD, or a baseline, comparison condition, the open (i.e., unprotected) ear. The four tests are **D**etection, **R**ecognition/**I**dentification, **L**ocalization, and **COM**munication; each test is designed to measure detection, recognition/identification, spatial orientation in azimuth and frontal elevation, and the speech perception aspect of ASA, respectively. The **D** test is designed to measure the detectability, or "at what level can the signal be heard" aspect of ASA, which is the first and most fundamental component that has to be accomplished before any further tasks involving cognitive processing of the signal can begin (see Figure 1). The **D** test measures detectability in four directions with respect to the listener's head center, facing-forward position: front (0-degrees or 12-o'clock), right (90-degrees or 3-o'clock), left (270-degrees or 9 o'clock), and rear (180-degrees or 6-o'clock), by measuring the hearing threshold level in dB over a nominal background pink noise of 40 dBA, which was used to "level out" the background noise spectrum to just above what a typical quiet bedroom level would be. The **R/I** test is designed to measure the recognition/identification capability of a user by measuring how well a user can recognize/identify a target sound signal. More specifically, this test invokes perception and invokes cognitive recall and decision-making, which occurs after a person detects (at first sensation) a sound. The **R/I** test measures recognition/identification from two directions with respect to the subject: front (0-degrees or 12-o'clock) and right (90-degrees or 3-o'clock). The **L** test is designed to measure how well a user can localize a sound signal in 360-degrees of azimuth and in frontal elevation. This test relates specifically to spatial processing of a supra-threshold sound in space, once the sound is detected. The **COM** test is designed to measure the performance level of non-radio communication by measuring how well a user understands a spoken sentence through an HPD or TCAPS, and with the open ear. The measure for the COM test is signal-to-noise ratio (hereafter SNR) loss for given speech-in-noise stimulus sound clips, and this provides a measure of the speech communications capabilities of the tested devices, though it is not specifically a measure of percent speech intelligibility, such as classic measures like the Modified Rhyme Test, which is more difficult to calibrate and implement. The **COM** test measures speech communications in four directions: front (0-degrees or 12-o'clock), right (90-degrees or 3-o'clock), left (270-degrees or 9 o'clock), and rear (180-degrees or 6-o'clock).

Because the DRILCOM test battery requires various combinations of test signal and speaker locations as well as background noise, VT-ASL prepared a large, hemi-anechoic room in which to build the test system and conduct the proof of concept experiments. The room is 18 feet wide by 19 feet long by 8.5 feet high with a tile (acoustically-reflective) floor, acoustic drop panel Celotex™ ceiling, and two-inch thick eggshell (Sonex™) acoustic foam on all walls. The octave-band reverberation times for the room at the subject's head center position is provided in Table 1, along with the steady-state noise floor of the room, which approximates a quiet bedroom level. An overall view of the installation of the DRILCOM test equipment in the room appears in Figure 3. Separate loudspeaker arrays for the test signal and background noise, as well as a rack that contained all test equipment (list of all equipment is provided below) were placed as photographed in Figure 3, and labeled schematically in Figure 4. A small desk, serving as the experimenter's station, was placed at the back of the room (Figure 4). The side of the desk that faced the center of the room was treated with a panel of two-inch thick acoustic foam (the same panel used on the hemi-anechoic room walls) to minimize reflected sound. Figure 4 schematically shows the relative locations of the test signal speaker array, background speakers, test equipment rack, experimenter's station, and subject's chair.

Test signal speakers were hidden underneath the white horizontal ring, which was built with a steel pipe structure that completely surrounds the subject 360-degrees in azimuth at 30-degrees increments (Figure 3). The signal speakers were directed toward the center of the circle and placed at approximately 1.14 meters in height; this was the approximate median ear height of a subject when s/he was seated at the center of the room. The diameter of the speaker array measured from the inward face of a speaker to the inward face of the opposite speaker is slightly greater than 3 meters. An additional steel pipe structure was built in the region to the front of the subject to hold signal speakers for frontal elevation tests as shown (Figure 5). This frontal structure for the speakers was slightly inclined inward so that the speakers placed at higher locations were equidistant from the subject at the center to the speakers on the azimuthal ring, and speakers were separated by 30-degrees in the vertical and horizontal dimensions. The speaker array, vertically and horizontally, was covered with acoustically transparent black fabric to conceal the location and number of speakers present. The subject was situated beyond the near field of the lowest test signal frequency for the salient signal bandwidths above about 500 Hz. A marker, suspended as a plumb bob from the ceiling, was placed at the center of the azimuthal speaker array, and it was used to locate a calibration microphone and the subject at the center of the speaker array. The marker was pulled away before each test was started.

Table 1. Reverberation time (RT60) and Noise Floor of the Auditory Systems Laboratory DRILCOM Test Facility, as measured in octave bands.

Frequency (Hz)	125	250	500	1000	2000	4000	8000
Noise Floor (dB SPL)	36	31	29	20	13	16	17
RT60 (ms)	--	685	378	261	213	138	--

The following is a list of the audio and signal control equipment used to build the DRILCOM test system: Behritone C50A powered speakers were used as signal speakers. These speakers have a 5.25 inch diameter round driver housed in a 6.25 inch cube, and comprise a 30-Watt powered speaker with a frequency response of 90 – 17,000 Hz, flat within ± 3 dB. A QSC CX1102™ power amplifier and 4 JBL SoundPower SP215-6™ speakers were used to form a background noise system. A TDT RP2.1™ real time processor and a TDT PA5™ programmable attenuator were used to create Detection test signals. A Beltone audiometer 114™ and a Sony CD player were used to play modulated test signals for the QuickSIN™ test. A PC with Windows 7 and LabView™ (2013 version) and MatLab™ (2013 Version) was used to run the detection test program, R/I test program and Localization test program.

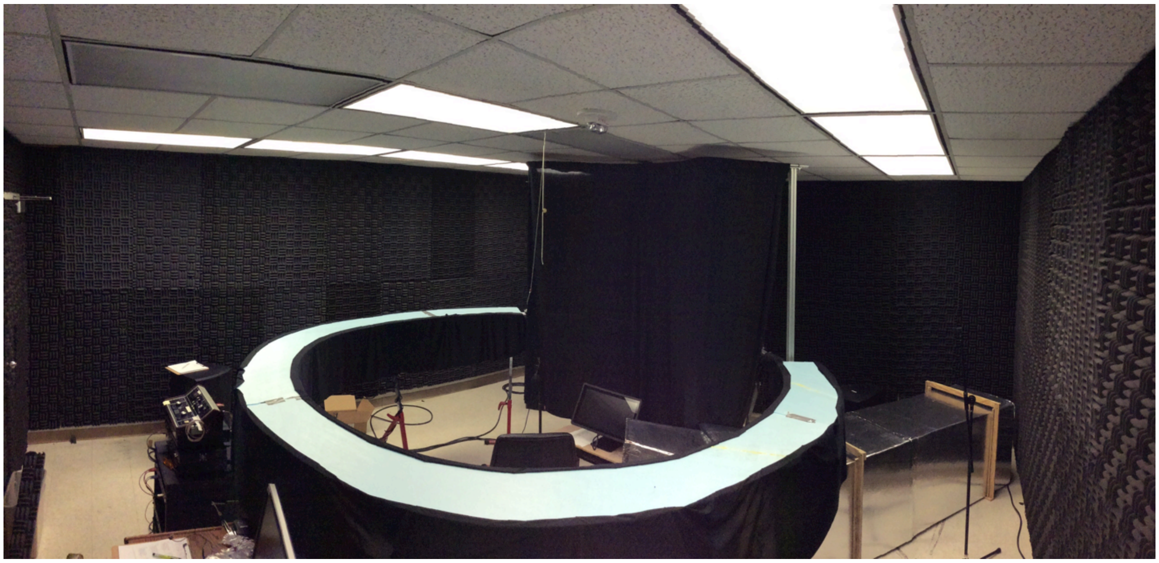

Figure 3. Overall photograph of the VT-ASL DRILCOM test apparatus located in the hemi-anechoic test room (wind generator and tunnel shown at right is not part of DRILCOM test battery, but was added as an additional condition over and above the DRILCOM experiment to explore the importance of wind effects).

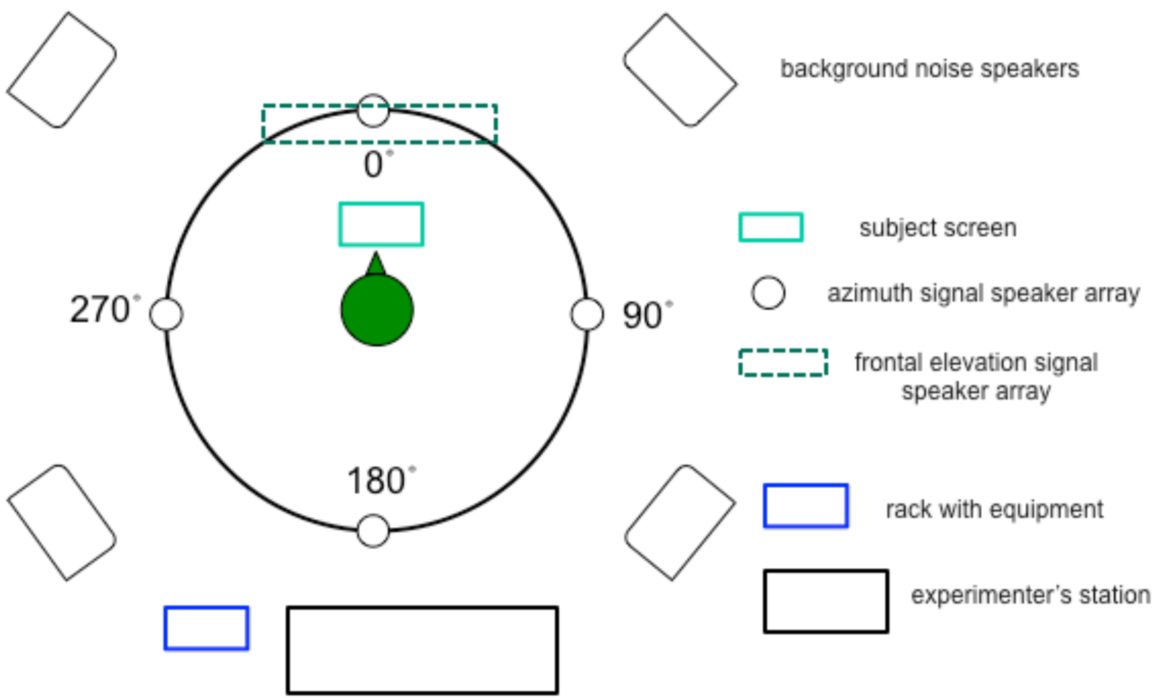

Figure 4.Schematic of the VT-ASL DRILCOM test apparatus.

Figure 5. Photograph of frontal elevation speaker array without curtain concealment cover, in the VT-ASL DRILCOM test apparatus.

3.2 Test 1: Detection (D)

The **D** test is designed to measure the detectability aspect of ASA (i.e., sensation threshold at detection), which is the first ASA subtask component that has to be accomplished before any other auditory processing can take place. It measures the detection capability by the subject with seven 1/3-octave band signals and two broadband signals. These signals are presented from four speakers located at the front (0-degrees or 12-o'clock), right (90-degrees or 3-o'clock), left (270-degrees or 9 o'clock), and rear (180-degrees or 6-o'clock)of the subject, and the dependent measure is threshold level in dB at detection. Per the SME team's suggestion, with the design of the detection test stemmed from the ANSI-standardized (ANSI, 2008) real-ear-attenuation-at-threshold (REAT) test procedure for HPDs, with substantial modifications, including: 1) addition of two military relevant broadband signals, one at the beginning and one at the end of the 1/3-octave band signals, 2) addition of background noise to mimic test environments that are similar to actual field use (both quiet room and noise-masking conditions), and 3) directional testing rather than the random incidence sound field testing that is normally applied in the standardized REAT tests per ANSI S12.6-2008.

The addition of two military-relevant broadband signals was implemented to overcome the limitation of traditional REAT tests for HPD attenuation measurements that only test individual 1/3-octave bands. The AK-47 Burst sound clip and bolt-action rifle cocking sound clip were selected, as they are both common in military combat situations and are broadband signals that are either low-frequency dominated (AK-47 Burst) and high-frequency dominated (bolt-action rifle cocking), respectively. The research team, with advice from SMEs, also wanted the Detection test to simulate actual field environments where a soldier might stand in a quiet building or rural field where it will be relatively quiet, but *not* be as quiet as an experimental REAT test room would be as required by ANSI S12.6-2008. Hence, the decision was made to introduce a pink noise of 40 dBA, which is intense enough just to exceed, in all octave bands, the building noise present in the VT-ASL hemi-anechoic test room and low enough to simulate a quiet in-field environment.

Normally, a REAT test program uses three or four loudspeakers simultaneously to create a sound field with random incidence 1/3-octave bands signals around the test subject's head. However, for this application, a new computer control program was devised. This MatLab language control program accomplishes the REAT test with both the traditional seven 1/3-octave band sounds and the aforementioned two additional military signals from one speaker at a time, enabling a directional REAT test to be conducted for the Detection task, instead of a random incidence presentation. Again, this Detection test is conducted with speakers located at the front, right, rear, and left of the subject to determine if devices perform differently with sound incident upon their exterior surfaces from different directions. Other than the addition of the two military sound signals and the highly directional speakers in the hemi-anechoic field, the Detection test runs very similar to traditional HPD REAT tests. The subject sits at the center of the azimuthal speaker ring, facing forward, and is given a response switch. The subject is asked to press and hold the switch as long as s/he can barely hear the test signal and to immediately release the switch as soon as s/he loses (can no longer hear) the signal.

The Detection test computer control program applies a Békésy tracking method to determine dB threshold levels for the seven 1/3-octave bands, the AK-47 Burst sound, and the Bolt-action rifle cocking sound. The dB step increments in the Békésy tracking method are 1 dB for the seven 1/3-octave bands and 2 dB for the two broadband sounds, with an attenuator rate of 2 dB/sec, and the measurement precision was 1 dB for the seven 1/3-octave bands and 2 dB for the two rifle sounds.

The first part of the Detection test program is a calibration program. Via prompts to the experiment through the host computer, it conducts a daily calibration of the TDT system and signal speakers by: 1) asking to measure the dB level of a 1/3 octave band with center frequency of 1,000 Hz, and 2) asking to verify the sound level of a reproduced 1,000 Hz 1/3 octave band. The experimenter is required to measure a 30 sec Leq with a 1/8-second time constant for this procedure. This program produces a text file with speaker calibration results for each of the four test speakers, located at the front, right, rear and left of a subject.

The second part of the Detection test program is the main test trial control and measurement program that conducts the actual detection task protocol. The program asks the user to input information about the test, including the device under test, subject information, and any special notes. Then it reads the daily calibration file and adjusts sound outputs to each of the four directional speakers. It then presents the seven 1/3-octave bands, with center frequencies of 125, 250, 500, 1000, 2000, 4000, and 8000 Hz and the AK-47 Burst and the Bolt-action rifle cocking sound. The program starts at low (sub-threshold) sound levels and increases the volume until a subject presses the response switch indicating that s/he can hear the sound. The program then reverses, starting to decrease the sound level until the subject releases the switch indicating that s/he has lost the signal. Once the switch is released, the program again reverses and starts to increase the sound level again. The program tracks through six reversals, excluding the first reversal, before it calculates the threshold level by averaging the peak and valley values for six acceptable reversals. Thus, the program performs the Békésy tracking method to determine the threshold level. The program repeats the tracking for all seven 1/3-octave bands and the two military-relevant gunshot and gun cocking signals. The threshold levels and test information about test subjects and devices, etc. are recorded in a results file by the program.

The experimenter's test protocol list used for a Detection test session is listed in Appendix A. Figure 6 shows the relative positions of various components of the Detection test apparatus.

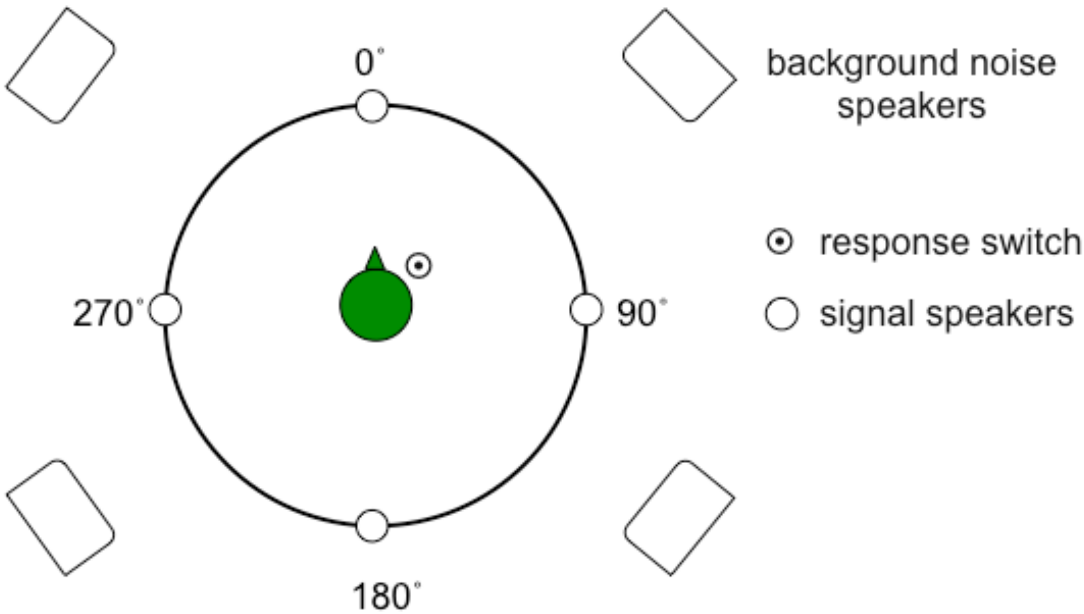

Figure 6. Schematic of test apparatus for Detection test.

3.3 Test 2: Recognition/Identification (R/I)

The **R/I** test is designed to measure the recognition/identification capability of a user wearing an advanced HPD or TCAPS by measuring how accurately and quickly that user can recognize/identify a target sound signal. This test is related to perception (post-sensation) of a sound which occurs after a person detects a sound, and it invokes cognitive processing of the sound. The **R/I** test consists of simple three-alternative forced-choice tests, which ask the subject to identify a target sound from three alternative sound samples that are presented. Subjects are instructed to make a decision on the target" signal among the three sounds presented, and to do so as accurately and as quickly as possible (i.e., a dual response objective, as emphasized on the subject's response screen). On each trial, the computer scores whether or not the subject correctly identifies the target sound (a binary dependent variable), and also the time required for response in seconds.

The SME team was consulted during the sound sample selection process and helped finalize the selection of the test signals. A total of 36 military-relevant sounds, such as various gunshots and military aircraft and vehicles, as well as ordinary sounds such as dog barking, were selected, and all sound clips were trimmed to three seconds in duration. The names of the entire set of sound clips are listed under Table 2. After the selections were made, the sound level of all clips were normalized to produce equal loudness levels, so that signal-to-noise ratio (SNR) could be maintained at a constant level across the set of stimuli. The SNR was controlled by changing the sound pressure level of a background pink noise which was simultaneously presented with the test signals during each trial.

The 36 test signal clips were grouped into 12 sets of three functionally-related sound clips termed "triads." An example of such a triad is a set including footstep sounds: footsteps in snow, footsteps in leaves, and footsteps in gravel -- all functionally-related but different in their sound spectra and temporal nature. Each triad remained as a single group and 12 triads were created for the test. As depicted in Figure 7, on each trial, first the subject is shown the question on the computer screen that is constructed as “Which of the following sounds is a dog barking sound?” When the subject presses the start button, the computer presents three sound clips that are each of three seconds length, and played in succession with a two-second interval between them. As soon as the third sound clip is finished playing, buttons for answer choices are shown on the computer screen (Figure 7) for the subject to make his/her selection and the computer timing clock starts. Then, the subject responds, and the computer clock stops and the response time is recorded, along with the correctness (or not) of the subject's answer.

Next, when the subject is ready for the next triad, s/he can press the start button on the screen to start the next question. A set of 10 randomly-selected triads among the 12 triads forms a test session. The test session is repeated with the triad-producing speakers located at front (12 o’clock or 0-degrees) and at right (3 o’clock or 90-degrees) side of a subject. The decision to only use two speakers instead of four or more speakers was made since the R/I test was designed to measure perception rather than detection, and perception for recognition/identification is clearly linked to cognitive processing for signal matching and recall. The SPL of test sound clips is adjusted to 70 dBA, and the background pink noise is played at three levels including 60, 70, and 80 dBA; thus, an SNR of 10, 0, and -10 is created to comprise three masking conditions. A LabView computer program was written to automate the R/I test process as much as possible. Once the experimenter enters all test conditions and adjusts the background noise via a separate CD player, the program runs a test session and records the test accuracy and response time results in a file.

The experimenter's test protocol used for the R/I test session is listed in Appendix B. Figure 8 shows the relative positions of various components of the R/I test apparatus.

Table 2. List of sound clip names used in Recognition/Identification test

Sound clip name	
Car driving by	Children playing
Diesel truck idling	Arabic being spoken
Motorcycle	English being spoken
Military tank track noise	Dog growling
Heavy truck driving in and stopping	Bell in a tower
Truck Engine’s compression "Jake Brake"	Bird singing
Helicopter passing by	Police car siren
Helicopter taking off	European emergency vehicle siren
Jet flying by	Fire truck siren and horn
Telephone ringing	AK-47 Rifle being cocked
Geiger counter	Bolt-action rifle being cocked
Vehicle’s backup alarm	Jackhammer working
Footsteps in snow	M-16 Rifle single shots
Footsteps in leaves	AK-47 Rifle burst of shots
Footsteps in gravel	Handgun (Pistol) firing with a silencer
Car horn	Semi-automatic Pistol shots
Train horn	Incoming mortar shell
Railroad crossing bell	M-60 Machine Gun burst of shots

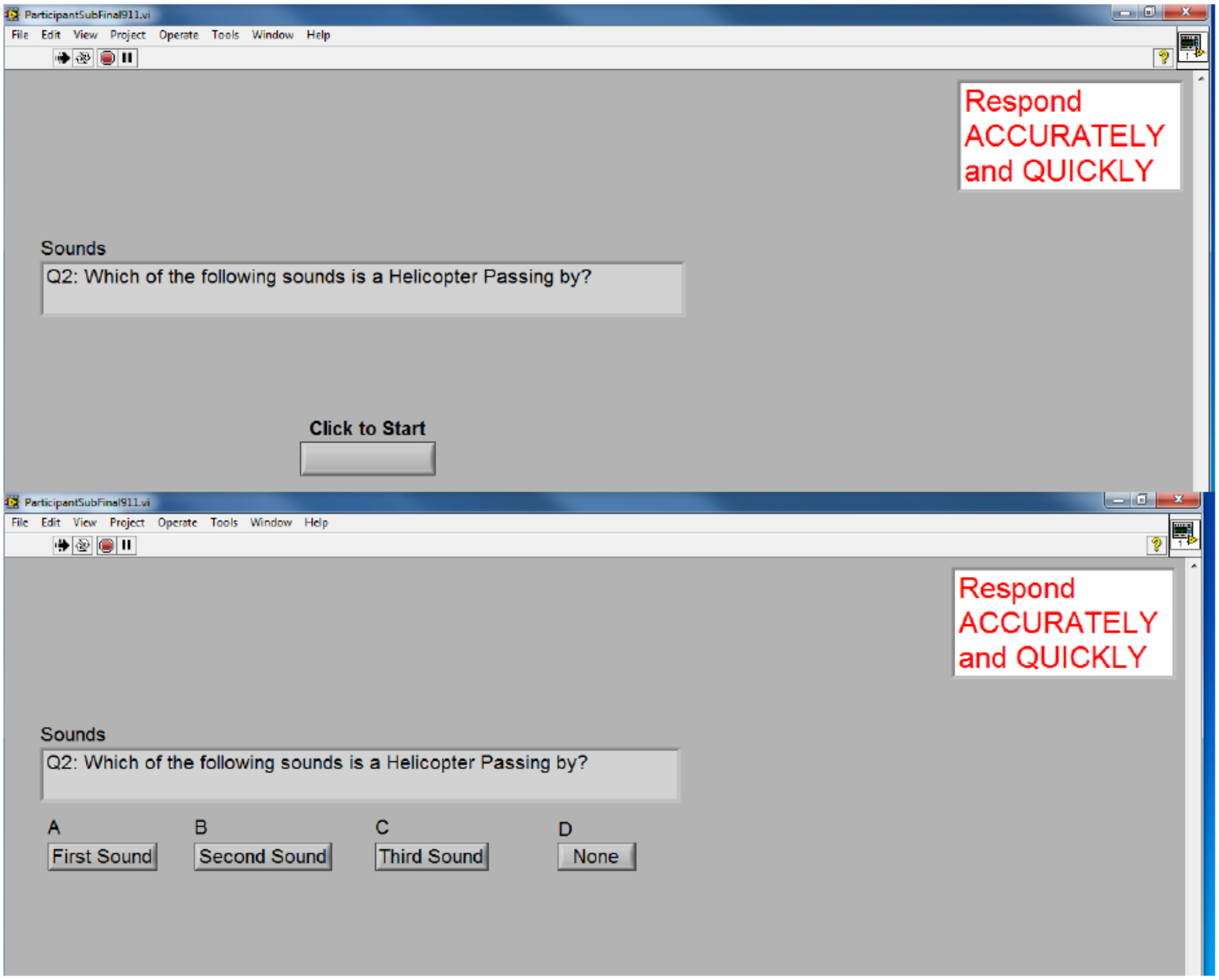

Figure 7. Two subject screens of the R/I test: Top screen is shown to the subject before a test starts; Bottom screen is shown after all three sound clips are presented and is the subject's answer screen.

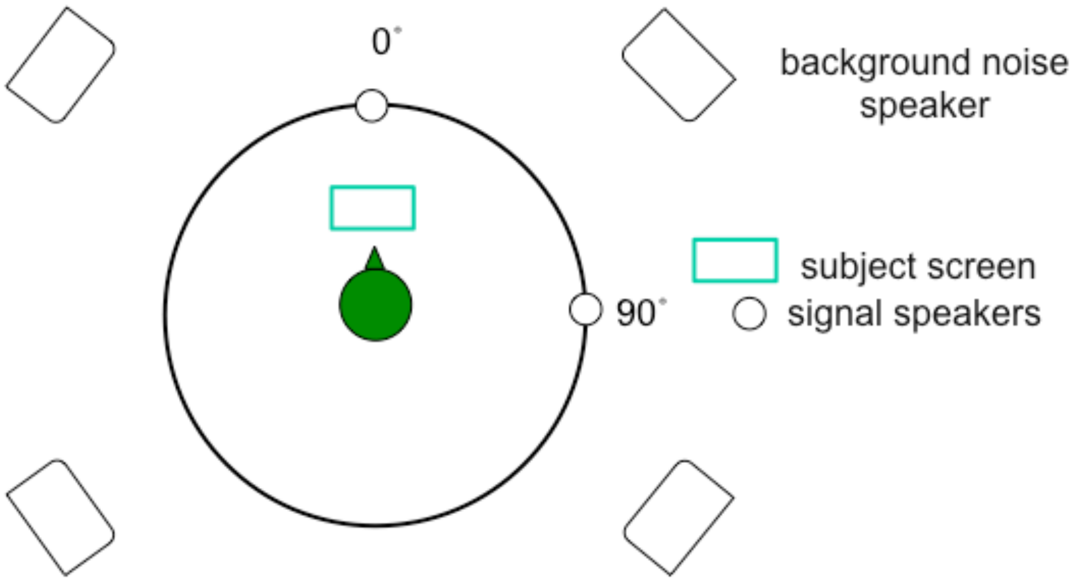

Figure 8. Schematic of test apparatus for Recognition/Identification test.

3.4 Test 3: Localization (L)

The **L** test is designed to measure how accurately and quickly a user can localize a sound signal in both azimuth and frontal elevation, while wearing an advanced HPD, TCAPS, or using open ears. The spatial localization of sound can only occur after detection of a sound is achieved, and is a very important component of auditory situation awareness because it conveys spatial orientation cues that may be critical to survival or lethality. The importance of localization to a warfighter is intuitively obvious, for locating threats as well as friendly activities or vehicles. Even in the civilian world, people often fail to maintain this ASA component, and for example, many accidents have occurred in construction sites, when a worker failed to localize a backup alarm of an approaching vehicle and was hit by the vehicle.

The L test of the DRILCOM battery is composed of two components: 1) an azimuth subtest that measures horizontal localization ability of a person in 360-degrees of azimuth, and 2) a frontal elevation subtest that measures localization ability for sounds from in front of the subject. Both the azimuth subtest and frontal elevation subtest are designed to use the same signal sounds and are controlled by the same computer program. The only difference is the location of the directional signal speakers, as well as the target speakers that include same number of dummy speakers. Figures 9 and 10 show subject screens for the azimuth and elevation subtests, respectively. On these screens, it appears to the subject that there are 24 possible target speakers for the azimuth test (Figure 9) and 12 possible target speakers for the frontal elevation test (Figure 10); however, in actuality, there are only 12 and six actual signal speakers, respectively, and the remaining targets are dummy targets. (Figures 11 and 12 depict the placement of the Localization test apparatus, including actual and dummy targets, for the azimuthal and frontal elevation setups, respectively.) This setup translates to 30-degrees separation of actual azimuth test speakers and 15-degrees separations for dummy targets in-between them. All speakers for the azimuth tests are located at the seated ear height of the subject, which is set to 1.14 meters for male/female median. The frontal elevation test speakers are located at 11, 12, and 1 o'clock azimuthal directions from the subject. The vertical elevations are achieved by actual speakers located 30-degrees above horizontal. The target speakers at the bottom row and the third row from the bottom are actual signal speakers and they are vertically separated by 30-degrees. Dummy target speakers are placed in the test screen between the first and third row and above the third row, representing 15-degree separations.

Actual subject response tasks during the L test are the same for both azimuth and elevation. Subjects are instructed to start the test by pressing the green rectangular button at the center of the response screen (Figures 9 and 10) and locate/press the button corresponding to the speaker which sounds the signal, as accurately and as quickly as possible (i.e., a dual response objective). Once the green button comes back on, the program is ready for the next trial and the subjects are told that they can start when they were ready. The use of the green button to start each test trial by the subject enables the start of the measured response time interval that contains minimal variations due to mouse travel in the subject screen, by "forcing" the start location of the mouse cursor in each test trial.

As the main focus of this Localization test is to measure spatial localization capability of a person with various devices or the open ear, the SNR is fixed to +10 (i.e., signal sound level is

10 dB higher than background noise level), even though the test provides two signal levels of low and high, corresponding to 50 dBA and 85 dBA. Background pink noise was created, adjusted to 40 dBA and 75 dBA, and recorded to a CD. The combinations of low signal level with low noise level and high signal level with high noise level maintains the +10 SNR. The Localization test was designed with two background noise levels to observe if/how each device performs differently at different incident sound pressure levels, since pass-through gain circuits across various electronic HPDs and TCAPS have widely different input-to-output characteristics and compression profiles that vary as incident sound level changes. The test signal is composed of a "dissonance chord:" a combination of pure tones that are naturally unpleasant when in combination, and hence more noticeable. Several pure tone signals whose frequencies spanned 100 – 8000 Hz (104, 295, 450, 737, 2967, 4959, 7025 and 7880 Hz) were shifted slightly in frequency to avoid the consonance that would normally occur with musical scale chording. Both low and high frequencies were incorporated to ensure that the subject had an opportunity to rely on both interaural time differences cues (below about 1000 Hz) and interaural level differences cues (above about 3000 Hz). Of course, the ability of the subject to rely on these frequencies, which were clearly part of the dissonance signal used, depends upon the advanced HPD's or TCAPS's ability to pass-through and process the spectrum of the signal faithfully. The dissonance signal was trimmed to one second in length and the system produces it at 50 dBA for the "low" test condition and 85 dBA for the "high" test condition.

The experimenter's test protocol used for a localization test session is listed in Appendix C. Again, Figures 11 and 12 show relative positions of the components of the Localization test apparatus.

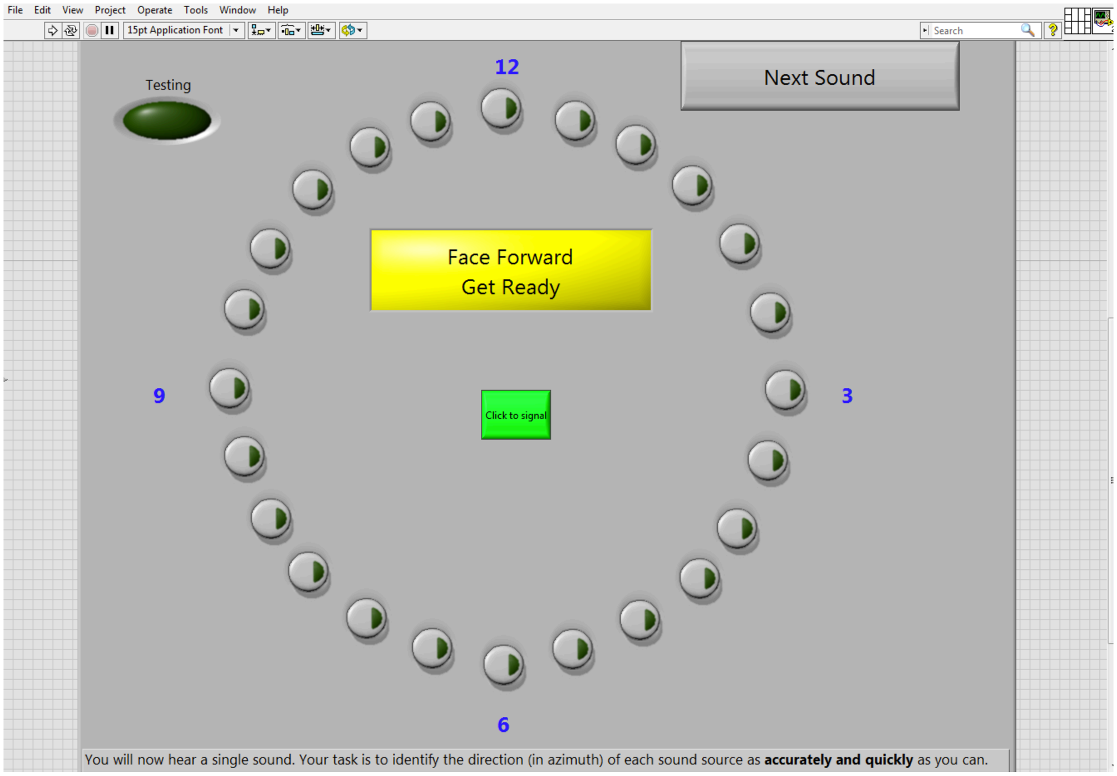

Figure 9. Subject screen for azimuth localization subtest.

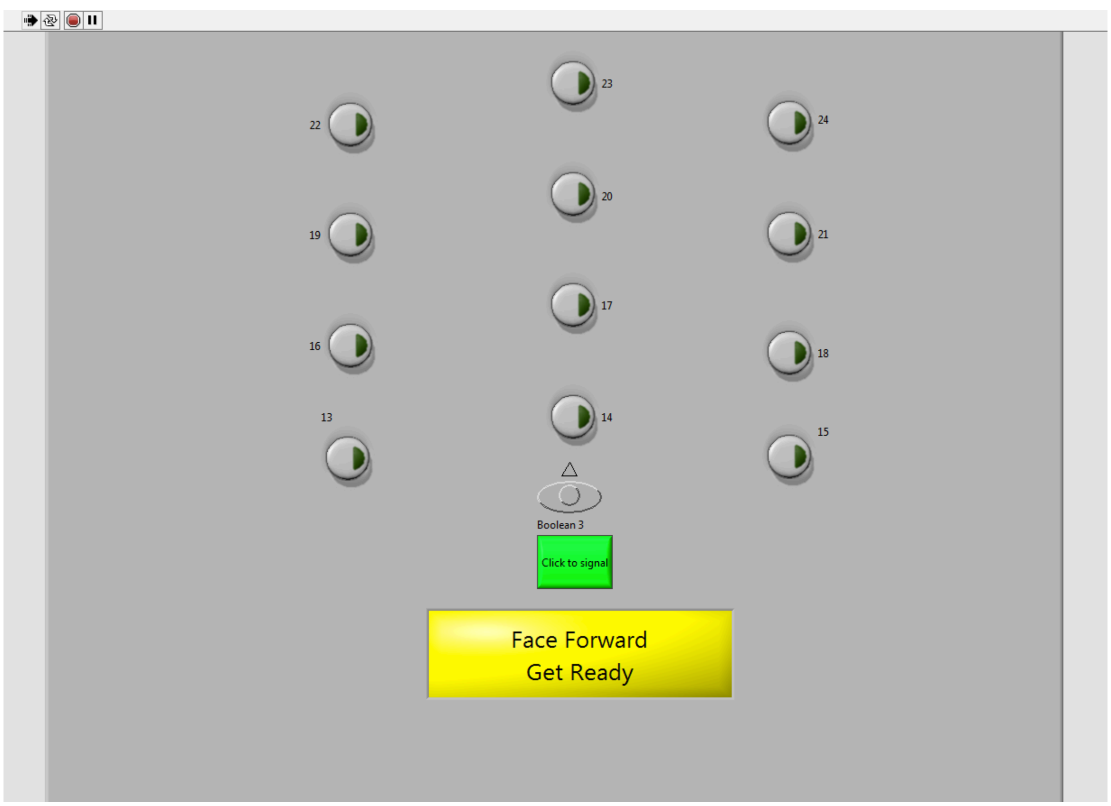

Figure 10. Subject screen for frontal elevation localization subtest.

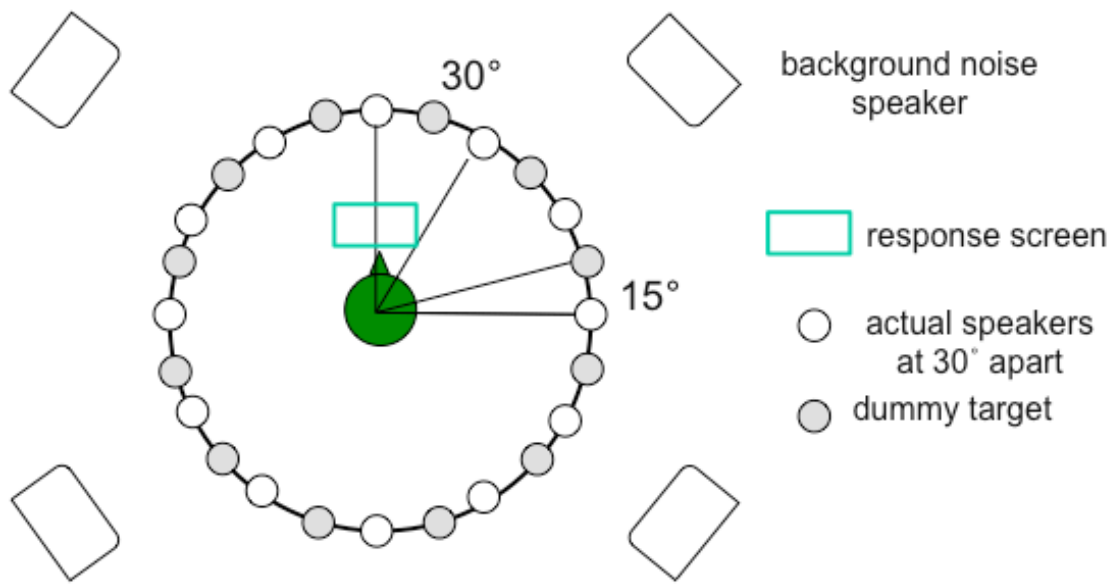

Figure 11. Schematic of test apparatus for Localization test: Azimuth subtest direction.

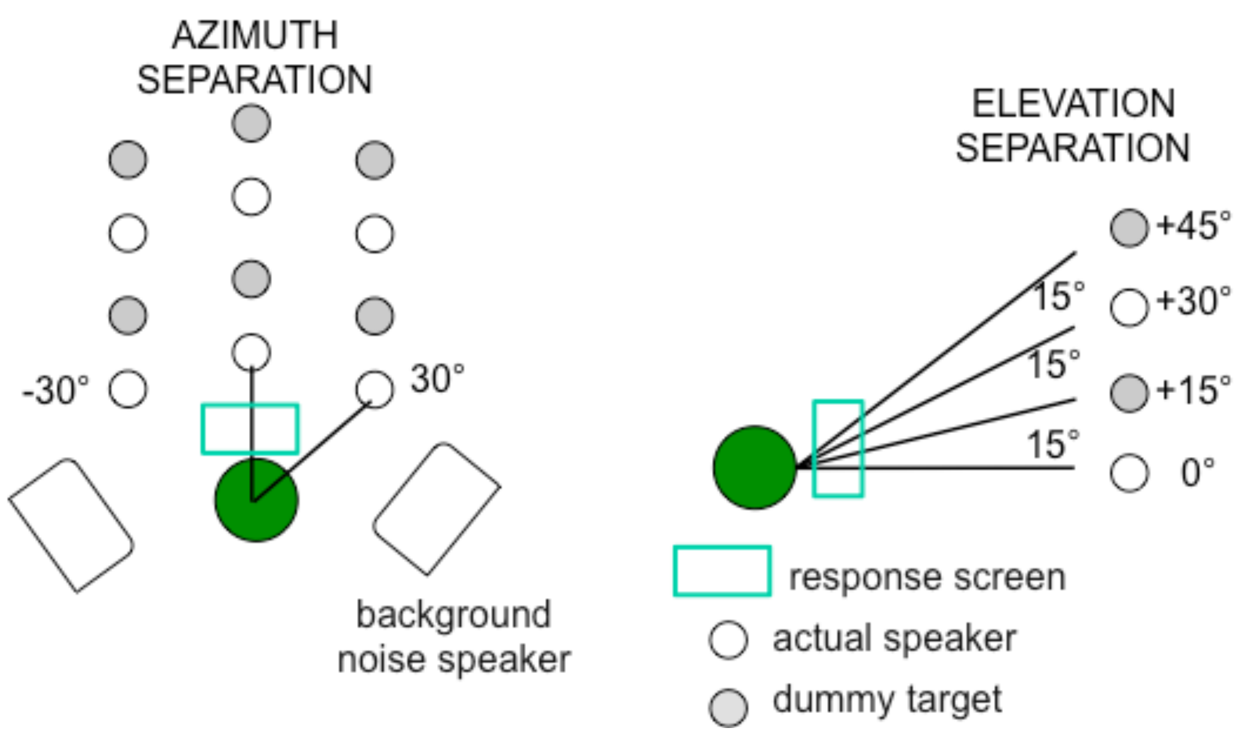

Figure 12. Schematic of test apparatus for Localization test: Frontal elevation subtest direction.

3.5 Test 4: COMmunication (COM)

The COM test is designed to measure the performance level for speech communications that is achieved via the pass-through sound transmission feature (whether it is a passive vent or an electronic microphone-amplifier-speaker circuit) of an advanced HPD or TCAPS. This test measures speech understanding achieved while the user wears a device (or when unoccluded), and listens to the spoken voice coming from outside the device. In view that there are separate military standards for testing radio communications intelligibility (e.g., MIL-STD-1472G, Sections 5.3.1.6 and 5.3.1.8.1-which references ANSI S3.2-2009; and, MIL-STD-1474E Paragraph 4.3 "Speech Communication"-which references ANSI S3.2-2009), the COM test was not designed to duplicate such a radio communications system test in a strict speech *intelligibility* scoring sense. Instead, a commercially-available speech test (QuickSIN™), which provided structured sentence test stimuli, was selected and modified. This test selection/modification was made with the objective of providing a test that has representative elements of situations where two warfighters who are wearing TCAPS or advanced HPDs are standing next to each other and attempting to converse.

For the COM test, the device under evaluation is tested in two separate gain configurations: 1) set to maximum (full on) gain, and 2) set to unity gain (defined later in Section 4.1.3 herein). Subjects are again seated in the center of the test room and instructed to fully repeat each QuickSIN™ test sentence just after the sentence is "read" to them (i.e., played through the test system, since the sentences are pre-recorded). The pre-recorded spoken sentences, together with the experiment's ambient sound condition (the pink noise was not introduced as the pre-recorded sentences included background noise), is therefore processed by the pass-through sound transmission circuit or vent of the TCAPS or advanced HPD worn by the subject. In essence, the TCAPS or HPD leaves its frequency response "imprint," which is a function of the passive acoustical barrier/vent characteristics and/or its electronic signal processing, on the test sentences before they reach the ears of the subject under the device. Figure 13 is a schematic of the relative position of a subject and the signal speakers for the COM test. As shown in the Figure, the COM test measures communication ability in four directions with respect to the subject's head center, facing-forward position: front (0-degrees or 12-o'clock), right (90-degrees or 3-

o'clock), left (270-degrees or 9 o'clock), and rear (180-degrees or 6-o'clock). A microphone is placed near the subject and s/he is told to repeat the sentences exactly as they are heard. The experimenter, sitting at the experimenter's station, listens to the subject's spoken response through a headphone, because the recording includes background noise between the pre-recorded sentences and the subjects' voices are difficult to listen to under the noise.

The QuickSIN™ SNR loss test by Etymotic (Killion et. al., 2004) was chosen for the pass-through communication performance measurement over other classic speech *intelligibility* tests (such as those in ANSI S3.2-2009, as referenced in the aforementioned MIL-STDs), based on the following reasons; 1) QuickSIN™ measures signal-to-noise (SNR) loss at different, pre-recorded SNRs, by presenting the talker's voice in quiet and in various levels of background noise, 2) QuickSIN™ was previously used by AFRL in early TCAPS testing (WHISPr report, 2008), and 3) QuickSIN™ includes its own stimulus recordings and thus does not require experimenter recordings of speech or noise, and calibration thereof. Although QuickSIN™ was designed to be administered with either headphones or produced in a sound field with speakers, it was modified for DRILCOM such that only one speaker was producing signals during each test. Thus, this created a directional QuickSIN™ test, similar to the modification that was done to the REAT test for the prior-explained DRILCOM Detection test. The reason that the COM test was performed from four different horizontal directions around the subject in azimuth is that it was of interest to determine if devices exhibited directional properties when they passed a talker's speech through the worn HPD, with this talker's speech possibly occurring from several directions about the listener's head (Figure 13). This design question was particular at issue for devices that fit deeply within the pinna and thus were affected by the funneling of the pinna, and devices that relied on external microphones that were mounted in a directional orientation, such as on the front surfaces of an earmuff.

The dependent variable that was used for the COM test was SNR Loss, which is what the QuickSIN™ is designed to measure. The SNR loss is defined by Etymotic as the dB increase in signal-to-noise ratio required by a hearing-impaired person to understand speech in noise, compared to someone with normal hearing. A normal-hearing person requires a talker to be about two dB louder than the competing background noise level for him/her to repeat 50% of keywords from the spoken sentences correctly. This indicates that *SNR-50* for normal–hearing person is 2 dB. As SNR loss is calculated as (*SNR-50* minus 2 dB), if a person scores a 10 SNR Loss it indicates that the person requires the speech to be 12 dB higher than background noise for him/her to identify 50% of the keywords.

The experimenter's test protocol used for a COMmunication test session is listed in Appendix D. Figure 13 shows the relative positions of components for the COMmunication test apparatus.

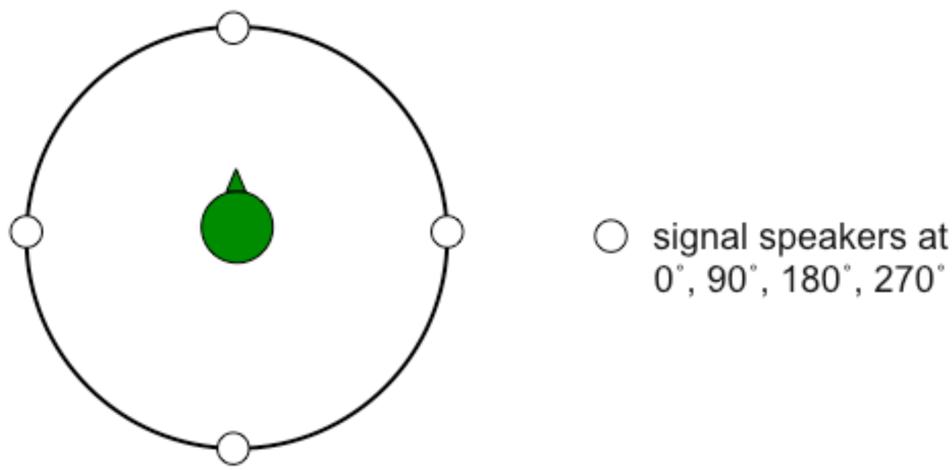

Figure 13. Schematic of test apparatus for COMmunication test.

3.6 Philosophical Questions Regarding Test Subject Pre-Training

An important question which was discussed by the research team and the SME team during the development of the test protocol was whether or not subjects should be pre-trained with the HPD or TCAPS device, prior to being tested while wearing the device. In other words, is it prudent, from a device testing standpoint, to require subjects to gain some level of experience with the device under test, perhaps even to the point of establishing an asymptotic level of performance with the device, prior to any situation awareness testing of that device? Extant research results with bearing on this question of whether pre-training has an important effect on situation awareness performance with TCAPS and augmented HPDs is scant, with the major exception of a very recent paper by Casali & Robinette (2015). They found that on an auditory azimuthal localization task, subjects performed more poorly when wearing either an Etymotic EB-15™ electronic sound-transmission earplug or a Peltor ComTac III™ electronic sound-transmission earmuff than with the open ear, *prior to training.* However, *after focused, extensive training* over 12 one-hour sessions on separate days with either device, localization performance with that device improved and was nearly equivalent to the open ear performance. Furthermore, when trained with the electronic earplug device, performance did not improve when the electronic earmuff was used, and vice-versa; this demonstrated that there was no cross-training benefit between in-the-ear and over-the-ear devices. The Casali & Robinette (2015) experiment thus served to illustrate the overall effect of training on the ability of the listener to adapt to a particular advanced HPD or TCAPS, and improve his/her performance as a result, and also that training with one device does not necessarily produce a learning benefit with a different device. So the question remained if this demonstrated training effect should be included in the test battery protocol that is the subject of this report.

The argument *for* including pre-test training with each HPD or TCAPS under test is primarily that a test battery which results in a rating or ranking of device situation awareness performance, but does not consider the effects of auditory learning with each device, may inadvertently bias military consumers against devices that would otherwise provide adequate performance *given sufficient training with the devices.* However, if it is indeed the case that the users must embark upon using and relying upon the devices in real situations *without adequate training/experience*, especially in those situations where the loss of auditory situation awareness is dangerous such as in combat operations, *then the addition of pre-test training trials to a device comparison or compliance test is contraindicated.* Furthermore, the training regimen in Casali & Robinette, which did result, post-training, in near open-ear performance levels with two very different electronic HPDs, involved approximately 12 days of intense training, one hour per day -- and this was with only one task element inherent in the test battery, that of localization. Training on all 4 tasks of the DRILCOM test battery with a given device would require much more time. Such a training regimen may be too time-consuming to implement in a product test battery, and it remains an open question as to whether it is reliably feasible for actual warfighters to gain such extensive training prior to deployment with a given device. Thus, one argument is that any training during the testing protocols for devices *should reflect the actual training to be received by the end users,* prior to use in hazardous situations. However, this begs the question as to whether there is strong evidence that warfighters are being adequately trained with their advanced HPDs and TCAPS, or more so that they will trained to an asymptotic performance level, prior to actual dependence upon the devices in combat situations. Lacking hard evidence on this question of whether warfighters actually receive adequate TCAPS training, coupled with the aforementioned other unanswered issues, it was decided that extensive training with the device to be tested was more inadvisable than not prior to implementation of the DRILCOM test battery, at least for its proof-of-concept experiment detailed later herein. Finally, it is important to note that any test battery should help motivate HPD and TCAPS designers to endeavor to develop devices which deliver auditory performance that is as close to open-ear performance as possible, without placing a burden on training the user prior to device usage. The importance of this objective cannot be overstated.

Of course, the DRILCOM test protocol consists of the four separate auditory task elements, and a researcher/tester could certainly decide whether or not to train subjects with the devices under test, prior to implementation of each individual task test of the test battery. It is important to note that the test battery discussed herein can thus be implemented *with or without pre-training* of the subject prior to device testing.

4. DRILCOM "Proof of Concept" Experiment

4.1 Overall Experimental Design and Objectives

A rather extensive "proof of concept" experiment was designed and conducted using the DRILCOM test battery, comprising a "sub-experiment" on each DRILCOM test. The purposes of this experiment were to: 1) to try out the test battery, both hardware and software, to evaluate its operational reliability and functionality, 2) to determine the time required to conduct a DRILCOM evaluation on a per-device basis, 3) to determine if the DRILCOM test stimuli and test protocols were capable of distinguishing amongst various HPDs/TCAPS as to their performance on the four tasks of auditory situation awareness, in a statistically-significant manner which indicates test sensitivity, and 4) to determine if the DRILCOM test stimuli and test protocols were capable of distinguishing differences between open ear performance and performance with various HPDs/TCAPS on the four tasks of auditory situation awareness, for the purpose of quantifying device performance in terms of "percent better/worse than open ear." Obviously, purposes 3 and 4 are of very high importance to the viability and application efficacy of DRILCOM. Each sub-experiment was a full-factorial, within-subject design. Originally, it was desired that the full experiment would be within-subject (i.e., a common group of 10 subjects) across all four sub-experiments, but due to the very long span of thousands of experimental trials and the occasional attrition of subjects, each of the four DRILCOM sub-experiments was conducted separately, and all subjects within a given test were exposed to all experimental conditions for that particular test. However, approximately half of the subjects completed all four sub-experiments, and half of the subjects completed at least two of the four sub-experiments.

4.1.1 Test Subjects

Per recommendation of the SMEs, the gender ratio of male to female subjects was decided as 8:2 to mimic that of the current U.S. military enlisted population. College students with U.S. citizenships were recruited and vetted by the Virginia Tech Office of Export and Secure Research Compliance before serving in the DRILCOM tests; this security measure was invoked for ITAR compliance since some of the TCAPS devices are export-controlled. Pure-tone audiogram tests using a Beltone 114 audiometer were conducted, and subjects with hearing levels of 25 dBHL or better at all test frequencies (125, 250, 500, 1000, 2000, 4000, and 8000 Hz) in *both* ears were allowed to participate. All subjects were interviewed to ensure that they had no more than five hours with any type of HPD usage within the previous six months, and no military experience requiring auditory situation awareness of the types being tested. Furthermore, subjects were checked with an otoscope to ensure no ear canal blockage or lesions. The total of 10 participants (two female and eight male) with mean ages of 21.4 years, participated in the Localization sub-experiment. Very similar groups of subjects participated in the other three DRILCOM sub-experiments, and in all four tests, the same gender ratio and hearing level requirements were met.

4.1.2 Protection of Human Subjects

None of the protocols of the four DRILCOM tests imposes "more than minimal risk" to the subjects, and this fact thus held true for the proof-of-concept experiment's protocols on all four sub-experiments. Subjects wore military-issue TCAPS and HPDs, and also listened with their open ears. While masking noise is presented in some conditions of DRILCOM, at no time is the noise exposure together with test signal or communication levels exceeding the 85 dBA time-weighted 8-hour average "Action" level as mandated by OSHA (CFR, 1983) for U.S. workers in industry. In comparison to the OSHA-regulated limits, the masking noise conditions used in DRILCOM are of much shorter duration and with no significant impulsive characteristics. For the proof-of-concept experiment, all aspects of human subject recruitment, scheduling, informed consent, testing, debriefing, and compensation were documented and submitted to the Virginia Tech IRB for Human Subjects, and to the US Army Medical Research and Materiel Command (USAMRMC), Office of Research Protections (ORP), Human Research Protection Office (HRPO). Approval from both VT IRB and the USAMRMC ORP HRPO were obtained prior to the start of human subject testing.

4.1.2 Test Devices: Advanced HPDs and TCAPS

The sample of advanced HPD and TCAPS devices for the proof-of-concept experiment was chosen with help of the SME team to reflect the most relevant and current military devices at the time of the experiment. These particular devices also span various types and styles of products used, circa 2015, by various branches of the U.S. military in applications where auditory situation awareness is needed. Therefore, they represent a spectrum of products that would typically be tested by the DRILCOM battery, or any test devoted to situation awareness performance evaluation. The final selection of devices for the experiment included the following: INVISIO X50™, Nacre-Honeywell Quiet PRO+™, Peltor ComTac III™, 3M Combat Arms™ fourth generation (i.e., rocker-style, single-ended) earplug, and Etymotic EB15LE™ electronic earplug. All devices are electronic systems except Combat Arms™, which is a passive device and the current "standard-issue" U.S. Army hearing protector. All devices were tested under two electronic gain settings with the exception of the Combat Arms™ earplug, which was tested under its "open" or controlled resistance pass-through vent condition only. Also, as mentioned earlier, an "open ear" (i.e., unoccluded with no device) hearing condition was included in all four DRILCOM tests as a control test condition.

In each of the four DRILCOM sub-experiments, the presentation order of the 10 hearing conditions (including open ear) was counterbalanced to avoid ordering effects. Ordering of all other independent variable conditions, to be discussed next, was randomized in each sub-experiment.

4.1.3 Unity Gain Setting

The unity gain setting was defined as the setting where gain of the system is transparent to the user, that is, the gain setting at which the achieved passive attenuation of the protector is offset (i.e., compensated by) by the electronic amplification of the pass-through circuit. The unity gain setting was determined by measurement of the SPL in the ear canal while underneath the protector, and adjusting that SPL such that it equals the SPL measured in the ear canal without the protector in place.

The experimental measurement protocol for determining unity gain was as follows:

1. Record product name, serial number, brand, and other information.
2. Take photographs of the device.
3. Review the device instruction manual for gain setting control and possible settings.
4. Set up the reverberation test room with 80 dBA pink noise.
5. Measure pink noise of the system inside the ear canal of KEMAR manikin without the device: dBA, 10 sec Leq, fast time constant.
6. Measure pink noise of the system inside the ear canal of KEMAR manikin the device with each gain setting. In case of the EB15LE™ which has a binary gain control, low gain setting was defined as "unity" gain setting.
7. Repeat Steps 5 and 6 twice for each gain setting.
8. Transfer measurement data to PC for analysis.
9. Get average passive insertion loss for the device by subtracting 6 from 5.
10. Determine the unity gain setting as the setting with the value from step 9 closest to zero.

Following the above protocol, unity gain settings of the tested devices were determined to be as follows: INVISIO X50™ - gain level 5; Nacre Quiet Pro+™ – gain level 6; Peltor ComTac III™ – gain level 3; Etymotic EB15LE™ – low gain level (of the binary settings of low and high). The maximum gain setting was the highest gain position achievable on each device, and this included the high binary switch position on the EB15LE™.

4.1.4 Experimental Design for each DRILCOM Test

As mentioned above, the proof-of-concept sub-experiments on each of the four DRILCOM tests were conducted as 10-subject, within-subject experiments with two females and eight males in each. Also, all four sub-experiments were conducted with the same 10 hearing conditions: open ear, Combat Arms™ earplugs in open setting, INVISIO X50™ at unity and maximum gain setting, Quiet Pro+™ at unity and maximum gain setting, Peltor ComTac III™ at unity and maximum gain setting, and Etymotic EB15LE™ at low (unity) and high (maximum) setting.

The Detection sub-experiment was conducted as a three-factor, 9x4x10, within-subject design. The first 9-level factor is test signal, consisting of the seven standard REAT test sounds (1/3-octave bands with center frequencies of 125, 250, 500, 1000, 2000, 4000, and 8000), and the two previously-described military relevant sounds, AK-47 Burst and bolt-action rifle cocking, were used. The second 4-level factor is speaker location: 0-degrees, 90-degrees, 180-degrees, and 270-degrees, with 0-degrees located at the 12 o'clock position, directly in front of the subject. In clockwise fashion, the other three locations are to the right, behind, and left of a subject. The third 10-level factor is the 10 aforementioned hearing conditions, consisting of unity and maximum gain on each electronic product, the open setting of the Combat Arms™ earplug, and open ear. Figure 14 is a block diagram of instrumentation for the Detection test.

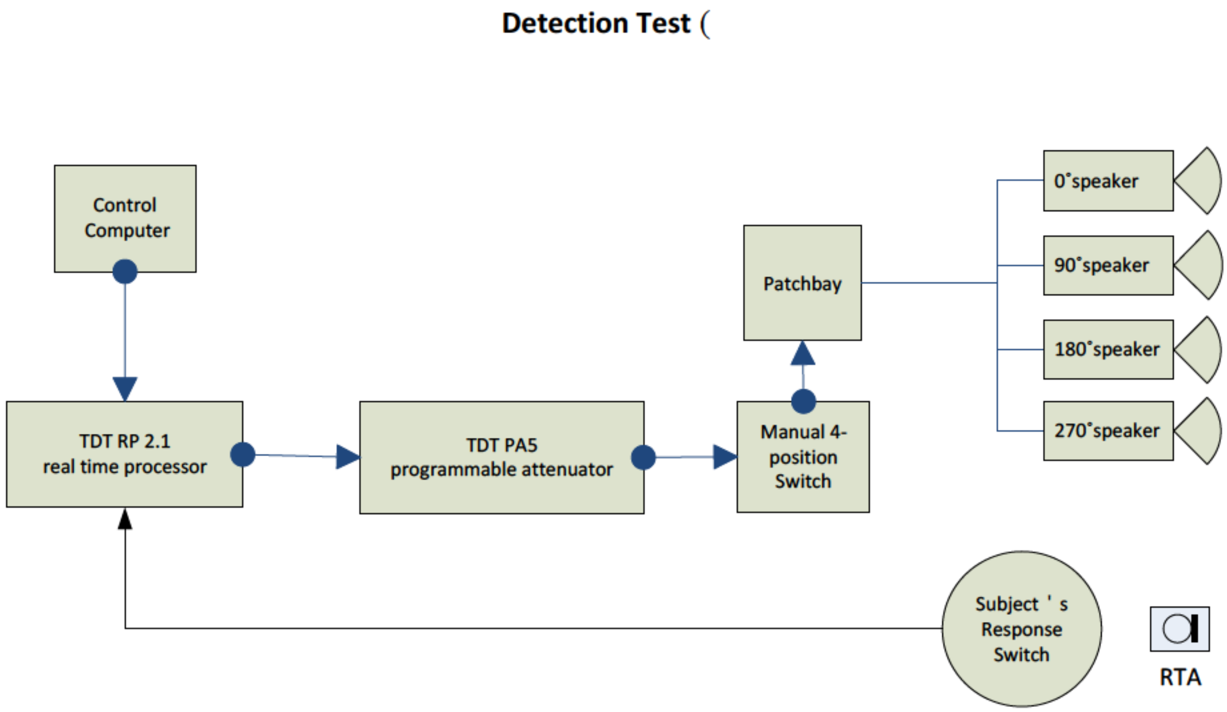

Figure 14. Network block diagram of instrumentation for the Detection test.

The <u>Recognition/Identification</u> sub-experiment was conducted as a four-factor,3x2x10x3, within-subject design. The first 3-level factor is SNR, including levels of: -10, 0, +10. As previously described, these SNR levels are achieved by fixing the signal sound level at 70 dBA, while varying background pink noise to 60, 70, and 80 dBA. The second 2-level factor is speaker location, 0-degrees and 90-degrees, located directly in front of a subject and at the right side of a subject, respectively. The third 10-level factor consists of the 10 hearing condition levels, as prior described under the Detection sub-experiment. The fourth 3-level factor in the experiment is wind speed, which represents an additional factor that was exploratory, over and above the DRILCOM test battery (i.e., it is, at this point, not a formal part of the DRILCOM battery). Even though wind speed is not part of standard DRILCOM battery, it was added to the proof-of-concept experiment to investigate potential additional test conditions that could easily incorporated into DRILCOM without requiring a full redesign of the entire test battery. The effect of wind on the performance of subjects wearing TCAPS or advanced HPDs, in particular Recognition/Identification and pass-through Communication, was investigated as an add-on to this proof-of-concept experiment. The three levels of constant wind velocity are: 0, 5, and 10 mph. Figure 15 shows a network block diagram of instrumentation for the R/I test.

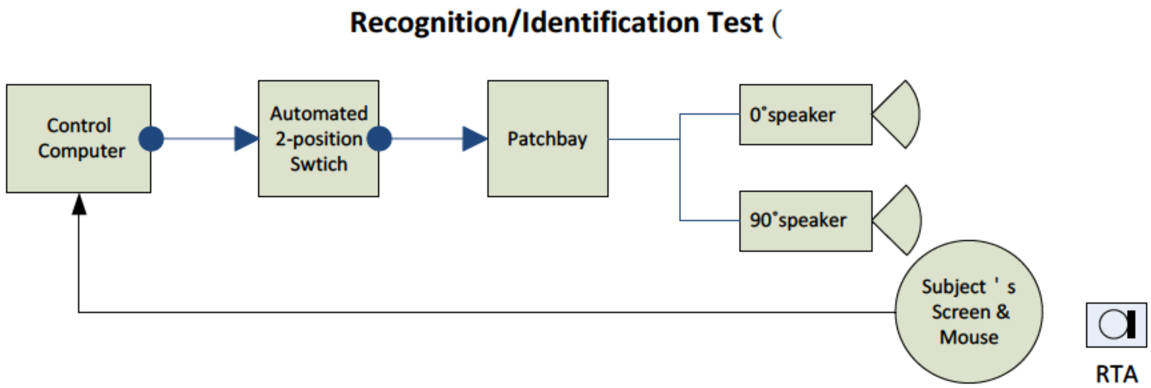

Figure 15. Network block diagram of instrumentation for the Recognition/Identification test.

The Localization sub-experiment was conducted as a three-factor, 2x2x10, within-subject design. The first 2-level factor is test direction: azimuth and frontal elevation, as previously described in Section 3.4. In the azimuth subtest, 12 signal speakers are in a 360-degrees ring with 30-degrees separation at the ear height of test subjects. In the frontal elevation subtest, six speakers in two rows are directly in front of the test subject. The first row is at the subject's ear height and the second row is 30-degrees above. The second 2-level factor is the test signal sound pressure levels, either low (50 dBA) or high (85 dBA). As described earlier, in the Localization test, SNR is kept at constant +10 by changing background pink noise levels to 40 dBA and 75 dBA. The third 10-level factor is the 10 aforementioned hearing conditions. Figure 16 shows the network block diagram of instrumentation for the localization test.

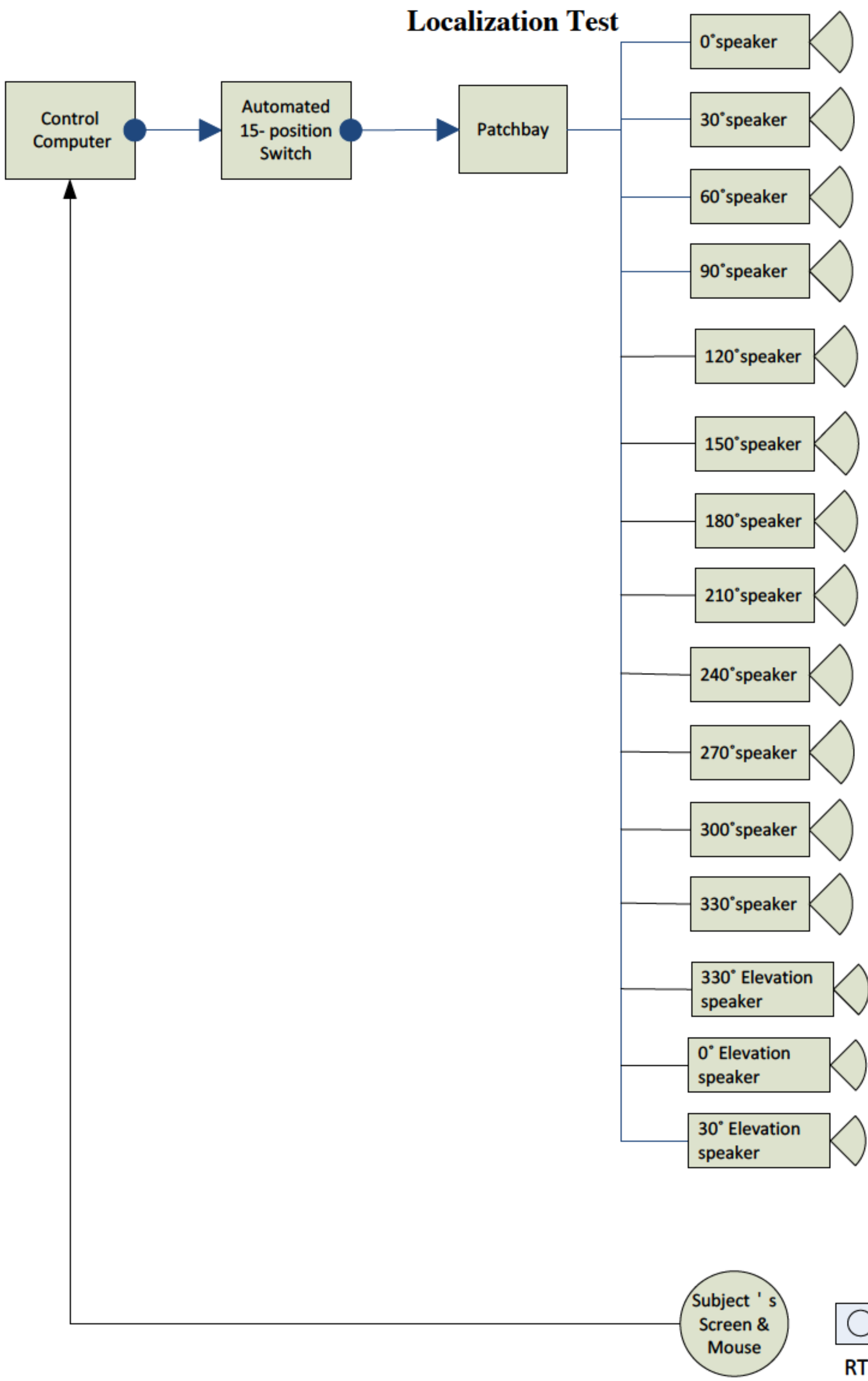

Figure 16. Network block diagram of instrumentation for the Localization test.

The COMmunication sub-experiment was conducted as a three-factor, 4x10x3, within-subject design. The first 4-level factor is test direction, with four levels at 0-degrees, 90-degrees, 180-degrees, and 270-degrees, the same as described above under the Detection experiment. The second 10-level factor consists of the 10 hearing condition. The third 3-level factor is wind speed, as earlier explained under the Recognition/Identification experiment section. Figure 17 shows the network block diagram of instrumentation for the COMmunication test.

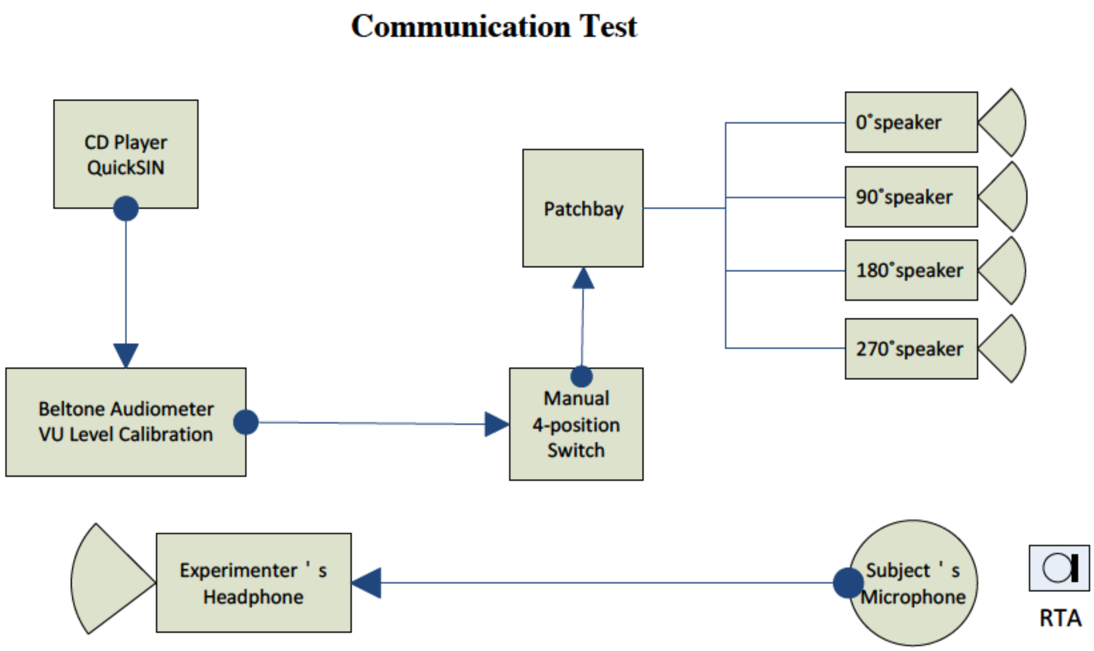

Figure 17. Network block diagram of instrumentation for the COMmunication test.

4.2 Statistical Analysis and Results

In each of the four individual sub-experiments, one per DRILCOM test, the mean data were first reduced from the raw data values, and the data were then analyzed for statistically-significant differences at a $p<0.10$ level. Given that this experiment was a proof-of-concept effort to primarily ascertain whether the DRILCOM tests were *sensitive* to inter-device auditory situation awareness (ASA) performance differences, as well as ASA differences between devices and the open ear, it was deemed a priori that significance would be achieved if the mean values differed at a significance level of $p<0.10$, rather than the more traditional $p<0.05$ that is often applied to highly-controlled parametric experiments. Tukey's Honest Significant Difference (HSD) test, using an alpha value of 0.10 was conducted to determine if there were significant differences among hearing conditions (TCAPS, HPDs, and open ear) at each level of each of the other independent variables discussed previously. On each Tukey's HSD test, a classical post hoc, multiple-comparisons test based on the studentized range *(q)* distribution, is also amenable to a priori application, as done in this experiment. It has the conservative advantage that it controls Type 1 statistical error by controlling experiment-wise error rate by taking into account the mean square error of the effect being tested. Tukey's HSD test was consistently applied to all test results from each the four DRILCOM experiments, and the results are included in the Appendices E, F, G, and H.

From the data analysis, graphs of selected test results were chosen for presentation herein; thus, the graphed data represents only a partial subset of the data obtained in the four experiments, as there are simply too many individual graphs to cover the whole DRILCOM experiment's data set. For example, there would be 36 plots for the detection sub-experiment alone. Because one major purpose of this proof-of-concept experiment was to show that the DRILCOM test battery has sufficient sensitivity to show performance differences among different devices and between devices and the open ear, only a representative subset of the whole data set is needed for demonstration of this sensitivity, and these graphs are shown in text as Figures 18 - 44. However, for each of the four DRILCOM sub-experiments, the entire set of test results are included in tabular format in Appendices E-H to this report, one Appendix per DRILCOM test. These data tables in the Appendices include, for each combination of experimental conditions: mean values, 90% confidence limits, and statistically-significant differences (by the presence of different alphabet letter coding on means) at $p<0.10$.

Herein, in each of the ensuing data graphs, the Y (vertical) axis of the plot represents the 10-levels of hearing condition previously described, and the X (horizontal) axis represents various measurements obtained, depending on the accuracy, time, or SNR metrics specific to each DRILCOM test. Also, in each graph, different alphabet letters represent statistically-significant differences, i.e., the mean values are not significantly different at $p<0.10$ if they contain any of the same letters. For example, A and B represent statistically different means, while A and AB indicate a difference that is not statistically-significant at $p<0.10$.

4.2.1 Detection Test Results

Below are partial test results from the Detection test sub-experiment. The sample from the full data set in Appendix E includes test results from test signals of a 1/3-octave band of pink noise centered at 125 Hz, AK-47 Burst, and bolt-action rifle cocking sound. As described earlier, the latter two sounds are broadband sounds that VT-ASL added to the standard 1/3-octave band REAT testing signals, since they are both military-relevant sounds and are comprised of several octaves of sound, unlike the seven REAT 1/3-octaves. Figures 18 - 21 are graphs of test results from the 125 Hz 1/3-octave band signal at each of the four speaker locations. Figures 22 - 25 are the plots of test results with the M16 gunshots, and Figures 26 - 29 are the plots with the bolt-action rifle cocking sounds being detected. In view that the dependent measure of the detection test is the (threshold dB level under the device minus the threshold dB level of the open ear), smaller values represent better device performance for signal detection. Figure 18 shows that various TCAPS and advanced HPDs devices perform differently, and are statistically-different in many cases, with a 125 Hz-centered 1/3-octave band signal from the speaker at a 3 o'clock direction. The remaining Figures 19 - 29 demonstrate that a 125 Hz-centered 1/3-octave band signal from different speaker locations, as well as the two broadband signals, produce different results across devices and the open ear. While not all hearing conditions are statistically different from each other, their performances are ranked in the graph from best (top) to worst (bottom) and it is evident that the DRILCOM Detection test was indeed quite sensitive to device and open ear performance differences.

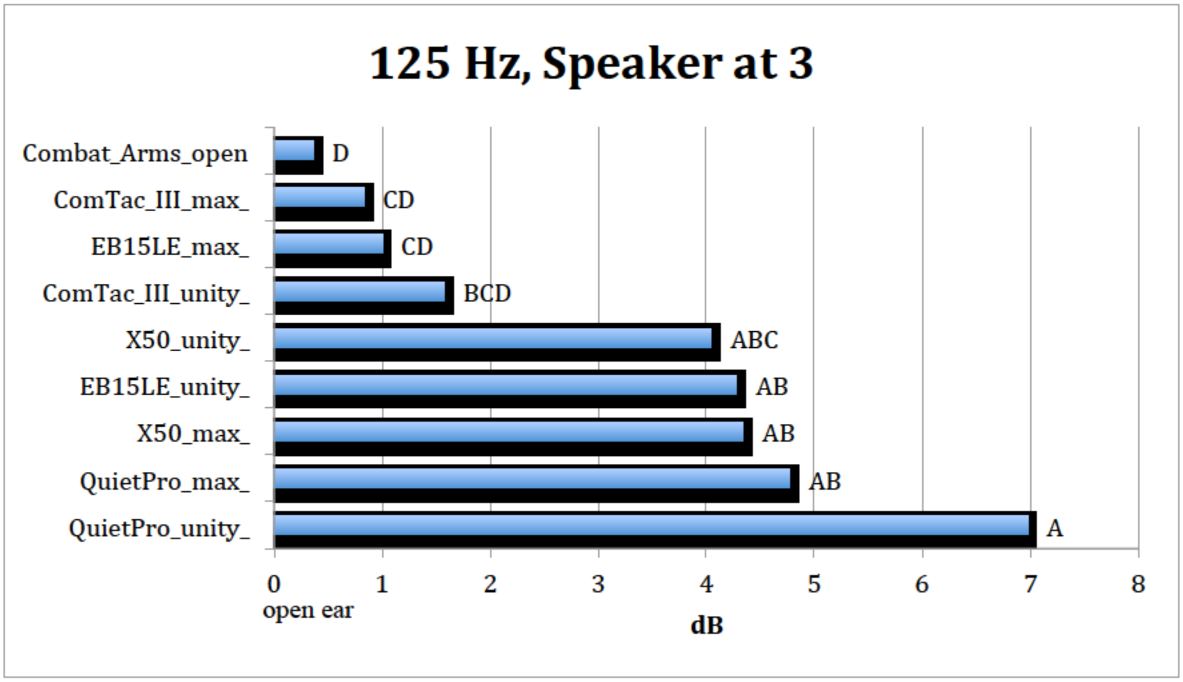

Figure 18. Detection test result for 125 Hz-centered 1/3-octave band signal from the speaker located at 3 o'clock. X-axis measure is the dB amount by which the performance with the device is worse than the open ear threshold level in dB. (Means with different letters are significantly different at $p<0.10$.) The score computed for each device is the dB difference between threshold level of detection with the device and with the open ear, per the REAT protocol (see text). Thus, for the graph, the open ear score is represented by 0 dB.

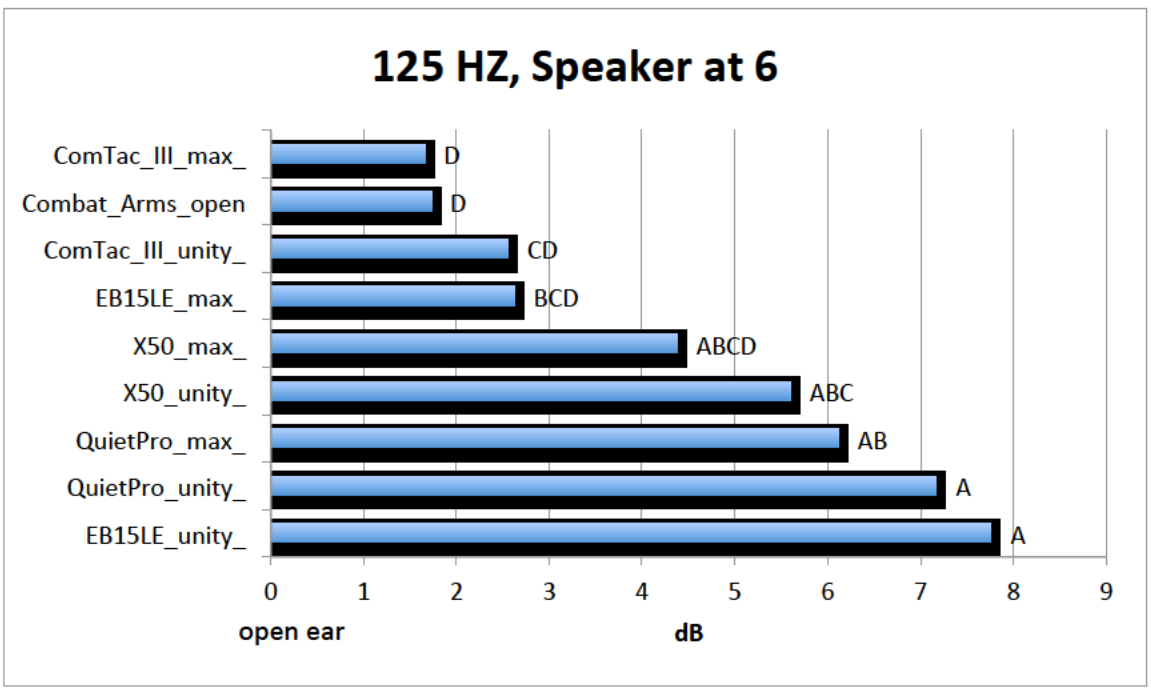

Figure 19. Detection test result for 125 Hz-centered 1/3-octave band signal from the speaker located at 6 o'clock. X-axis measure is the dB amount by which the performance with the device is worse than the open ear threshold level in dB. (Means with different letters are significantly different at $p<0.10$.) The score computed for each device is the dB difference between threshold level of detection with the device and with the open ear, per the REAT protocol (see text). Thus, for the graph, the open ear score is represented by 0 dB.

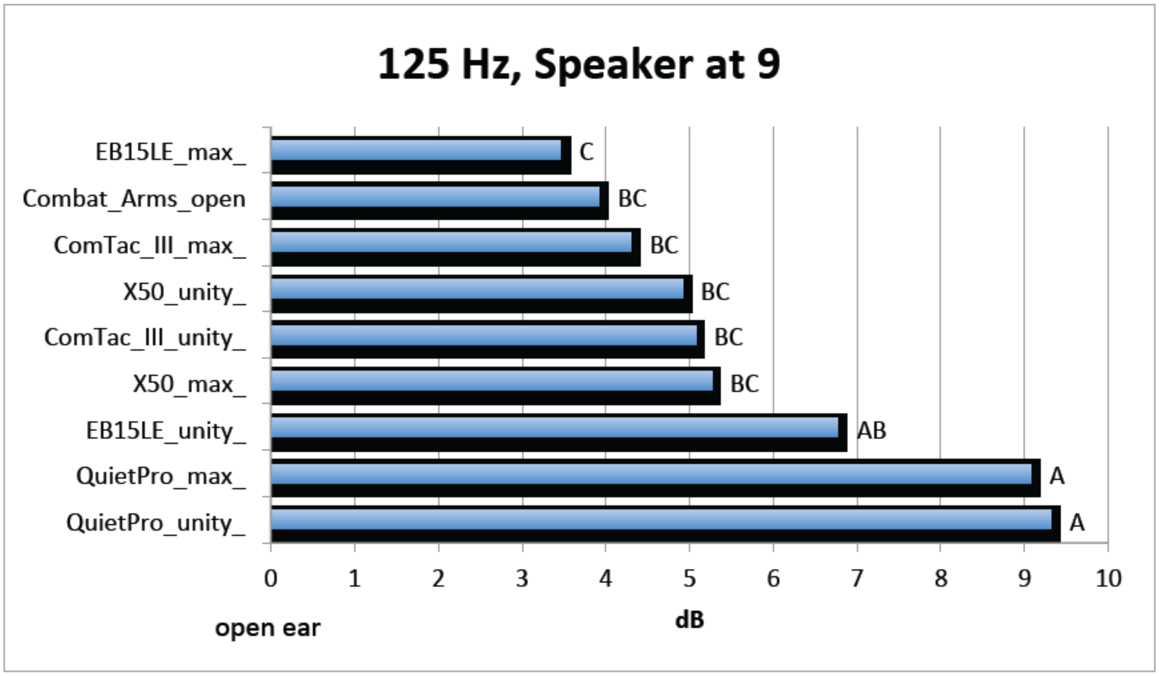

Figure 20. Detection test result for 125 Hz-centered 1/3-octave band signal from the speaker located at 9 o'clock. X-axis measure is the dB amount by which the performance with the device is worse than the open ear threshold level in dB. (Means with different letters are significantly different at $p<0.10$.) The score computed for each device is the dB difference between threshold level of detection with the device and with the open ear, per the REAT protocol (see text). Thus, for the graph, the open ear score is represented by 0 dB.

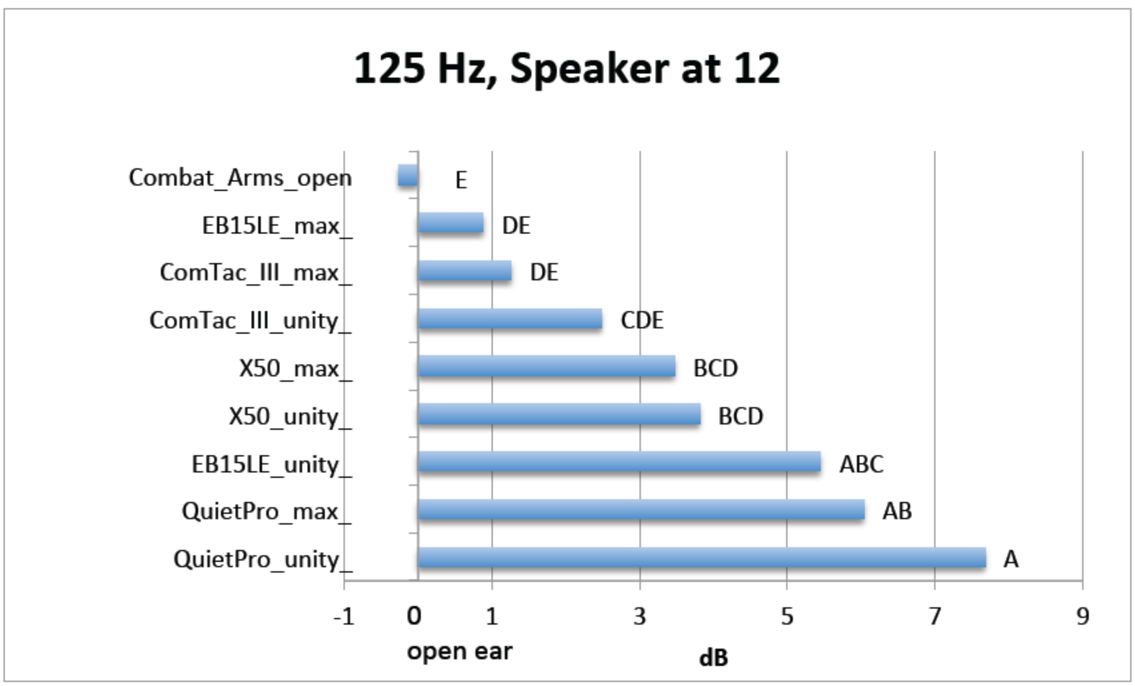

Figure 21. Detection test result for 125 Hz-centered 1/3-octave band signal from the speaker located at 12 o'clock. X-axis measure is the dB amount by which the performance with the device is worse than the open ear threshold level in dB. (Means with different letters are significantly different at $p<0.10$.) The score computed for each device is the dB difference between threshold level of detection with the device and with the open ear, per the REAT protocol (see text). Thus, for the graph, the open ear score is represented by 0 dB.

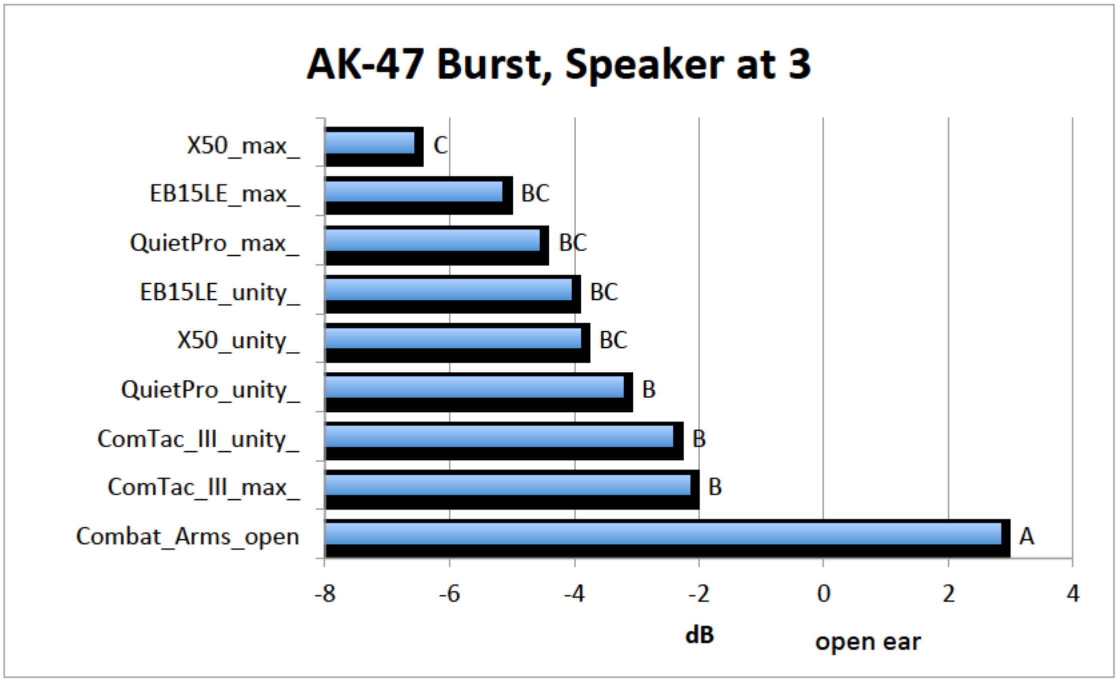

Figure 22. Detection test result for AK-47 Burst sound from the speaker located at 3 o'clock. X-axis measure is the dB amount by which the performance with the device is worse than the open ear threshold level in dB. (Means with different letters are significantly different at $p<0.10$.) The score computed for each device is the dB difference between threshold level of detection with the device and with the open ear, per the REAT protocol (see text). Thus, for the graph, the open ear score is represented by 0 dB.

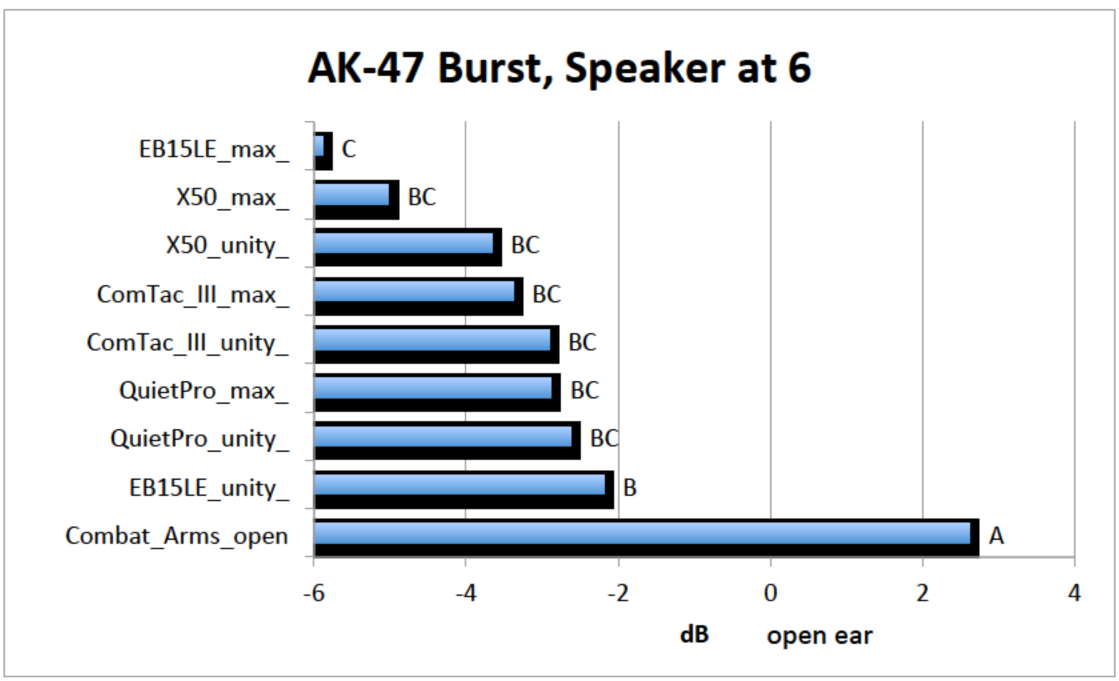

Figure 23. Detection test result for AK-47 Burst sound from the speaker located at 6 o'clock. X-axis measure is the dB amount by which the performance with the device is worse than the open ear threshold level in dB. (Means with different letters are significantly different at $p<0.10$.) The score computed for each device is the dB difference between threshold level of detection with the device and with the open ear, per the REAT protocol (see text). Thus, for the graph, the open ear score is represented by 0 dB.

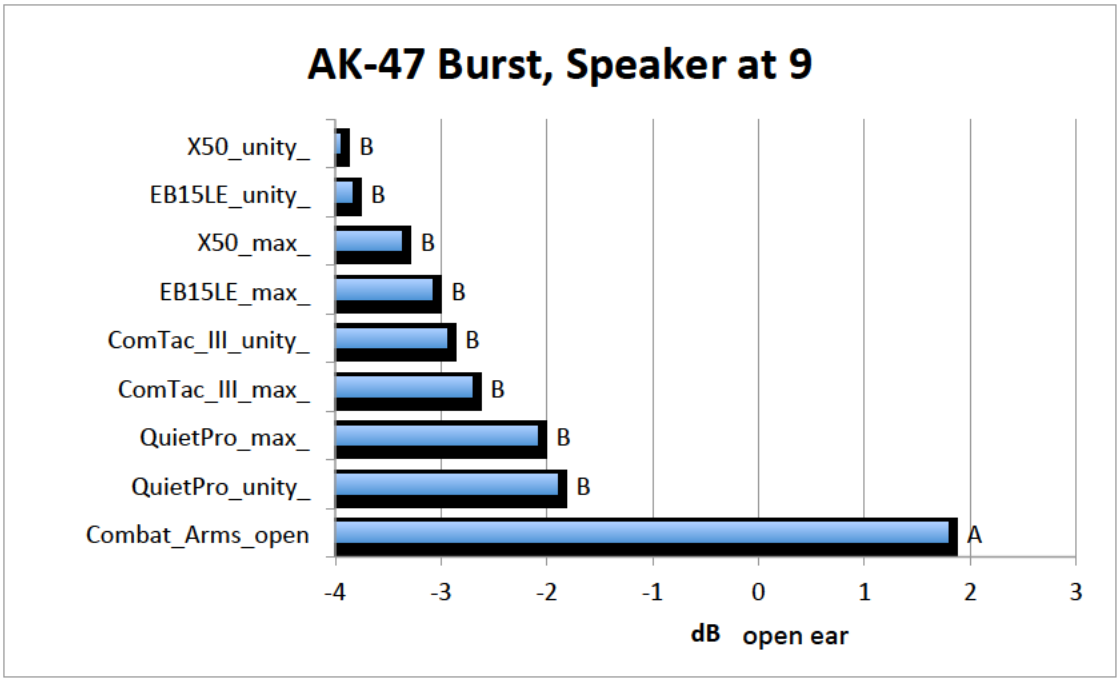

Figure 24. Detection test result for AK-47 Burst sound from the speaker located at 9 o'clock. X-axis measure is the dB amount by which the performance with the device is worse than the open ear threshold level in dB. (Means with different letters are significantly different at $p<0.10$.) The score computed for each device is the dB difference between threshold level of detection with the device and with the open ear, per the REAT protocol (see text). Thus, for the graph, the open ear score is represented by 0 dB.

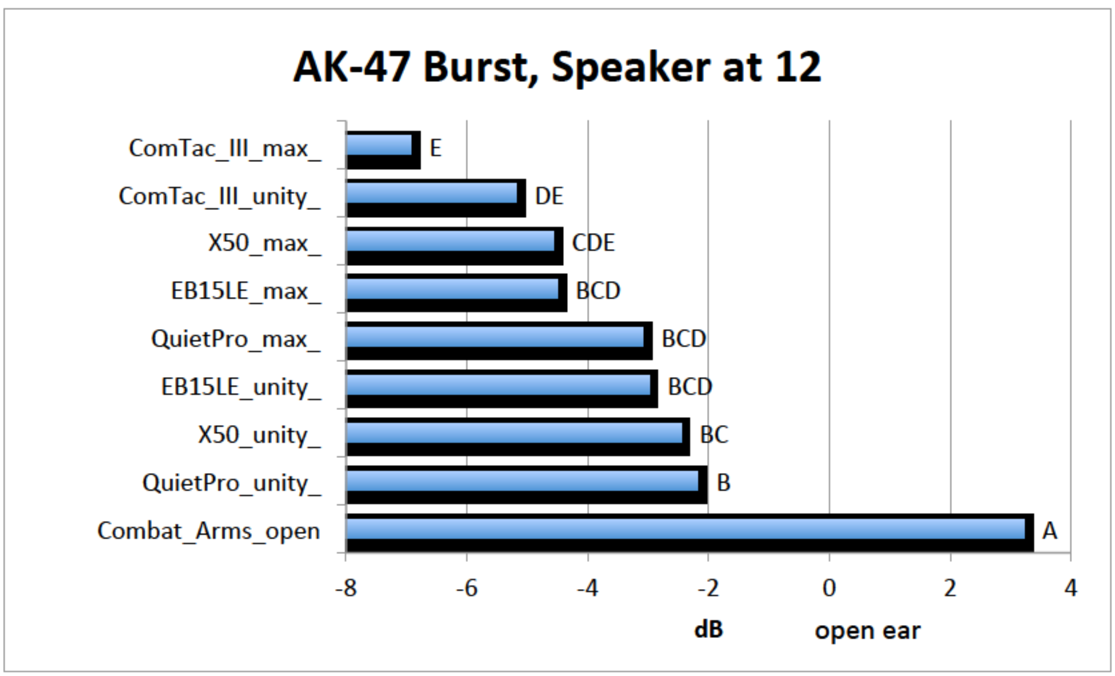

Figure 25. Detection test result for AK-47 Burst sound from the speaker located at 12 o'clock. X-axis measure is the dB amount by which the performance with the device is worse than the open ear threshold level in dB. (Means with different letters are significantly different at $p<0.10$.) The score computed for each device is the dB difference between threshold level of detection with the device and with the open ear, per the REAT protocol (see text). Thus, for the graph, the open ear score is represented by 0 dB.

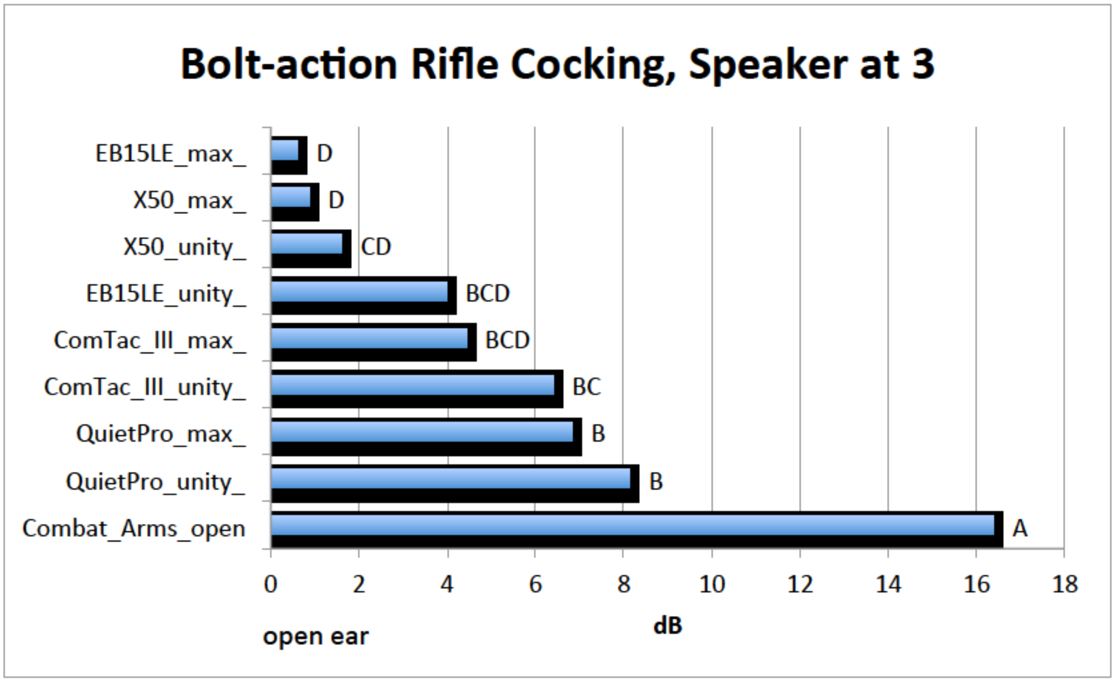

Figure 26. Detection test result for Bolt-action Rifle Cocking sound from the speaker located at 3 o'clock. X-axis measure is the dB amount by which the performance with the device is worse than the open ear threshold level in dB. (Means with different letters are significantly different at $p<0.10$.) The score computed for each device is the dB difference between threshold level of detection with the device and with the open ear, per the REAT protocol (see text). Thus, for the graph, the open ear score is represented by 0 dB.

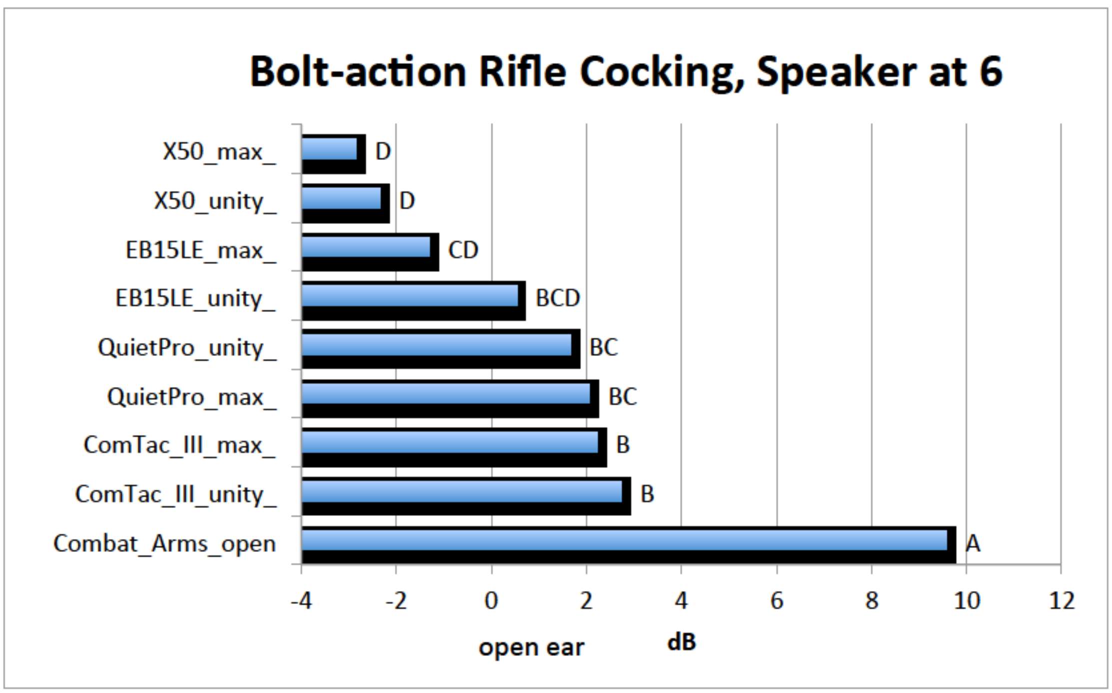

Figure 27. Detection test result for Bolt-action Rifle Cocking from the speaker located at 6 o'clock. X-axis measure is the dB amount by which the performance with the device is worse than the open ear threshold level in dB. (Means with different letters are significantly different at $p<0.10$.) The score computed for each device is the dB difference between threshold level of detection with the device and with the open ear, per the REAT protocol (see text). Thus, for the graph, the open ear score is represented by 0 dB.

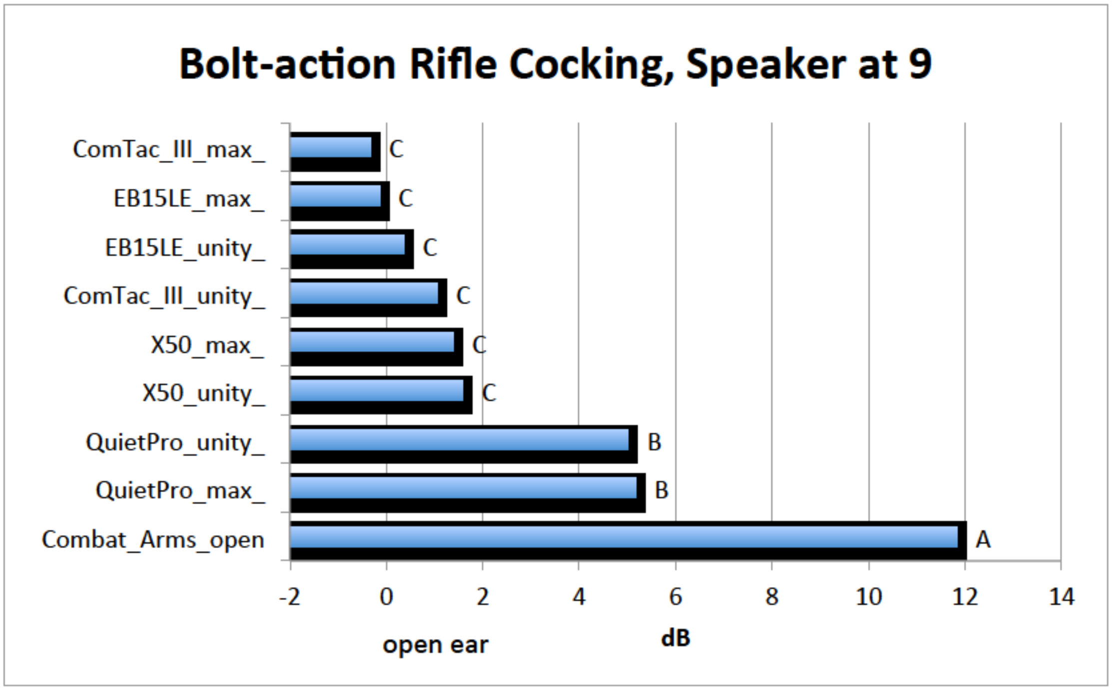

Figure 28. Detection test result for Bolt-action Rifle Cocking from the speaker located at 9 o'clock. X-axis measure is the dB amount by which the performance with the device is worse than the open ear threshold level in dB. (Means with different letters are significantly different at $p<0.10$.) The score computed for each device is the dB difference between threshold level of detection with the device and with the open ear, per the REAT protocol (see text). Thus, for the graph, the open ear score is represented by 0 dB.

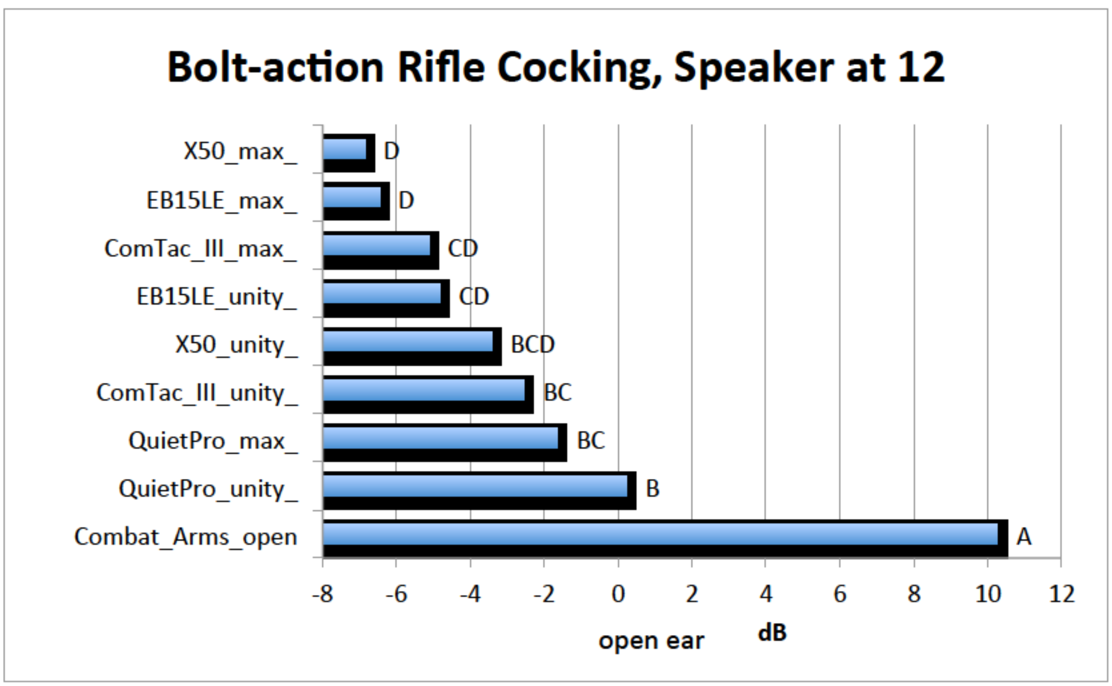

Figure 29. Detection test result for Bolt-action Rifle Cocking sound from the speaker located at 12 o'clock. X-axis measure is the dB amount by which the performance with the device is worse than the open ear threshold level in dB. (Means with different letters are significantly different at $p<0.10$.) The score computed for each device is the dB difference between threshold level of detection with the device and with the open ear, per the REAT protocol (see text). Thus, for the graph, the open ear score is represented by 0 dB.

4.2.2 Recognition/Identification Test Results

Figures 30 - 33 show partial test results for the recognition/identification test, sampled from the full data set that appears in Appendix F. As prior discussed, during the DRILCOM recognition/identification test, both the accuracy of subject responses identification, as well as the time in seconds it took them to answer are recorded. The mean response times are plotted in Figures 30 and 32, were respectively measured under two different wind testing conditions of no wind or 10 mph wind. Because a shorter response time is considered better in a tactical environment (at least as long as accuracy is maintained), hearing conditions (i.e., devices or the open ear) at the top of the plot can be considered as better in recognition/identification performance that the ones at the bottom. Similarly, Figures 31 and 33 are plots of accuracy (number of correct answers out of 10 questions, with 10 being the highest possible score), for testing conditions of either no wind or 10 mph wind. Again, hearing conditions at the top of the plots reflect better performance. As before, all graphs' bars include letter coding, where different letters represent statistical differences between the means of any given pair of bars. While not all hearing conditions are statistically-different, they are ranked per their mean values.

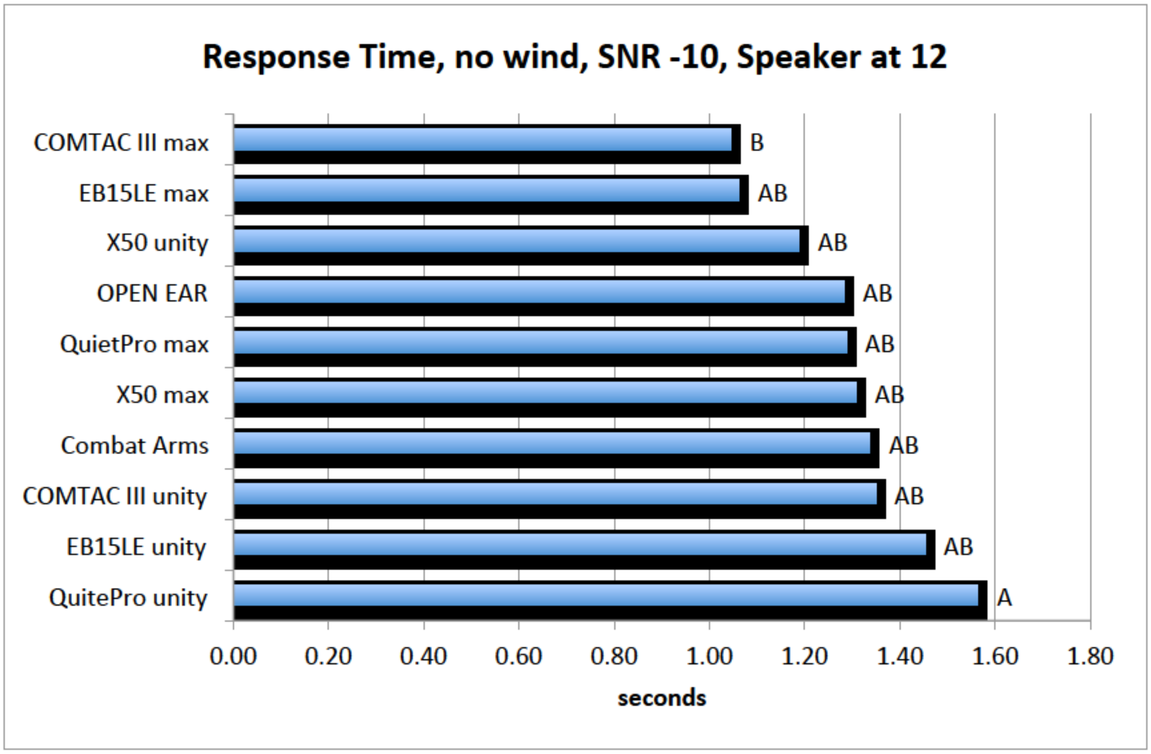

Figure 30. Recognition/Identification test result for Response Time measure with no wind (0 mph), SNR of -10, and signal speaker located in front of the subject at 12 o'clock. (Means with different letters are significantly different at $p<0.10$.)

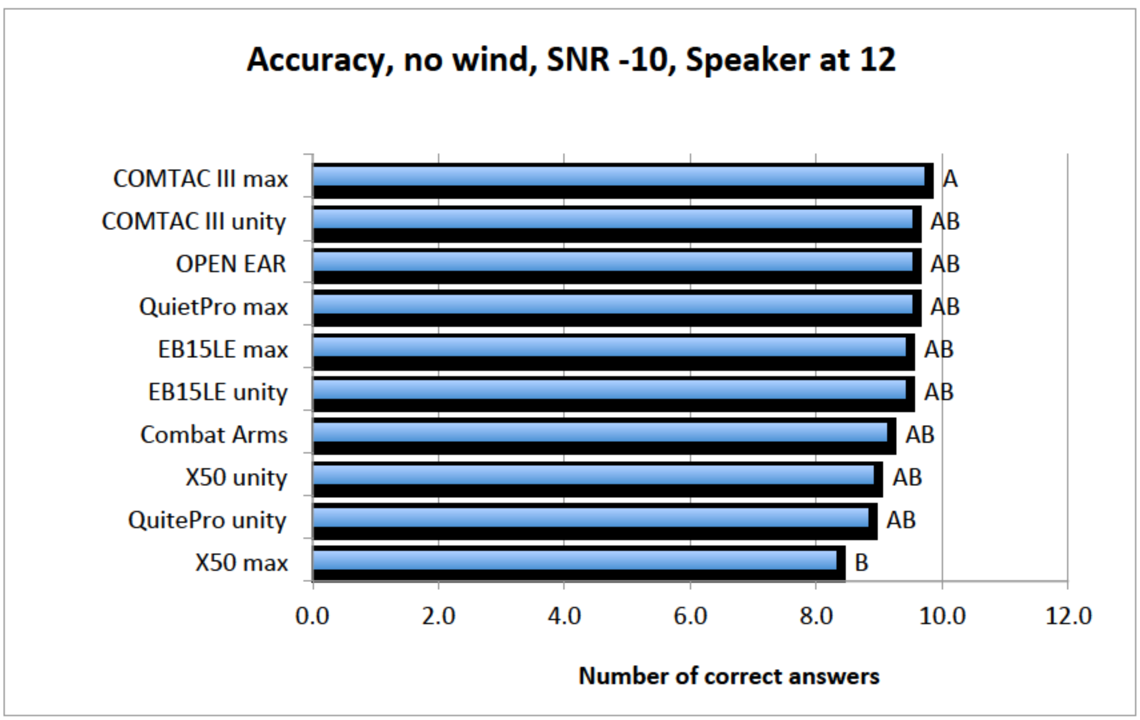

Figure 31. Recognition/Identification test result for Accuracy measure (number of correct answers out of 10) with no wind (0 mph), SNR of -10, and signal speaker located in front of the subject at 12 o'clock. (Means with different letters are significantly different at $p<0.10$.)

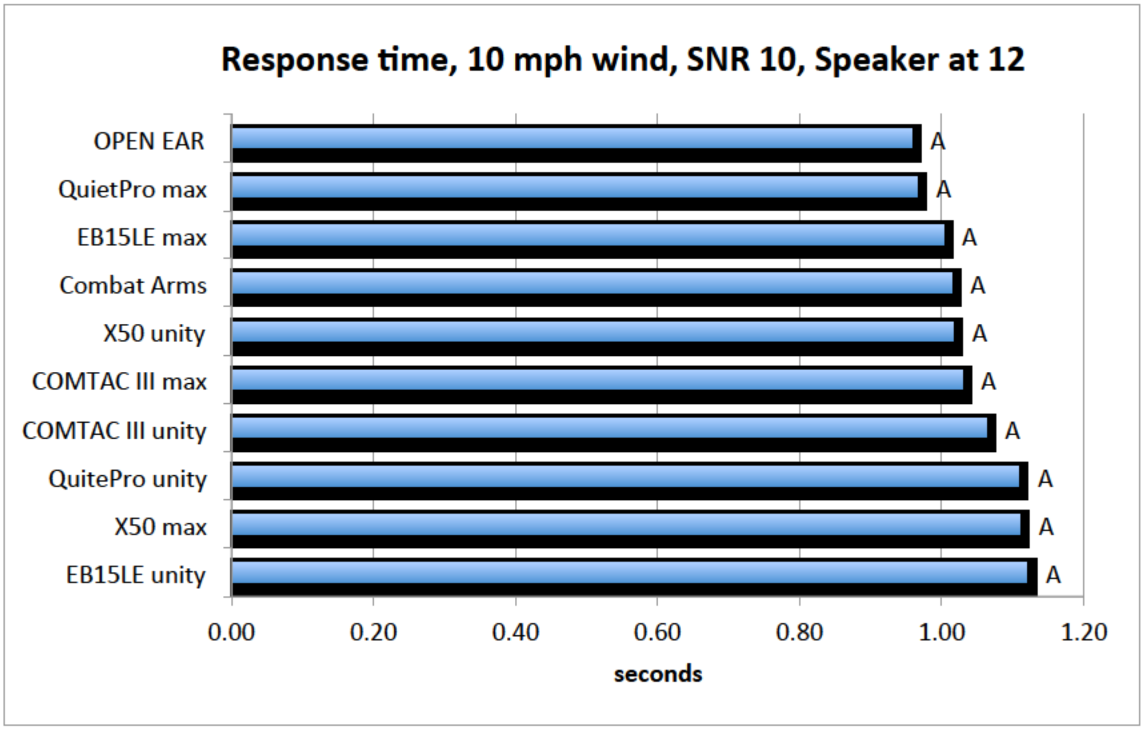

Figure 32. Recognition/Identification test result for Response Time measure with 10 mph wind, SNR of +10, and signal speaker located in front of the subject at 12 o'clock. (Means with different letters are significantly different at $p<0.10$.)

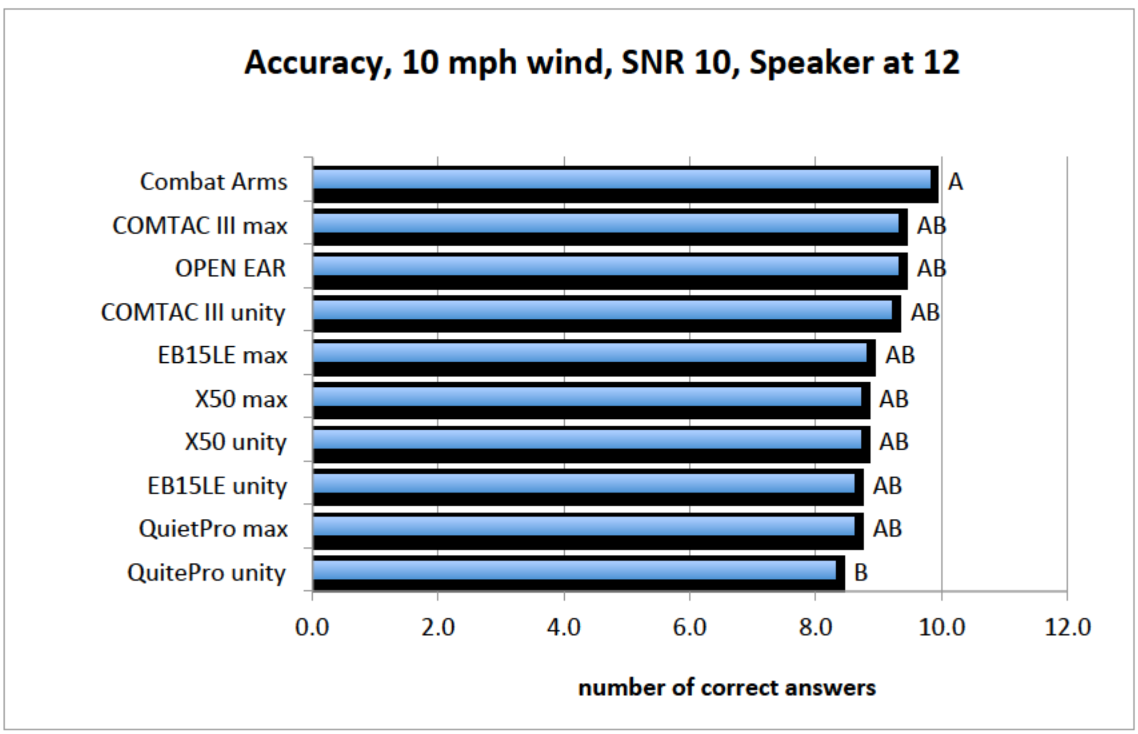

Figure 33. Recognition/Identification test result for Accuracy measure (number of correct answers out of 10) with 10 mph wind, SNR of +10, and signal speaker located in front of the subject at 12 o'clock. (Means with different letters are significantly different at $p<0.10$.)

4.2.3 Localization Test Results

Figures 34 – 41 are plots of example results from both the azimuthal and frontal elevation localization tests, for which the complete data set appears in Appendix G. For the azimuth localization test, the subject's response is considered as "absolute correct" if it matches exactly the actual signal speaker location. It is considered "ballpark correct" if the subject's response is within ±15-degrees of the actual signal speaker location in the horizontal plane. In an analog clock face sense, the ballpark correctness translates to within a half an hour error rate in the 12-hour direction scheme as given to the subjects. Similarly, for the frontal elevation test, "absolute correct" refers to a result that matches the signal speaker exactly, while the "ballpark correct" refers to subject's responses within the ±15-degree error in the vertical plane, since targets were separated by 30-degrees horizontally. Half of the graphs are for the low SPL condition, which refers to the test signal being played at 50 dBA in a background pink noise presented at 40 dBA. The remaining graphs labeled as high SPL are test results for the test signal being played at 85 dBA in a background pink noise presented at 75 dBA. Hence, the signal-to-noise ratio is maintained at +10 dB throughout the test to maintain clear identification of the signal. But using a wide range of incident SPLs exercises the pass-through circuits of the devices tested, and some sound transmission devices are known to reduce their amplification when external signals reach about 80-85 dBA -- when this occurs, localization performance may be affected, and thus it was deemed important to the DRILCOM test. Since the X-axis of all plots represents percent correctly localized, hearing conditions at the top are reflective of better performance. While the ballpark correct plots show similar trends and approximate ordering of hearing conditions as the absolute correct plots, the ballpark correct plots show finer groupings.

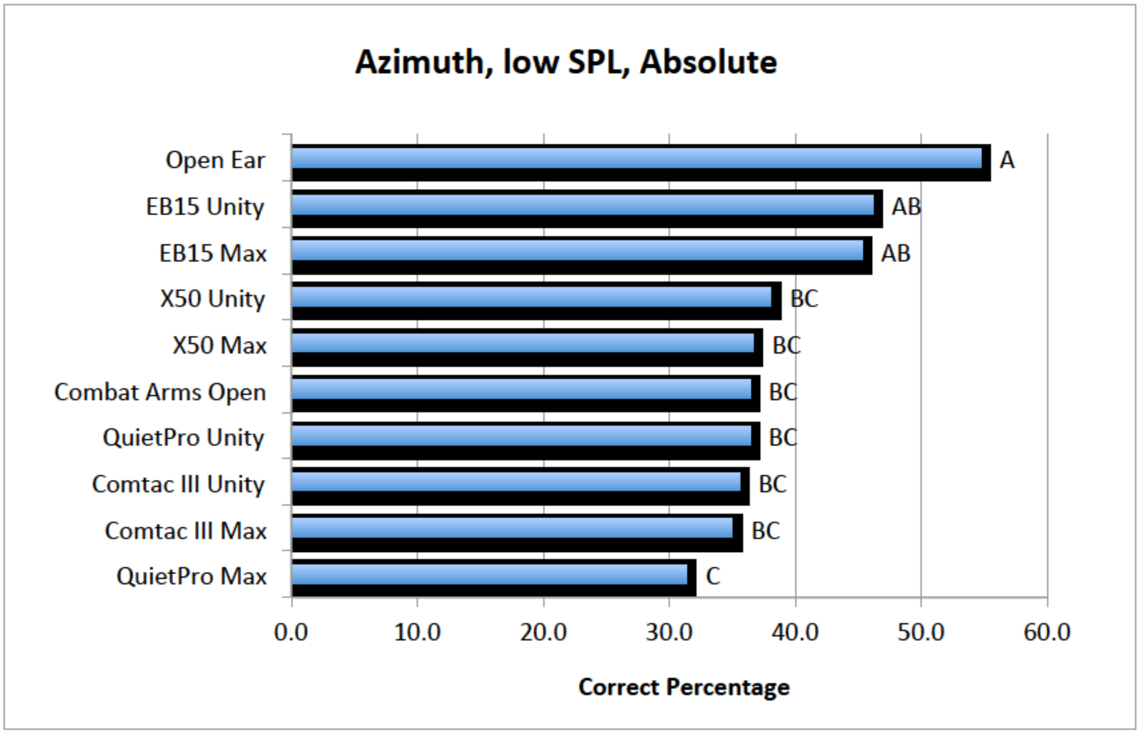

Figure 34. Azimuth Localization test result for Absolute Correct percent at Low signal level of 50 dBA in a 40 dBA pink noise background, SNR of +10. (Means with different letters are significantly different at $p<0.10$.)

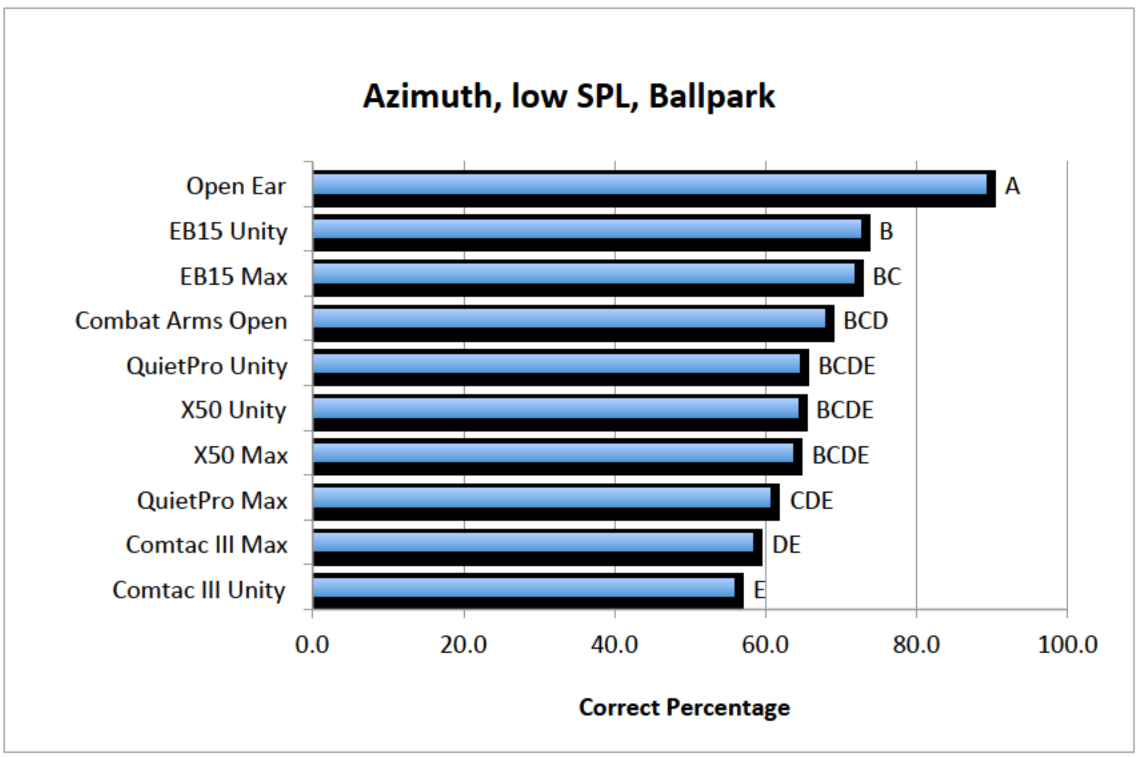

Figure 35. Azimuth Localization test result for Ballpark Correct percent at Low signal level of 50 dBA in a 40 dBA pink noise background, SNR of +10. (Means with different letters are significantly different at $p<0.10$.)

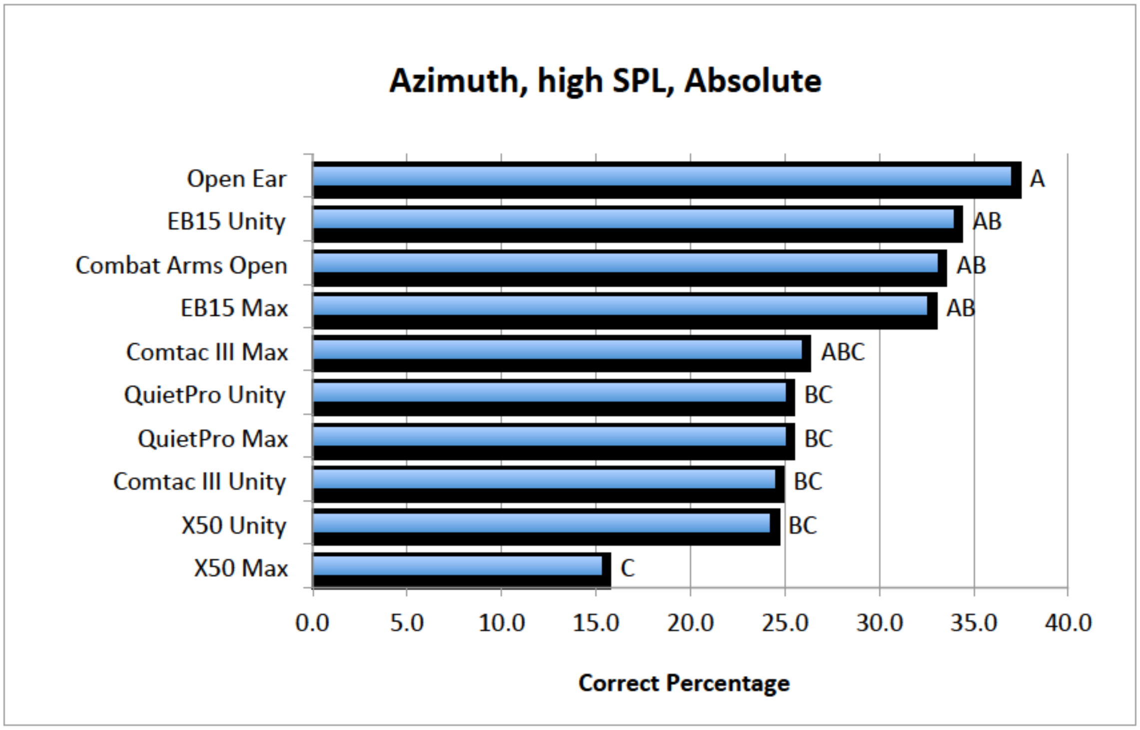

Figure 36. Azimuth Localization test result for Absolute Correct percent at High signal level of 85 dBA in a 75 dBA pink noise background, SNR of +10. (Means with different letters are significantly different at $p<0.10$.)

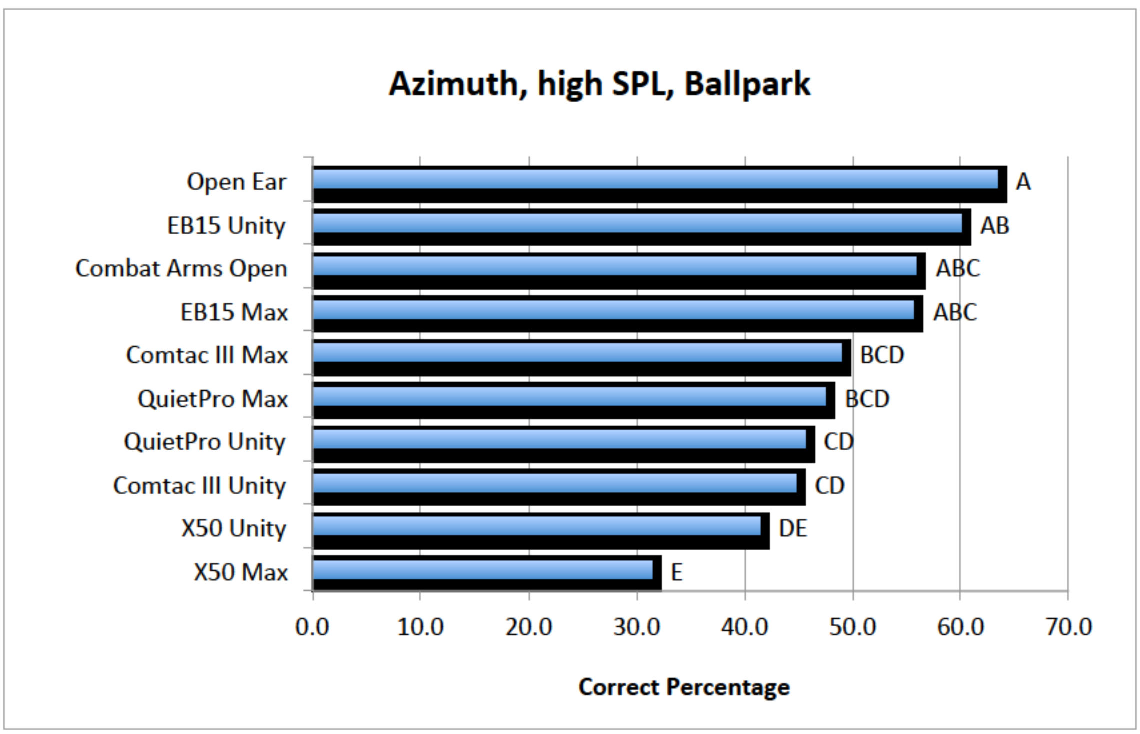

Figure 37. Azimuth Localization test result for Ballpark Correct percent at High signal level of 85 dBA in a 75 dBA pink noise background, SNR of +10. (Means with different letters are significantly different at $p<0.10$.)

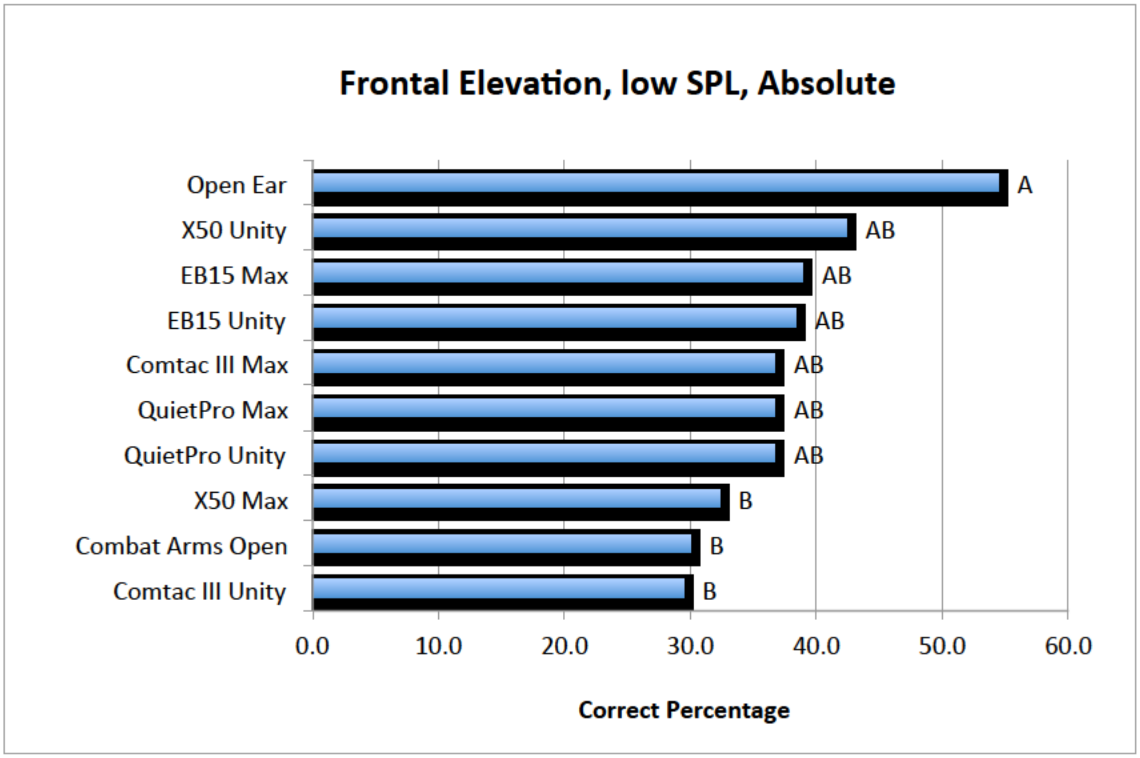

Figure 38. Frontal Elevation Localization test result for Absolute Correct percent at High signal level of 85 dBA in a 75 dBA pink noise background, SNR of +10. (Means with different letters are significantly different at p<0.10.)

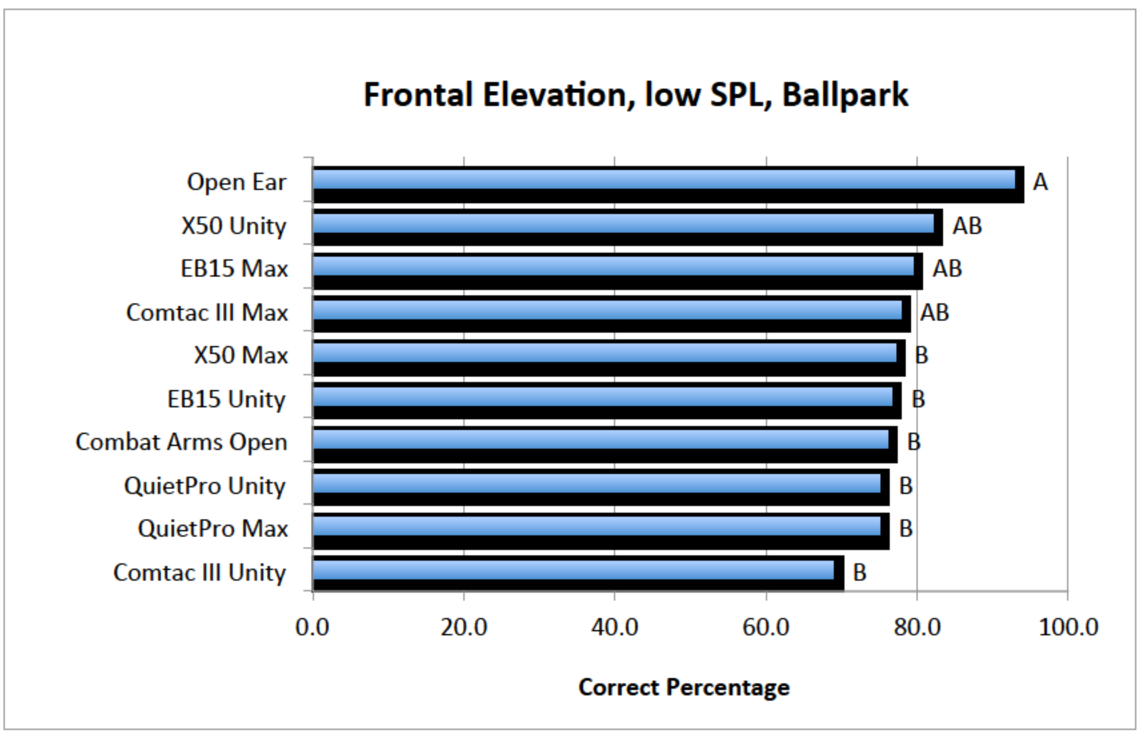

Figure 39. Frontal Elevation Localization test result for Ballpark Correct percent at Low signal level of 50 dBA in a 40 dBA pink noise background, SNR of +10. (Means with different letters are significantly different at p<0.10.)

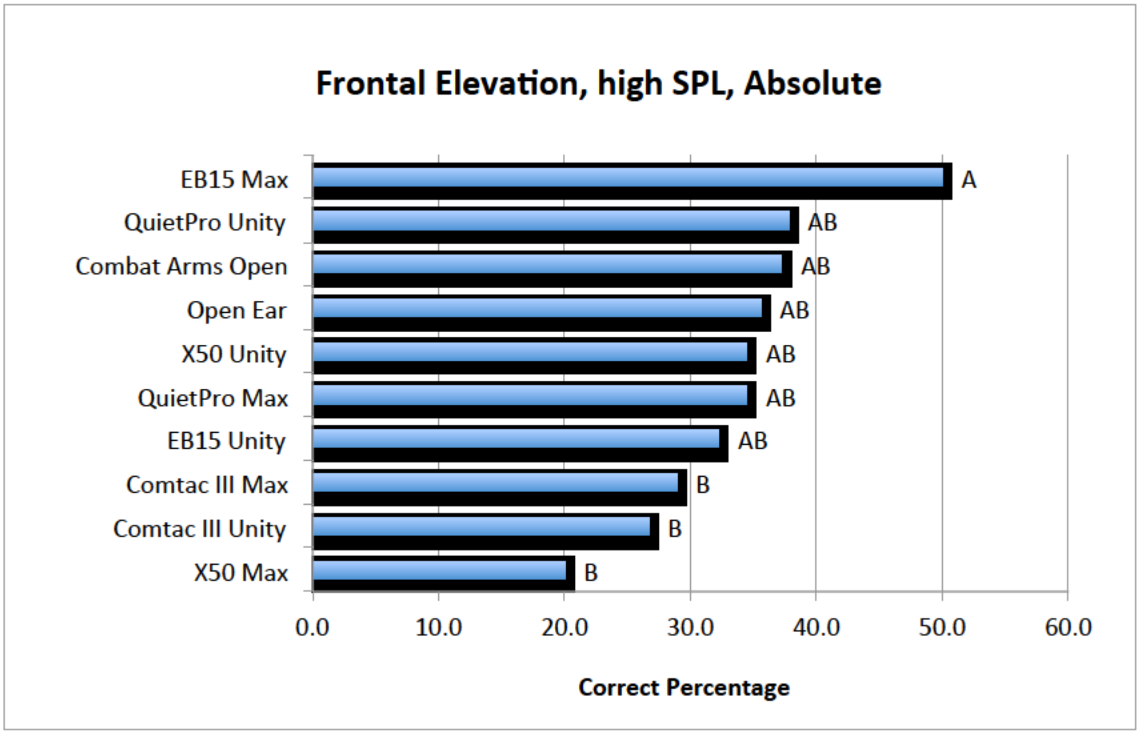

Figure 40. Frontal Elevation Localization test result for Absolute Correct percent at High signal level of 85 dBA in a 75 dBA pink noise background, SNR of +10. (Means with different letters are significantly different at $p<0.10$.)

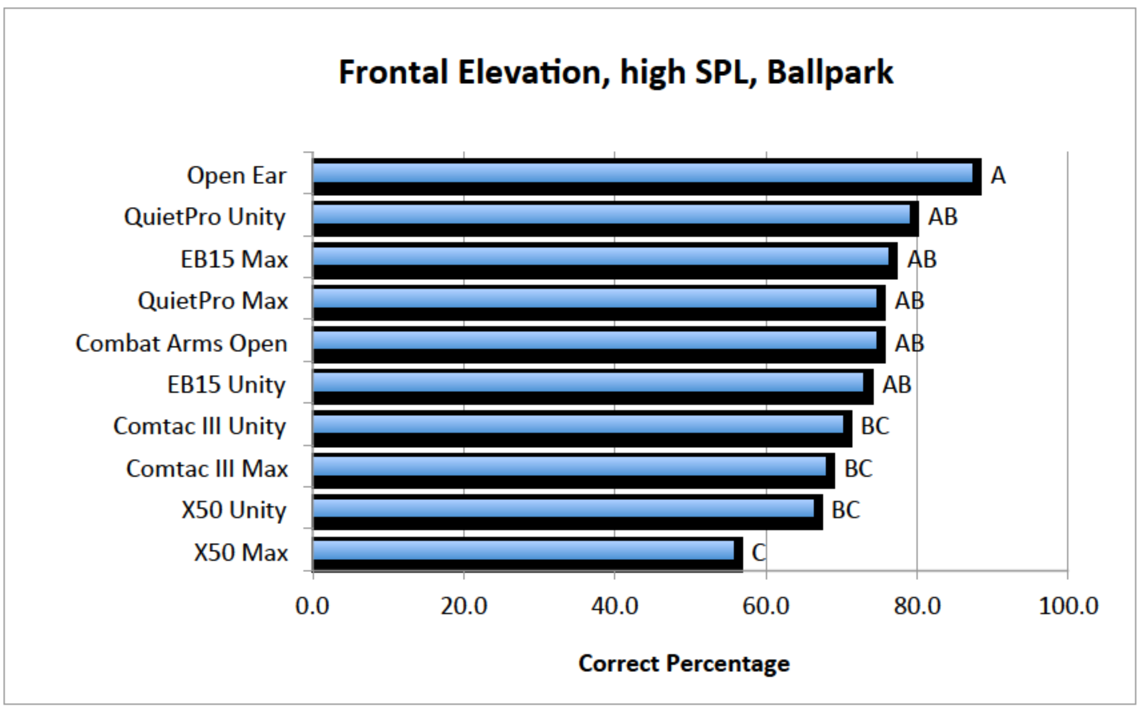

Figure 41. Frontal Elevation Localization test result for Ballpark Correct percent at High signal level of 85 dBA in a 75 dBA pink noise background, SNR of +10. (Means with different letters are significantly different at $p<0.10$.)

4.2.4 COMmunication Test Results

Examples of the pass-through communication test results are shown in Figures 42 - 44, and the full COM test data set appears in Appendix H. As previously explained, the QuickSIN™ by Etymotic test produces a measure of SNR loss, and a lower number means less loss and thus better performance. Hence, the hearing conditions at the top of these graphs can be considered as performing better for pass-through speech communications purposes than those at the bottom. Because certain hearing conditions produced negative SNR losses, the vertical axes are plotted to cross the horizontal axes at SNR = -2.0 to make the plots easier to compare. Hearing conditions with different letters are statistically different at $p<0.10$ and they are plotted in order by rank. The addition of winds at speed of 5 mph and 10 mph caused variation in the ordering of hearing conditions and is evidence that different devices process wind noise differently, to the point that performance differences in communications ability ensued.

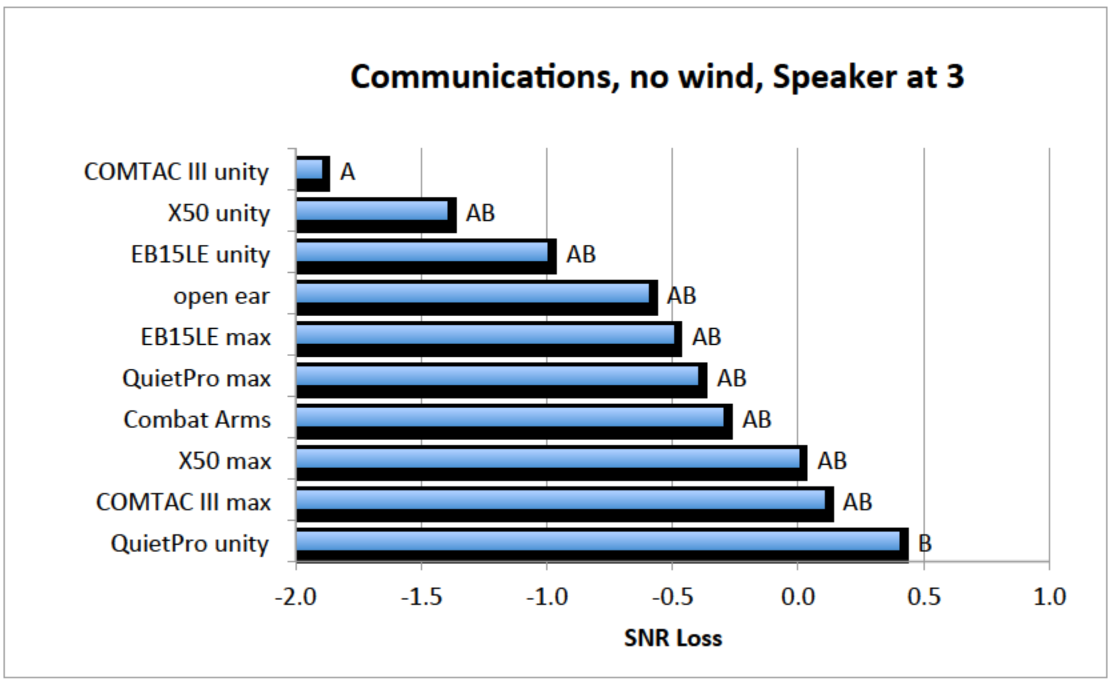

Figure 42. Communication test result measured by SNR loss per QuickSIN™ with no wind (0 mph) and signal speaker located at 3 o'clock. (Means with different letters are significantly different at $p<0.10$.)

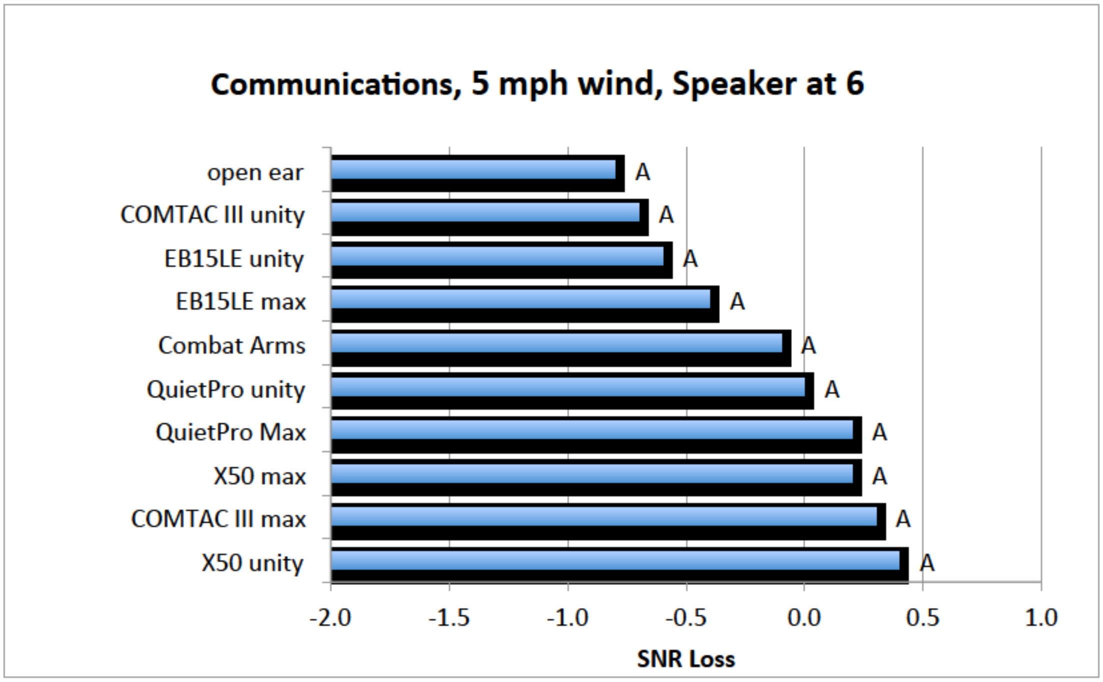

Figure 43. Communication test result measured by SNR loss per QuickSIN™ with 5 mph wind and signal speaker located at 6 o'clock (directly behind subject). (Means with different letters are significantly different at $p<0.10$.)

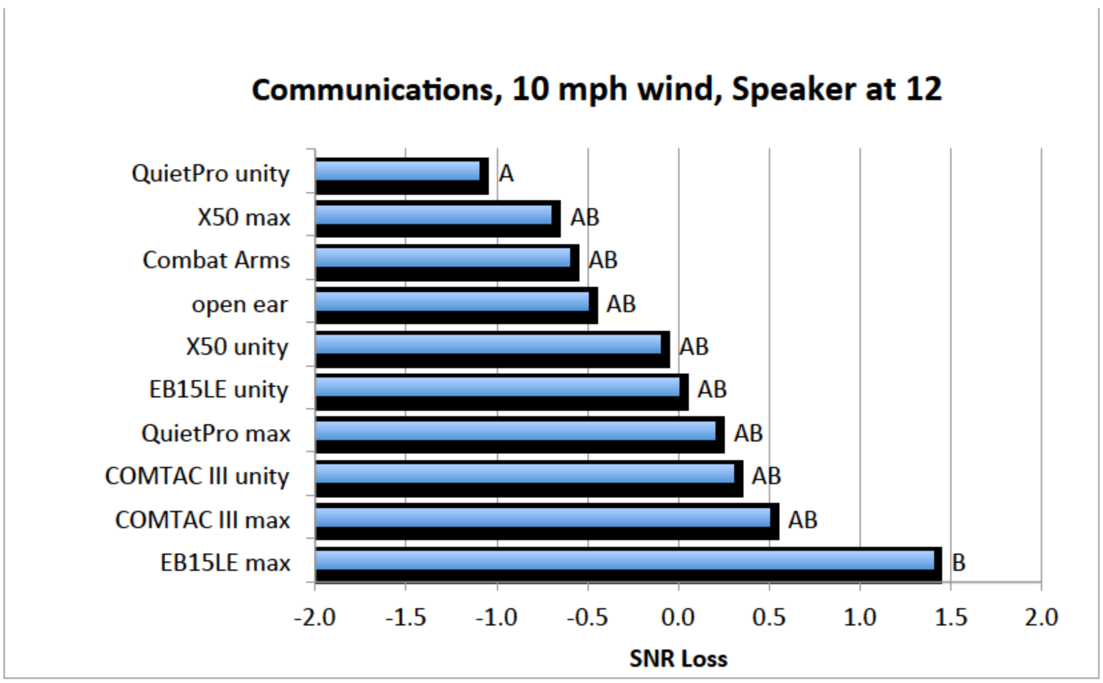

Figure 44. Communication test result measured by SNR loss per QuickSIN™ with 10 mph wind and signal speaker located at 12 o'clock (directly in front of subject). (Means with different letters are significantly different at $p<0.10$.)

KEY RESEARCH ACCOMPLISHMENTS

- Designed and instrumented a DRILCOM test battery that objectively measures the level of auditory situation awareness (ASA) afforded to a person wearing a an advanced HPD or TCAPS device, in four ASA subtasks of **D**etection, **R**ecognition/**I**dentification, **L**ocalization (both azimuth and frontal elevation), and **COM**munication via the device's pass-through vent or circuit.
- Developed a comprehensive set of stimulus materials and dependent measures, reflective of both accuracy and speed of response, for the DRILCOM tests.
- Built and configured the hardware and audio apparatus for the DRILCOM test battery. All components were selected from those available from off-the-shelf commercial sources. The test room was configured as a hemi-anechoic space that was retrofitted within a large classroom in a quiet area.
- Wrote all necessary software control programs, in MatLab and LabView languages, to provide computer control and scoring for the Detection, Recognition/Identification, and Localization tests in the battery.
- Conducted an extensive proof-of-concept experiment that demonstrated the efficacy of the DRILCOM test battery in measuring human-system situation awareness performance achieved with various advanced HPDs and TCAPS that are currently deployed by various branches of the U.S. military. In particular, all four tests within the DRILCOM battery demonstrated measurement sensitivity to differences amongst various devices, and between individual devices and the open ear, to the point that statistical-significance was achieved with a relatively small subject sample of 10 individuals who were untrained in the use of the devices.
- Augmented the DRILCOM test battery with a wind noise source and duct to explore the potential to measure wind noise effects in a laboratory environment, on auditory situation awareness performance.
- Provided several briefings for meetings of the DoD Hearing Center of Excellence, the U.S. military CAVRN meeting, and presented two papers to date at the National Hearing Conservation Conference.

- Developed a set of recommendations for potential applications of the DRILCOM test battery for military use in advanced HPD and TCAPS testing and training of users of these devices, and recommendations for future research for refinement of DRILCOM with an eye toward streamlining and field-validating it.

REPORTABLE OUTCOMES

- Lee, K. & Casali, J. G. (2015). Wind Noise Effects on Auditory Situation Awareness Attained with Sound Transmission HPDs and TCAPS. *Spectrum*, Vol. 32, Supplement 1, and *Proceedings (on NHCA website) of the 40th Annual National Hearing Conservation Association Conference,* New Orleans, LA, February 19-21, 2015.

- Lee, K. & Casali, J. G. (2015, March). *DRILCOM Study.* 2015 Annual Collaborative Auditory Vestibular Research Network (CAVRN). San Diego, CA.

- Lee, K., & Casali, J. G. (accepted, in press). Effects of low speed wind on the recognition/identification and pass-through communication task of auditory situation awareness afforded by military hearing protection/enhancement devices and tactical communication and protective systems. *International Journal of Audiology,* NHCA 2015 Special Issue.

- Lee, K. & Casali, J. G. (2016, February). Auditory Situation Awareness Testing of HPDs and TCAPS: Detection Subtest of DRILCOM Test Battery. National Hearing Conservation Association Conference, San Diego, CA, February 18-20, 2016 (accepted, to appear)

CONCLUSION

5. Test Battery Overview

In summary from this project, the DRILCOM test battery has been developed and implemented using custom software to control and score three of the four tasks, and a common, standard test was selected and modified for the communication task. The complete hardware set and test stimuli have been implemented using relatively straightforward and off-the-shelf commercial components and materials. The custom software for the test was developed using MatLab™ and LabView™ and runs under Microsoft Windows 7™, and this software controls the presentation of all tests with the exception of the **COM**munication test, which incorporates commercially-available QuickSIN™ test stimuli sets. The four tests offer comprehensive coverage for the primary tasks involved in auditory situation awareness, addressing the four elements of **D**etection, **R**ecognition/**I**dentification, **L**ocalization (azimuthal and elevation), and **COM**munication. The **D**etection test evaluates a device's effect on detection of narrow-band (1/3-octave) and broadband signals (AK-47 Burst and Bolt-action Rifle Cocking) in four directions: front, left, right, and rear of the user. The **D**etection measurement variable is the hearing threshold level change in dB from that of open ear detection to device-occluded detection, both ascertained in a nominal 40 dBA background pink noise.

The **R**ecognition/**I**dentification test is designed to evaluate how well a user can recognize/identify a target sound signal from other signals, all presented in a triad grouping of the stimuli and tested at two positions, in front of and to the right of the subject. The measures for the **R**/**I** test, which invokes perception and cognitive processing of the signals, include both percentage accuracy as well as time to respond.

The **L**ocalization test is designed to measure how accurately a user can localize a sound signal in both 360-degrees of azimuth and in frontal elevation, with the additional measure of time to respond. For **L** accuracy, both absolute correct rate and ballpark correct rate (considered correct if an answer is within ±15 degrees of its actual emitting loudspeaker) are scored.

The **COM**munication test is designed to measure the subjects' communication performance, i.e., understanding of key words in a sentence, when the communication message is heard via the pass-through vent or electronic sound transmission circuit of a passive advanced HPD or TCAPS, respectively. The **COM**munication test's measure is SNR loss, defined by Etymotic as the dB increase in signal-to-noise ratio required by a hearing-impaired person (or in this experiment, a subject whose ears are occluded with a device) to understand speech in noise, compared to someone with normal hearing (or in this experiment, a subject whose ears are unoccluded).

To determine a device's influence on situation awareness as a function of the direction of the incident signal to be heard or understood, azimuth-directional measurements are included at various angles (detailed herein) for **D**etection, **R**ecognition/**I**dentification, and **COM**munication. Furthermore, of course for the **L**ocalization tests, relatively small angle directionality determinations included 30-degree increments in 360-degrees of azimuth and 30-degree increments in frontal elevation. The test battery was implemented in a modified test room of the VT-ASL, which is a hemi-anechoic room with dimensions of 18-feet wide by 19-feet long by 8.5-feet high. Background pink noise of different sound pressure levels is added to each test, depending on the particular ASA element of DRILCOM under evaluation.

6. Proof of Concept Experiment Overview

To briefly recapitulate the prior experimental design, ten subjects (eight males and two females) participated in the experiment. Due to the fact that the subject pool was largely composed of members of the Virginia Tech (VT) community, and all were vetted to be U.S. citizens, and a longer than expected experimental span across the four DRILCOM sub-experiments, some of the subject left the university before finishing all experimental sessions. Hence, new subjects were recruited as needed, but in each of the four sub-experiments, the same ten subjects conducted all trials; thus, each DRILCOM sub-experiment was strictly within-subject. Final selection of the test devices (hearing conditions) was made with the help of the SMEs, and all devices were current U.S. military issue circa early 2015. The devices included: INVISIO X50™ TCAPS, Nacre-Honeywell Quiet PRO+™ TCAPS, Peltor ComTac III™ electronic earmuff 3M Combat Arms™ fourth generation (i.e., rocker-style, single-ended) passive, restrictive-vent earplug, and the Etymotic EB15LE™ electronic earplug. All electronic devices were tested under two gain settings: “unity” and “maximum”. “Unity” gain setting was different with each device and is explained in Section 4.1.3 herein.

Details about individual TCAPS, advanced HPD, and open ear performance with each hearing condition are voluminous and thus are included in the full data set for report as Appendices E, F, G, and H. However, several bottom-line observations are warranted here. First, the test battery, across all four of its DRILCOM components, clearly demonstrated an ability to distinguish various devices and the open ear as to situation awareness task performance, and it did so with statistical-significance using a relatively small group of subjects (10) and a conservative statistical test. Second, it was empirically determined that when each subject served as his/her own control, that is, in the sense that performance with a given device was compared against the open ear, each of the DRILCOM tests provided clear, face-valid evidence about how a given product influenced a subject's natural hearing sensation/perception. Both of these conclusions are important to note, in part since they provide evidence that inter-product comparisons, and product versus open-ear comparisons, will not require large groups of subjects if the DRILCOM test protocols are held to those specified in the test battery.

7. Metric of Percent Worse (or Better) than Open Ear

As discussed in prior publications from the VT-ASL (e.g., Casali & Clasing, 2013), a metric that simplifies the unit-based dependent measures of accuracy and response time into a "unit-less" metric of "percent worse/better than open ear," can be beneficial in conveying the effects of an HPD or TCAPS when compared to a person's normal, unoccluded or aided hearing. To some audiences, this percentage performance metric serves as a more clear, intuitive means by which to compare devices on one given auditory task element of DRILCOM, or to grasp an individual device's effect across all auditory sensation/perception tasks of DRILCOM. This metric is normalized by each subject's "baseline" or open ear performance, thus removing the individual performance effect from the test results. A similar concept is found in HPD attenuation testing via REAT protocols (e.g., ANSI S12.6-2008), wherein each test trial results in a attenuation calculation by subtracting the individual subject's occluded ear threshold from his/her open ear threshold level for a given frequency on a given trial. This REAT technique essentially results in a metric comprising "occluded dB threshold worse than open ear threshold dB," which can then easily be converted into a "percent worse/better than open ear" value that is proposed here.

An example of computing the "percent worse/better than open ear" for one of the DRILCOM tests, Recognition/Identification, is as follows. For a given hearing condition with a particular TCAPS, with the signal triads being emitted from 90-degrees, and a background pink noise of 80 dBA, a subject scores 6 out of 10 on the questions posed. For that same combination of conditions but with the open ear, the subject scores 9 out of 10. Thus, the "percent worse/better than open ear" for that TCAPS in that condition is (100 x [1-(6/9]) = 33%, which is then signed as negative (-33%) because the device performance is 33% worse than the open ear performance.

8. Percent Worse/Better than Open Ear: Comparison across Devices by Individual DRILCOM Test Element

One means of comparing performance across different devices and the open ear is to partition the DRILCOM proof-of-concept experiment into each of the four test elements, and then to plot the performance for each of the 10 hearing conditions on a given DRILCOM test in a single graph. Figures 45, 46, and 47 are example plots of the percent worse than open ear metric from the azimuthal Localization test, Recognition/Identification test, and COMmunication test. A negative percentage value indicates that the particular device degraded the person's auditory situation awareness ability by that percentage, as compared to the open ear, while a positive percentage value indicates that the device exceeded the open ear's performance. In Figure 45, for the azimuthal Localization task with a ballpark (within ±15 degrees) measure of accuracy, it is evident that every TCAPS and advanced HPD was considerably poorer in performance than the open ear, since all values are negative. However, in Figure 46, Recognition/Identification of a frontal (12 o'clock) signal at a low SNR, one device (ComTac III), actually was equal to or slightly better than the open ear in performance by the percent metric (not to imply any statistical-significance here). Finally, in Figure 47, for the measure of SNR loss in the COMmunication test, it is obvious that there was wide variance among devices as to their pass-through communications performance, that this variance depended somewhat on the gain setting, and that some devices were better, and others worse, than the open ear (again, not intended to imply statistical-significance with the percent metric).

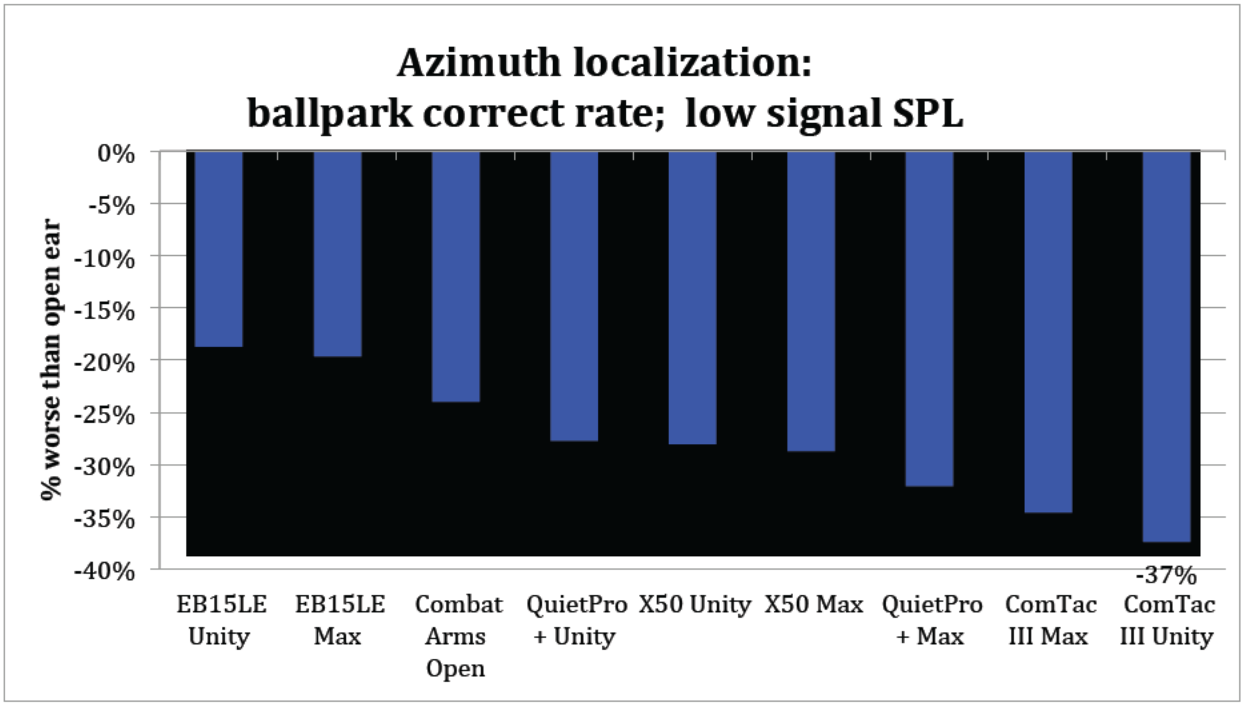

Figure 45. Azimuth Localization test result, measured as percent worse (-) or better (+) than open ear, converted from Ballpark Correct percent at Low signal level of 50 dBA in a 40 dBA pink noise background, SNR of +10. (No statistical differences implied with percentage data.)

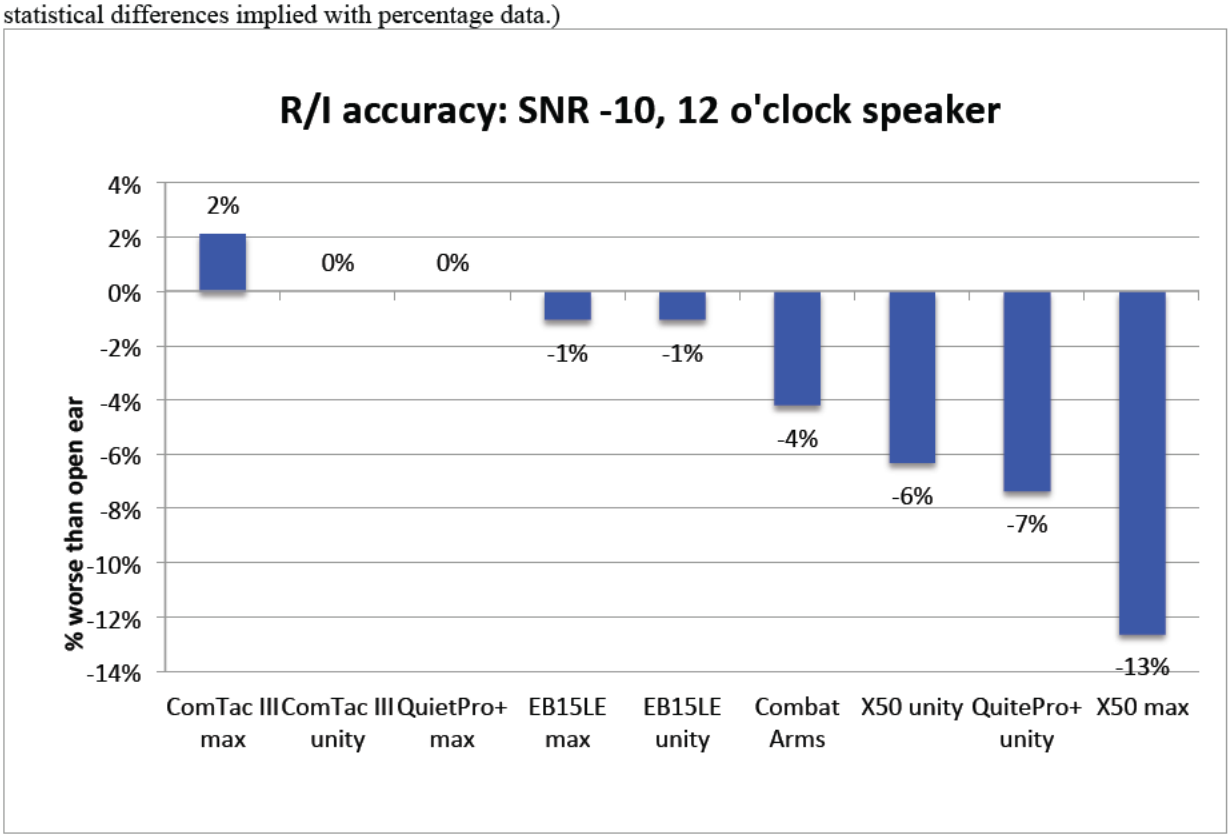

Figure 46. Recognition/Identification test result, measured as percent worse (-) or better (+) than open ear, converted from Accuracy measure (number of correct answers out of 10), signal-to-noise ratio of -10, and signal speaker located in front of the subject at 12 o'clock. (No statistical differences implied with percentage data.)

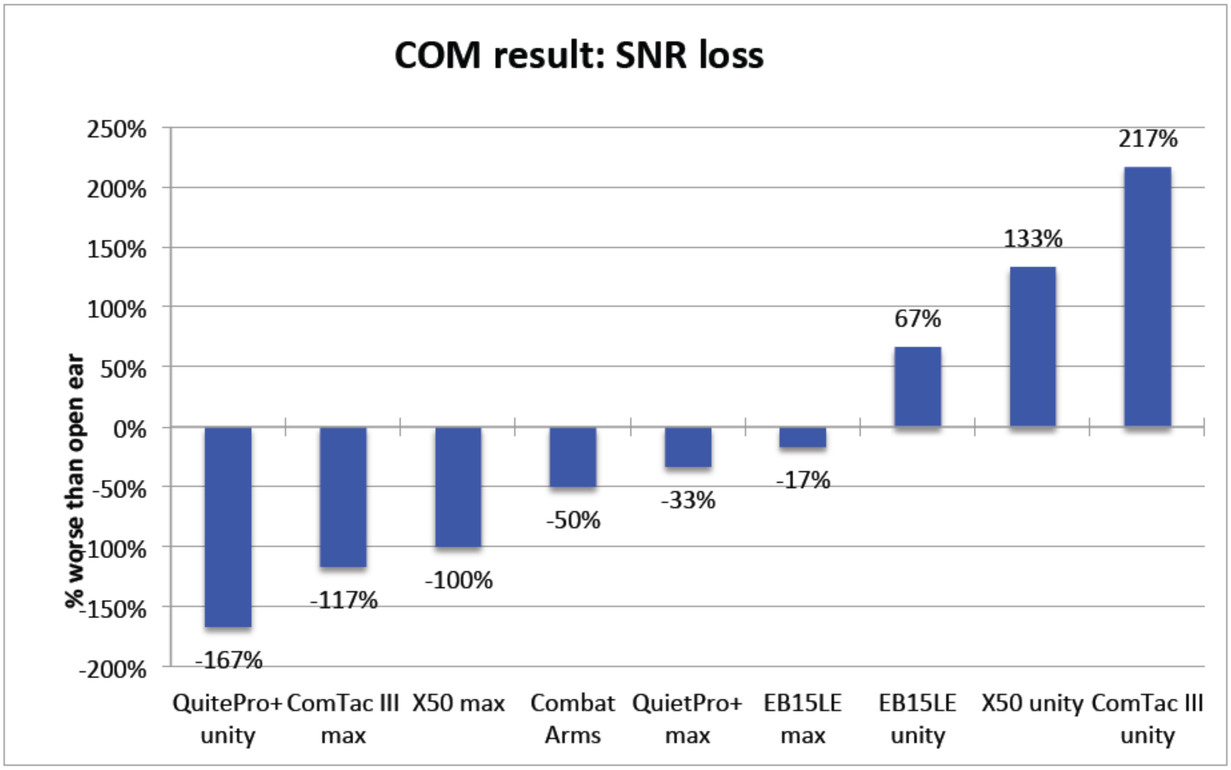

Figure 47. Communication test result, measured as percent worse (-) or better (+) than open ear, converted from SNR loss per QuickSIN™ with no wind (0 mph) and signal speaker located at 3 o'clock. (No statistical differences implied with percentage data.)

9. Percent Worse/Better than Open Ear: Comparison across DRILCOM Test Elements for each Individual Device

Another means of comparing auditory situation performance is to look at the strength of a given device across all of the DRILCOM task elements, again with a metric of percent worse/better than open ear. Figure 48 provides an aggregate of this for *all* devices, with each group of bars representing one device and each bar representing one of the four DRILCOM tests. While the graph is busy, it is readily apparent that the Combat Arms™ earplug in its open setting and the Honeywell Quiet PRO+™ TCAPS, both at unity and maximum gain, in particular, yielded a higher percentage worse than open ear values than other devices on the Detection task of detecting an Bolt-action Rifle Cocking and on the mean of detection values for the nine detection signals (1/3-octave bands and military-relevant signals).

More specific results on individual devices are shown in Figures 49 - 57, which plot percent worse/better than open ear per each device, with each gain setting of a given device considered as a different device. Thus, each graph portrays, in a percent worse/better than open ear sense, how the device performed on each DRILCOM test. For these graphs, only accuracy data is presented, since accuracy-derived measures cut across all four DRILCOM tests. Response time data, while included in Appendices E-H in units of seconds, is not graphed in these examples for percent worse/better than open ear. To ease interpretation of Figures 49-57, these tests and their labels in the graphs are as follows. The Detection test consists of bars for D: AK-47 Burst, D: Bolt-action Rifle Cocking, and D: average, the arithmetic mean of all nine test signals used in the Detection test. The Recognition/Identification test results consist of a bar for only the single metric related to the number of questions (out of 10 triads) answered correctly and converted to a percentage. The Localization test includes bars for L: azimuth and L: frontal elevation. The COMmunication test resulted in bars which contains SNR loss data that is averaged across all test conditions. For simplicity, in the case of the R/I and COM categories where the wind speed effects were explored as an add-on variable, the wind condition results were excluded in these percentage graphs. One final note about this set of graphs is that one subject's data were removed in the calculation of percent worse than open ear for Detection (and Detection only), because his data points for detecting the AK-47 Burst and bolt-action rifle cocking were clearly statistical outliers. His data on the other three DRILCOM tests were not removed, as they were not outliers. His data was not removed for the analysis at section 4.2.1, as authors were testing for statistical differences and inclusion of his data produced more conservative result.

While it is not the purpose here to extensively dissect each of the percent worse/better than open ear graphs for the nine device hearing conditions in Figures 49-57, and nothing here implies statistical-significance since the metric is percentage-based, several trends do stand out. One observation is that there were very isolated instances of any device outperforming the open ear, resulting in a positive (+) signed percentage. This occurred, and only slightly so in percentage magnitude, for the following: EB15LE™ electronic earplug at maximum gain setting for Detection of AK-47 Burst , EB15LE™ at unity gain for Communications performance, and INVISIO X50™ TCAPS at maximum gain for Detection of AK-47 Burst. A second general conclusion, again not intended to imply statistical significance, surmised from Figure 48 as well as 49-57, is that the passive Combat Arms™ earplug, in its open (pass-through) setting, showed considerably worse "percent worse than open ear performance" than any other device, and the Quiet PRO+™ TCAPS was ranked as second worst to the Combat Arms™ on some of the DRILCOM tasks.

Another very clear trend across Figures 49-57, is that Detection of the bolt-action rifle cocking, as well as the average detection across all nine Detection signals, are likely the most severe tests for most devices in a percent worse than open ear sense, and in the case of the bolt-action rifle cocking, this is likely due to its acoustical signature's high-frequency spectral bias. The *best* bolt-action rifle cocking detection percentage was -19% (i.e., worse than the open ear) with the EB15LE™ electronic earplug at maximum gain, tied with the INVISIO X50™ TCAPS at maximum gain. The *worst* bolt-action rifle cocking detection percentage was -111% achieved with the Combat Arms™ earplug in its open setting. Likewise, both the azimuthal and the frontal elevation tests comprised stringent tests, yielding percent worse than open ear values ranging from a best of -12% (azimuth) for the EB15LE™ at unity gain to a worst of -40% (azimuth) for the INVISIO X50™ TCAPS at maximum gain.

It is reiterated that the "percent worse/better than open ear" metric is not a panacea, but is intended to offer a robust, simplified, and common metric to compare the effects of advanced HPD and TCAPS on the various components of auditory situation awareness that are measured by the DRILCOM battery. Such a percentage-based metric may be more easily understood by some than the parameter-based measures that are collected by DRILCOM and reported previously in detail herein, such as Detection threshold shift in dB above open ear threshold, frequency of correct Recognitions/Identifications and response time, Localization accuracy in degrees and response time in seconds, and SNR loss in COMmunication. It is stressed that these parameter-based measures are very important for quantifying, on a known scale of measurement, the situation awareness afforded by various devices and by the open ear, and the "percent worse/better than open ear" metric in no way replaces these parameter-based measures. Furthermore, the parameter measures yield the data points necessary for performing statistical tests that are required to ascertain whether numerical score differences amongst devices, or between devices and the open ear, are indeed statistically-reliable.

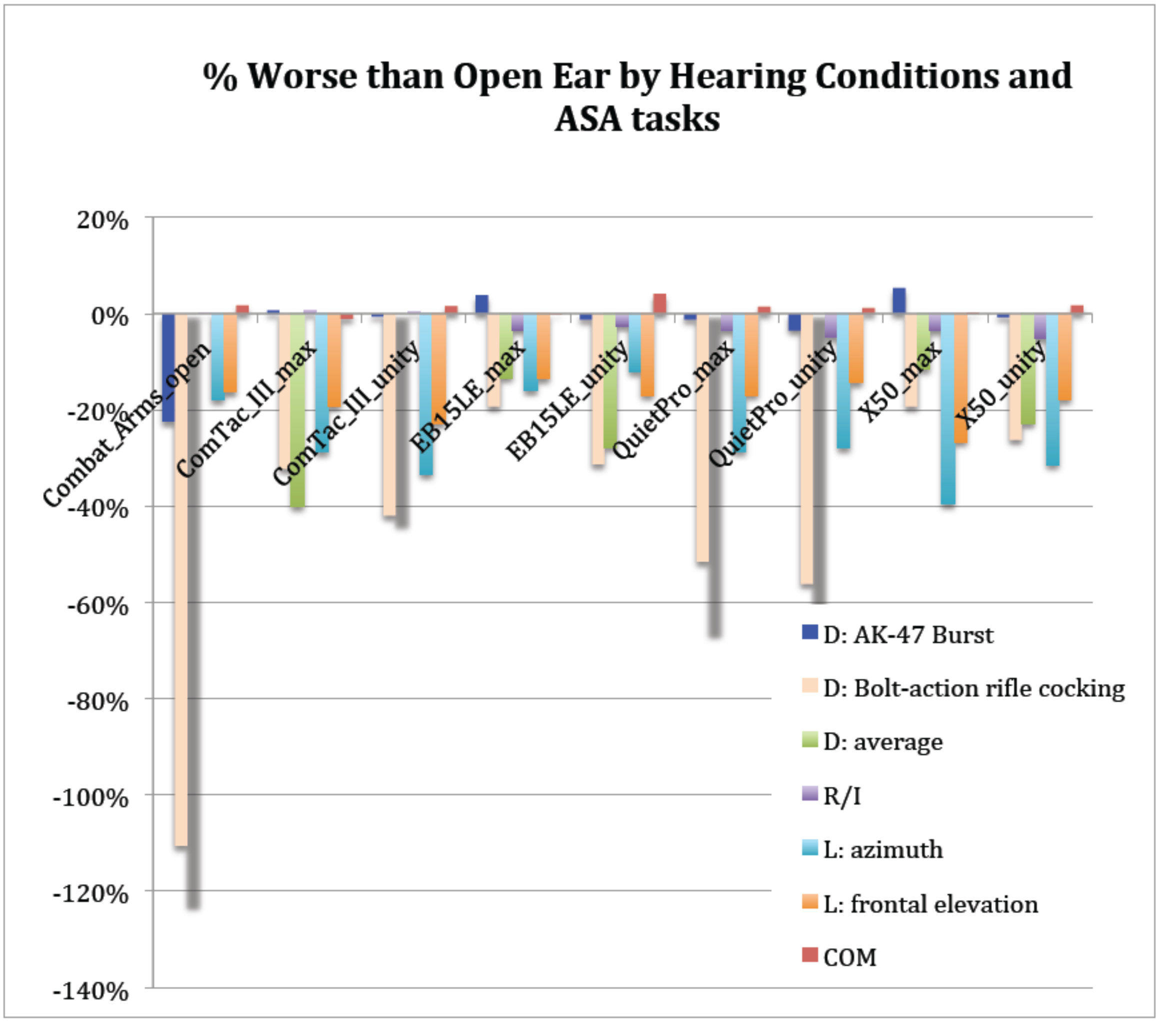

Figure 48. Percent worse (-) or better (+) than open ear, aggregated by hearing condition, with performance on all DRILCOM tests shown in each hearing condition (device) grouping.

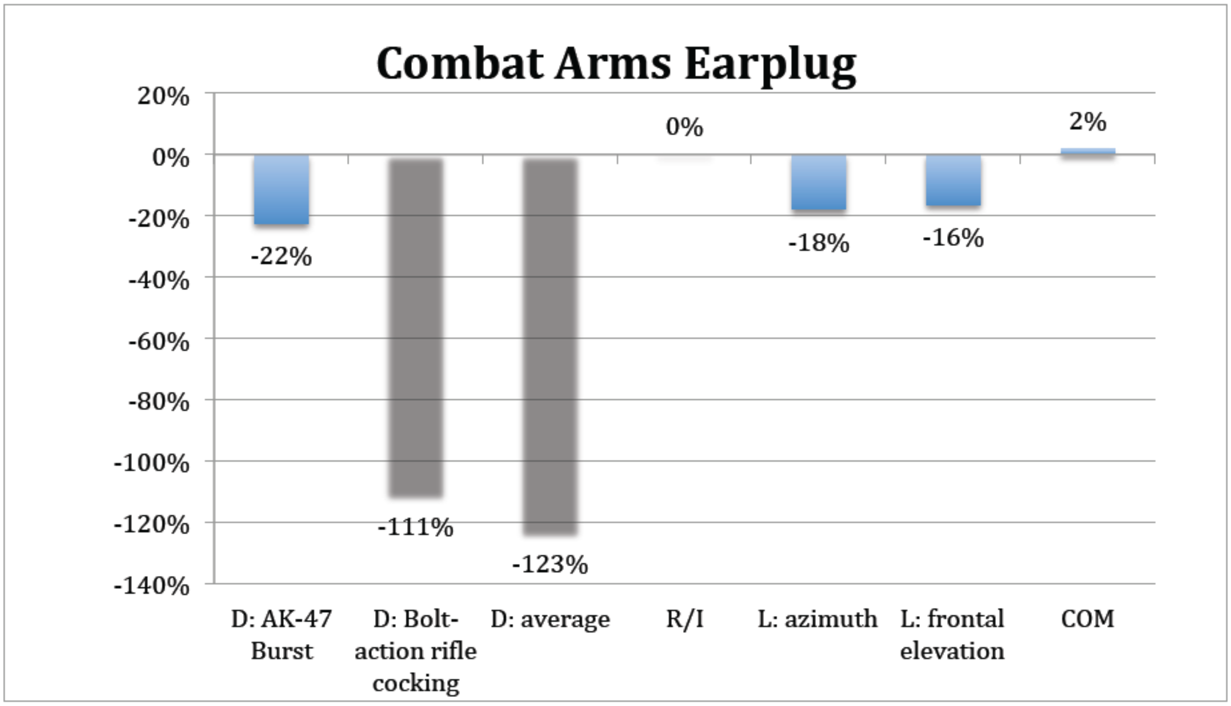

Figure 49. Combat Arms™ earplug-open end, measured as percent worse (-) or better (+) than open ear, with performance on all DRILCOM tests shown.

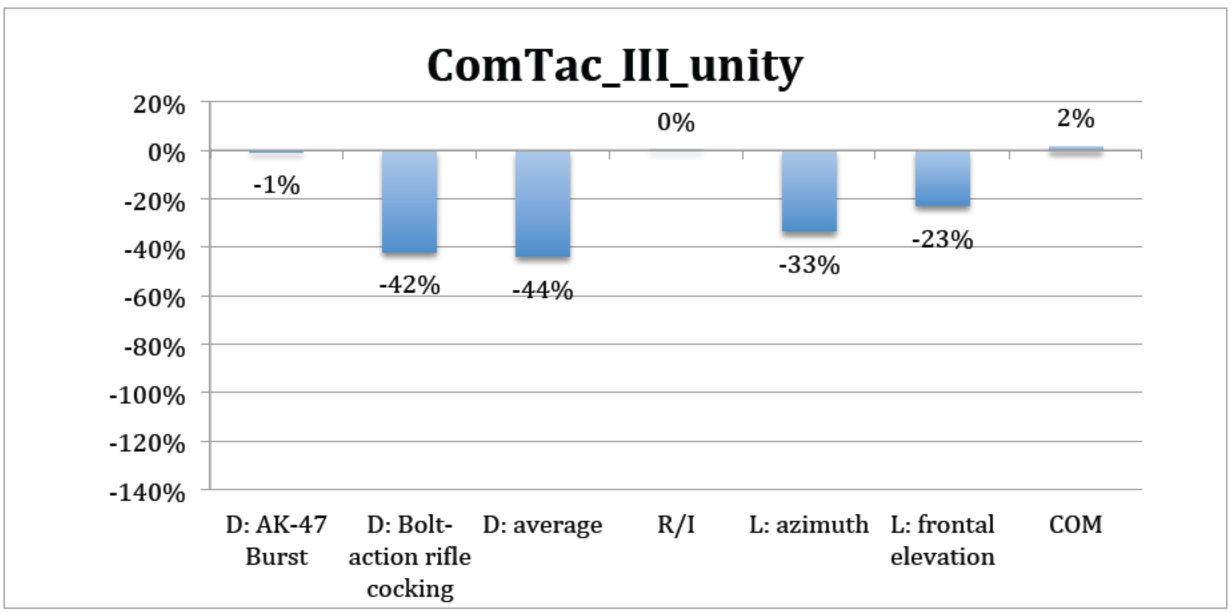

Figure 50. Peltor ComTac III ™ electronic earmuff with unity gain, measured as percent worse (-) or better (+) than open ear, with performance on all DRILCOM tests shown.

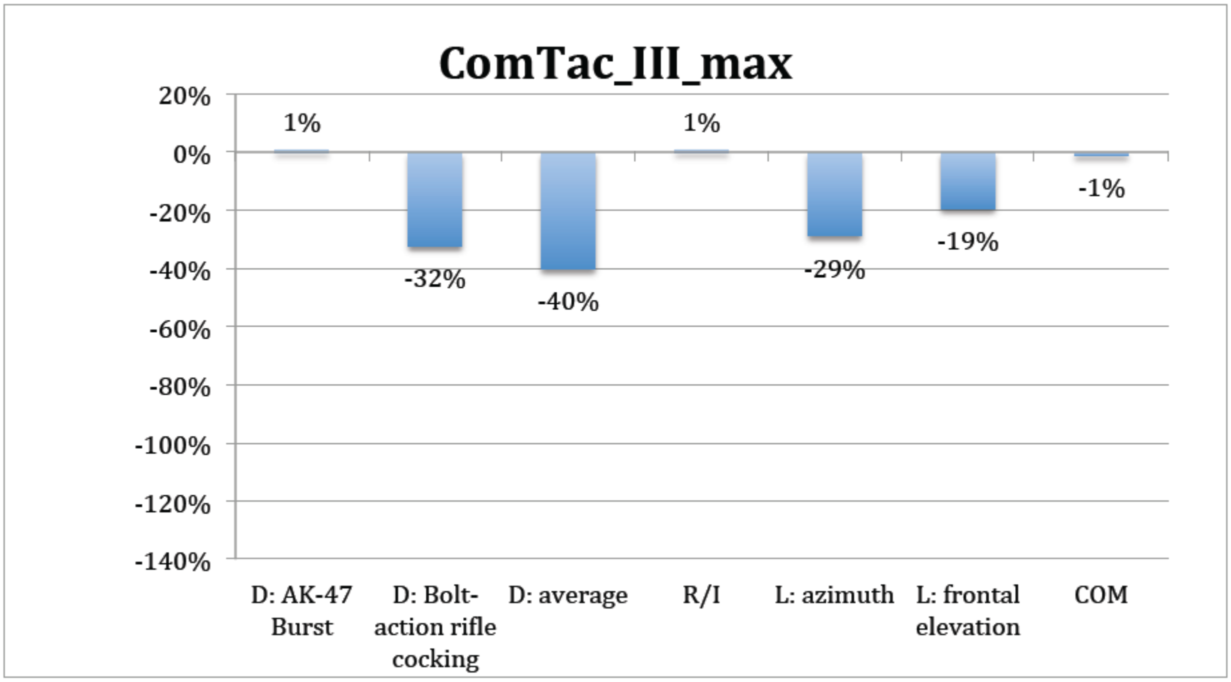

Figure 51. Peltor ComTac III ™ electronic earmuff with maximum gain, measured as percent worse (-) or better (+) than open ear, with performance on all DRILCOM tests shown.

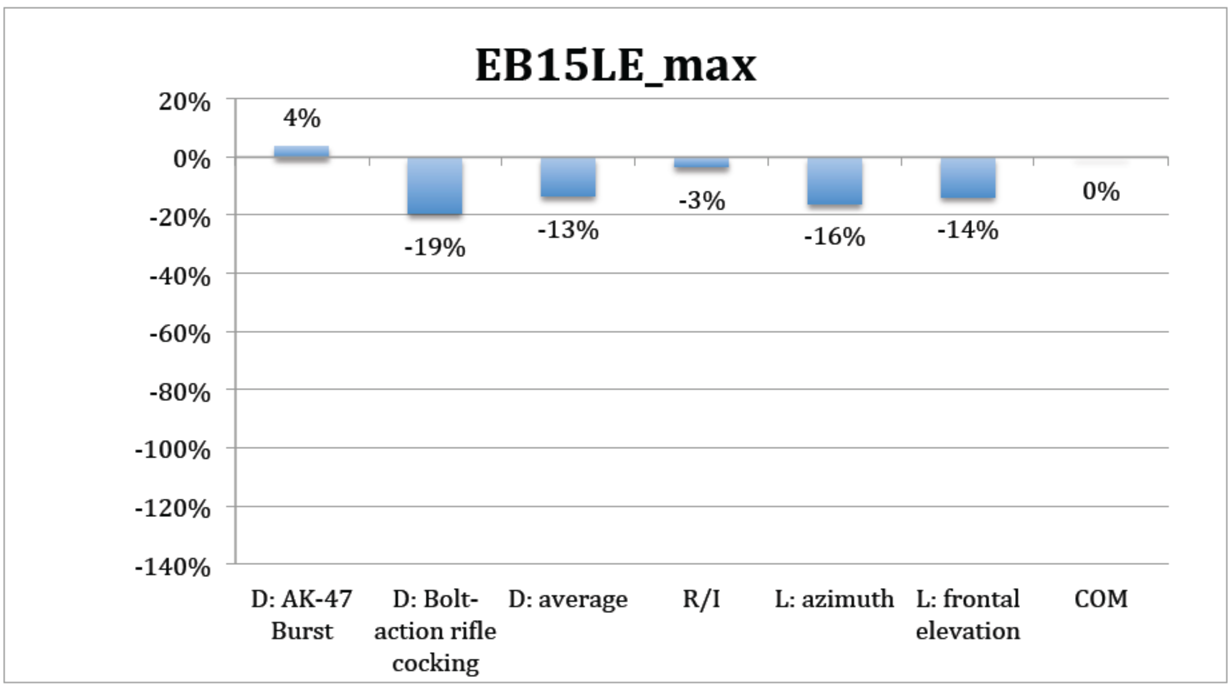

Figure 52. EB15LE™ electronic earplug with maximum gain, measured as percent worse (-) or better (+) than open ear, with performance on all DRILCOM tests shown.

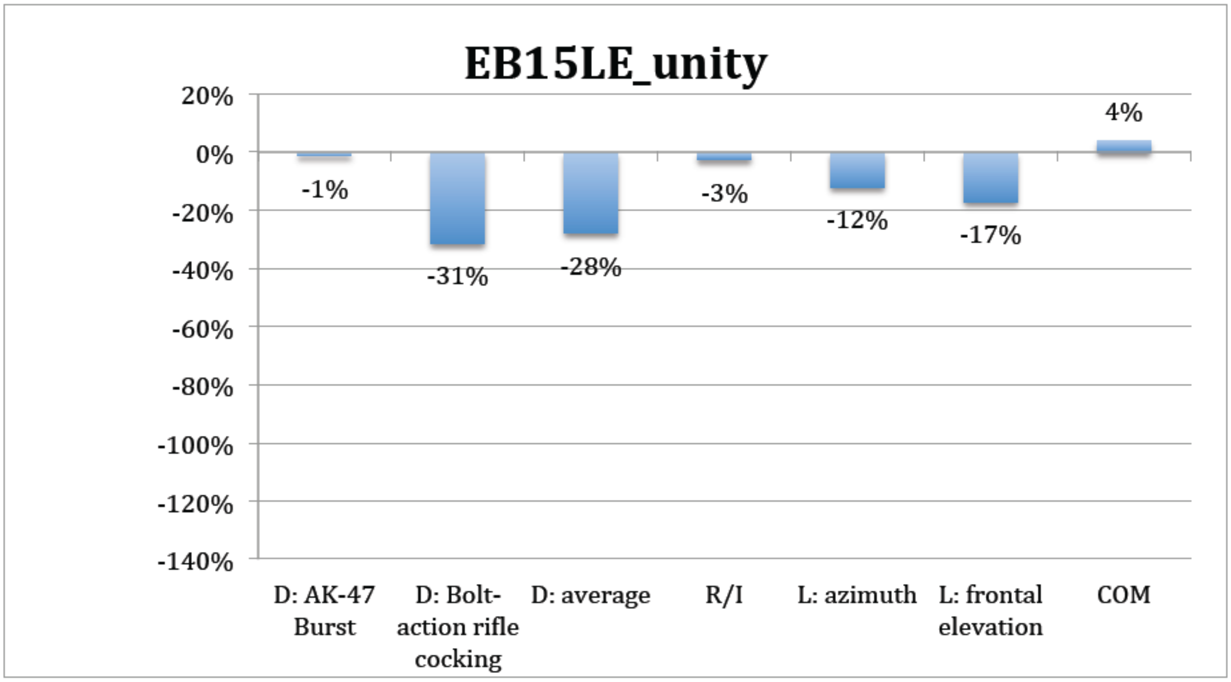

Figure 53. EB15LE™ electronic earplug with unity gain, measured as percent worse (-) or better (+) than open ear, with performance on all DRILCOM tests shown.

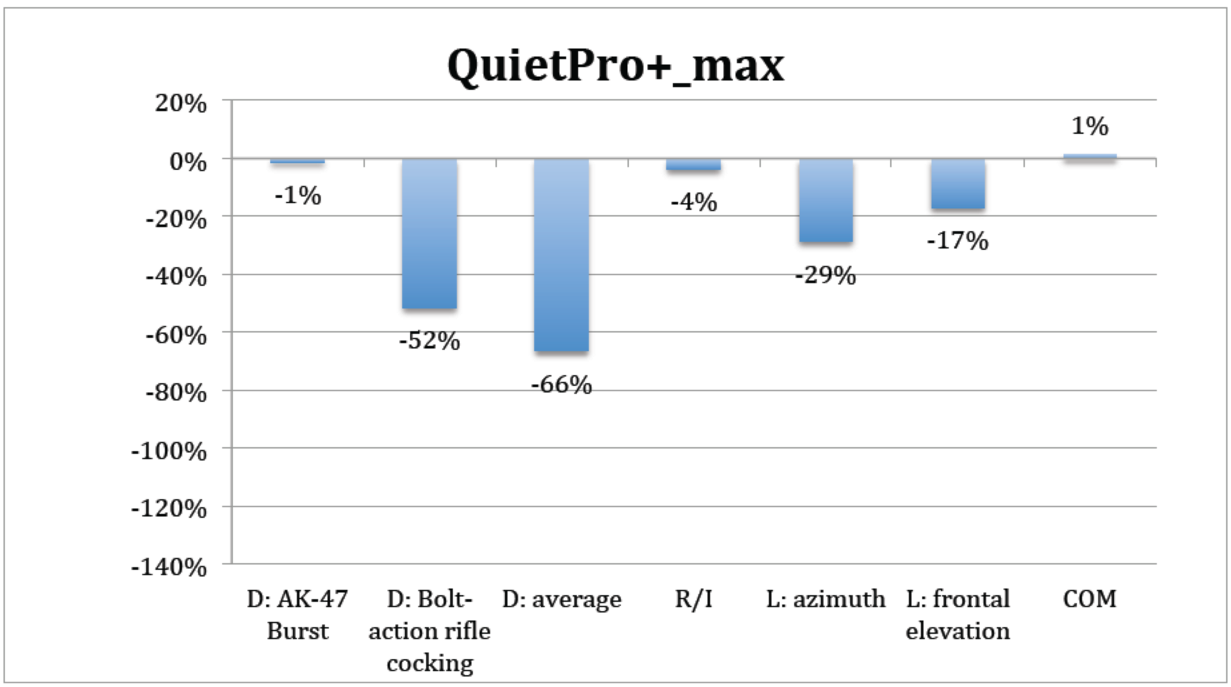

Figure 54. Quiet PRO+™ TCAPS with maximum gain, measured as percent worse (-) or better (+) than open ear, with performance on all DRILCOM tests shown.

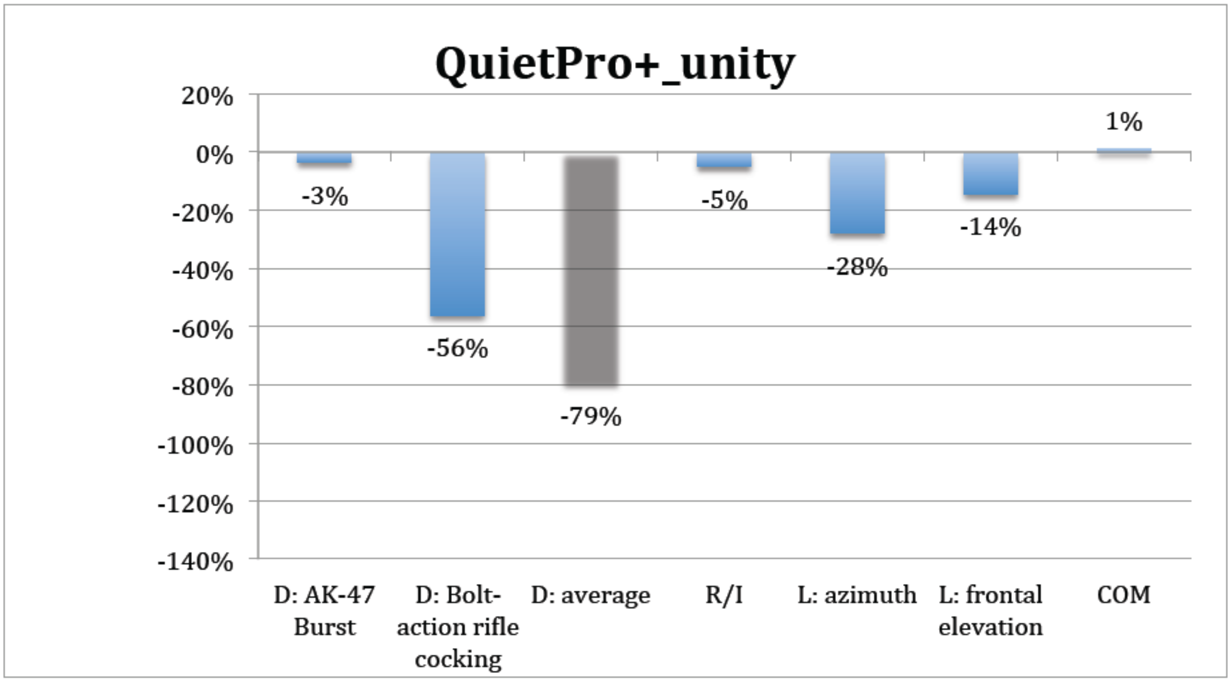

Figure 55. Quiet PRO+™ TCAPS with unity gain, measured as percent worse (-) or better (+) than open ear, with performance on all DRILCOM tests shown.

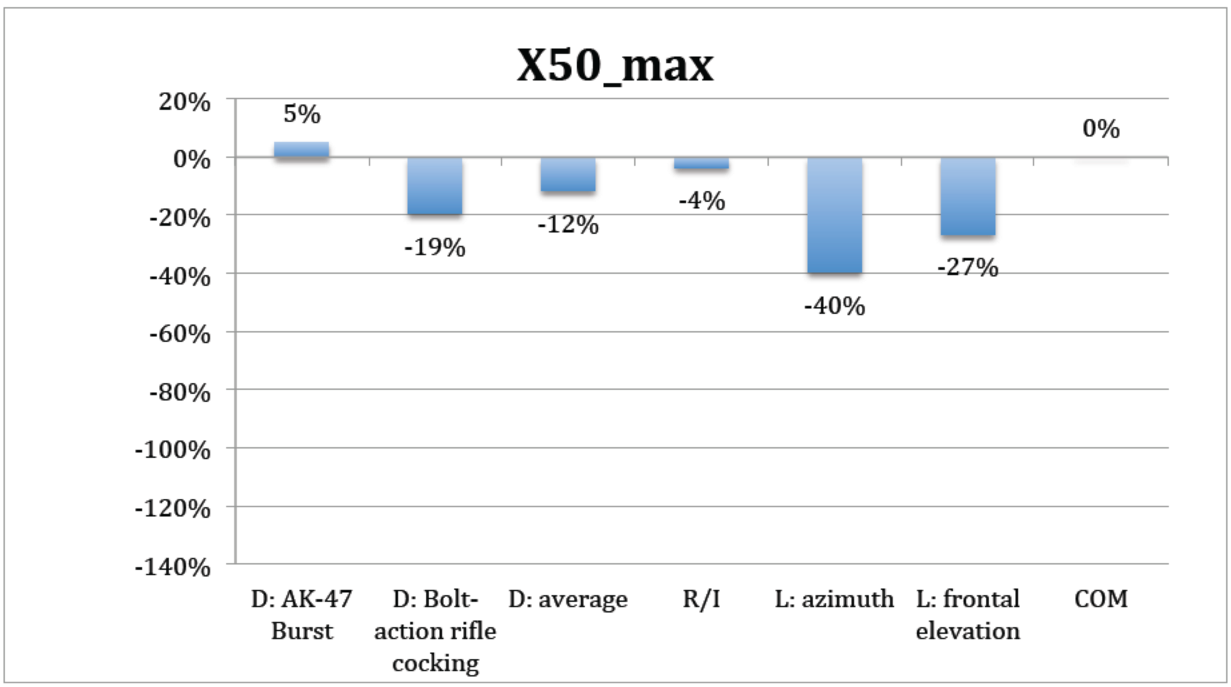

Figure 56. INVISIO X50™ TCAPS with maximum gain, measured as percent worse (-) or better (+) than open ear, with performance on all DRILCOM tests shown.

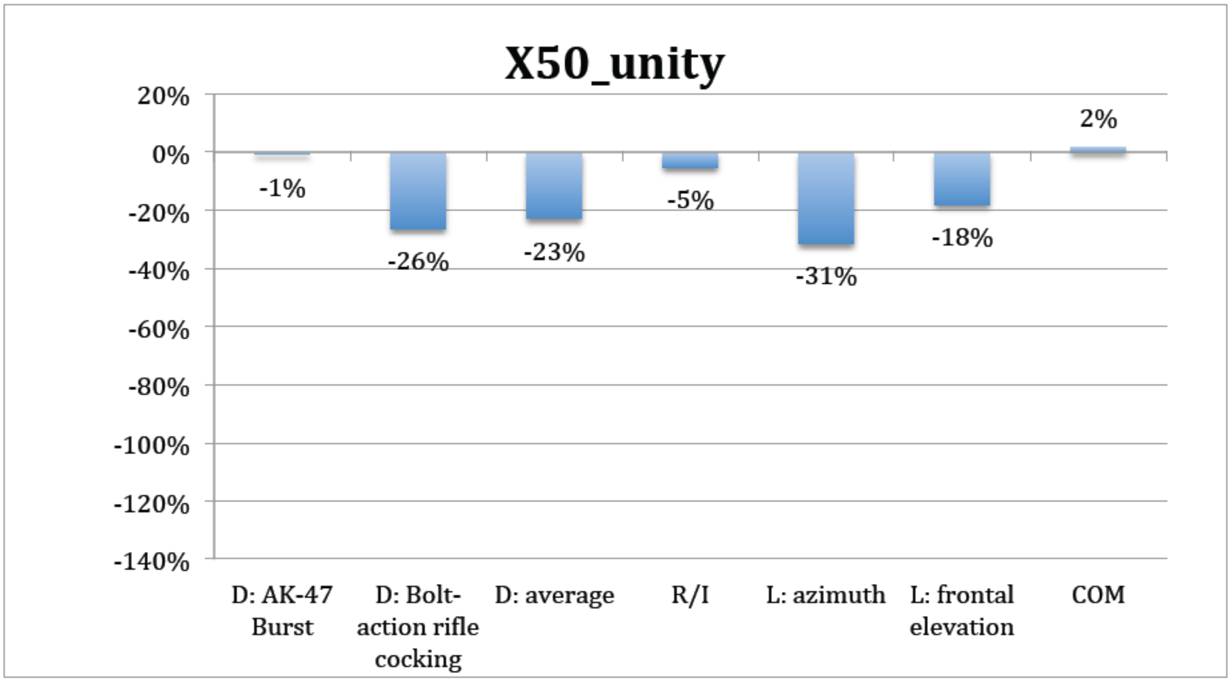

Figure 57. INVISIO X50™ TCAPS with unity gain, measured as percent worse (-) or better (+) than open ear, with performance on all DRILCOM tests shown.

RECOMMENDATIONS FOR APPLICATIONS OF THE DRILCOM TEST BATTERY AND RESULTS FROM THE EXPERIMENT

1. Since the significant negative effects of some advanced HPDs and TCAPS on auditory situation awareness has now been clearly and objectively demonstrated via seven experiments at the VT-ASL (five of military relevance and two of road construction relevance), as well as many anecdotal experiences from field reports, it is imperative that this problem be promptly addressed from both objective measurement and design improvement standpoints. The DRILCOM test battery can help serve both purposes, i.e., 1) to evaluate products *prior to* their selection and military deployment, and 2) to provide an objective means for feedback into the design/development cycle for retrofitting current devices and developing improved new ones. The former should be considered by DoD for application to performance requirements and procurement procedures. The latter should be applied by manufacturers of TCAPS and advanced HPDs. The DRILCOM battery has now been demonstrated, in the proof-of-concept experiment, to be a viable test procedure which is *sensitive* to performance differences amongst various devices, and between those devices and the open ear performance of a user, offering statistically-reliable results and reasonable statistical power with a small subject sample. (i.e., n=10 in the experiment) Thus, the DRILCOM test battery offers an empirical, relatively efficient, and face-valid means by which to conduct single product evaluations or multiple product comparison prior to selection and deployment.

2. In view that the DRILCOM test battery targets the four major auditory task aspects of auditory situation awareness (ASA), it can be used to help match an advanced HPD or TCAPS to specific MOS requirements or mission tactical requirements, for instance those which stress in-field threat localization or reliance on face-to-face communications. This can help ensure that there is a listing of acceptable products that are amenable to the specific auditory requirements for each MOS or mission, helping warfighters to receive the most compatible product for their situation.

3. Since the DRILCOM test battery is designed with four orthogonal, independent tests, it allows easy modification of stimuli (e.g., masking noise, wind, signal direction) conditions. Thus, the battery's test conditions can be altered to make individual DRILCOM tests more in line with MOS or mission-specific situation awareness needs.

4. Though it will require considerable additional work and careful military criteria-setting, another possible application of the DRILCOM test battery would ultimately be for the military to establish minimum performance requirements for advanced HPDs and TCAPS with respect to auditory situation awareness. (This is not being advocated by the VT-ASL research team, but is explained here due to questions that have been posed to the team about this aspect.) One likely benefit of criteria establishment would be to help motivate manufacturers to understand the expectations of the military for such devices, to work to develop devices that meet those expectations, and to demonstrate compliance via objective DRILCOM testing. (The latter could be a requirement placed on the manufacturer to provide the data, but a qualified DRILCOM-capable laboratory would need to be available and

contracted.) As mentioned in recommendation 1 above, manufacturers can readily apply the DRILCOM battery for determining whether performance requirements are being met within the design cycle, by applying the four DRILCOM tasks in a test-and-evaluation sense for improving product development and checking quality control before sale. Furthermore, the test results may suffice to provide objective, empirical support for literature and advertising claims, which to this point have not had such benefit of a comprehensive test battery for yielding objective data about device performance, and thus such claims could possibly be rather hollow in some instances.

5. As demonstrated by Casali and Robinette (2015), individual training with an assigned advanced HPD or TCAPS is important prior to actual field use. DRILCOM can be useful in this application to serve as a training system where warfighters can gain experience with assigned TCAPS under various acoustic conditions and signals, to a known performance criterion, prior to deployment with their devices. DRILCOM provides a comprehensive set of sensory-perceptual-cognitive tasks that rely on auditory information, and thus its stimulus conditions can be applied in a training sense to foster a user's learning with the device, and its measurement capabilities offer a means by which to determine when training effects, positive or negative, have indeed occurred. In similar fashion, the DRILCOM measures can also help determine if a warfighter who has some level of hearing loss can be hearing-assisted with an advanced HPD or TCAPS which provides appropriate input-to-output gain.

6. In view that DRILCOM provides a comprehensive assessment of the situation awareness effects of devices in a variety of auditory tasks, manufacturers and/or the military can use the empirical data obtained to develop custom instructions and training protocols that are tailored to individual devices and specific mission scenarios.

7. The VT-ASL research team respectfully recommends that this report be reviewed for military-sensitive information which may be present, particularly that based on discoveries in the proof-of-concept experiment. Thereafter, if it is deemed that the report is suitable to released for public dissemination, even after redaction of certain passages or figures as necessary, it is strongly recommended that the report be supplied to manufacturers of advanced HPDs and TCAPS for military and law enforcement applications. These manufacturers should have the benefit of gaining an increased awareness of the implications of compromised auditory situation awareness (ASA), the DRILCOM battery or other test procedures for measurement of ASA, and the objective performance data on example current devices yielded by the experiment reported herein, much of which demonstrate a degradation of ASA performance as compared to the open ear.

RECOMMENDATIONS FOR FUTURE RESEARCH

1. The DRILCOM test battery is composed of four tests that each represents a very different aspect of auditory situation awareness (ASA). Because the fundamental purpose of the current project was to develop a comprehensive ASA test battery but not a pass/fail product test or criteria therefor, an initial decision to keep each measurement scores from the four different tests as wholly separate was made. However, with the test battery now developed and subjected to a proof-of-concept experiment, it is possible to work toward the development of multiple regression predictors of overall ASA performance (possibly a single ASA score), via an appropriate formulae-based combination of the independent DRILCOM test scores from its four component tests. Such a predictive regression model, to output an overall ASA score that reflects expected device performance based on a combination of variables, may prove beneficial.

2. One subject can undergo the entire DRILCOM test battery (both open ear and a single device condition) in a little over two hours. Thus, if 10 subjects are required (as in the proof-of-concept experiment), the total DRILCOM assessment time per product will be about 20-25 hours. It may be beneficial to look toward development of a “DRILCOM-light” procedure to reduce testing time by optimizing the number of the most important stimuli, noise conditions, and directionality presentations -- this would save time and funds for the testing agency, which could be either the military or manufacturers. If “DRILCOM-light” is indeed a desirable objective, the first concentrated effort will be made to reduce the Detection test, as it takes about 60-70 % of total DRILCOM test time.

3. An exploratory study with two low-level (5 and 10 mph) wind speeds was conducted as an add-on experiment during the test battery development, with an eye toward determining if it is feasible to investigate wind effects in the laboratory environment. But before wind effects testing is integrated into the DRILCOM battery, additional experiments will need to be conducted with a wider spectrum of wind speed, random gusting vs. continuous wind, and azimuthal/vertical directions of wind.

4. While the DRILCOM test protocol is automated via PC computer to the degree possible, both for control and data capture, an experimenter will still need to run individual tests separately with some manual control input over and above the computer control. This compromise was unavoidable for building a prototype test battery that is relatively economical, with off-the-shelf hardware, to build and operate. A fully computer-controlled automatic DRILCOM test protocol presentation, integrating Detection, Recognition/Identification, Localization, and COMmunication into a single computer program with full data recording/reduction would make the test battery more adaptable by military agencies and other laboratories. One goal would be the computer generation of a test report generation, because the current computer program only produces raw data which is input to an excel spreadsheet, and thus a researcher needs to perform some post-test processing of data.

5. Because the DRILCOM test battery is designed to measure four specific and highly different aspects of auditory situation awareness in very objective terms, it does not include any ancillary test modules such as a one for usability test and evaluation. Therefore, it is recommended that consideration be given to the addition of an efficient human factors usability test module for assessing the form, function, switchgear functionality, intuitiveness of operation, fit quality, comfort, and overall acceptability of a device to an end user. While separate from DRILCOM per se, such a usability module will be complementary and provide important data about a device's appropriateness for field deployment.

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APPENDICES

A. Experimenter's test protocol for single test session of Detection test

B. Experimenter's test protocol for single test session of Recognition/Identification test

C. Experimenter's test protocol for single test session of Localization test

D. Experimenter's test protocol for single test session of Communication test

E. Proof-of-Concept Experimental Results: Detection Test

F. Proof-of-Concept Experimental Results: Recognition/Identification test

G. Proof-of-Concept Experimental Results: Localization test

H. Proof-of-Concept Experimental Results: Communication test

A. Experimenter's test protocol for single test session of Detection test

1. Turn on all equipment: TDT system, background noise system, PC and signal speakers.
2. Before a subject arrives at the lab, run daily calibration program if this is the first test of the day. Daily calibration program needs to be run only once per day as the results are saved in a file that is read by the main program to run the detection test.
3. Greet the subjects and present informed consent form document and get signature if it's not done previously.
4. Place the subject at the center of the room.
5. Fit the subject with test device and gain setting to be tested.
6. Start the main program (MatLab program) and enter all information about the test session including subject information and device information. There is also a section titled note where experimenter can store any additional note.
7. Start the background noise by turning on CD player with a CD marked as 40 dBA pink noise.
8. Direct the test signal to the speaker at 12, 3, 6, and 9 o'clock direction per program instruction.
9. Inform the subject that test will start soon and start the test.
10. Repeat 6-9 for the other three directions.

- Programs used: Windows 7, MatLab, TDT RPvdsEx, TDT ActiveX.
- Equipment: Behritone C50A powered speakers were used as signal speakers. A QSC CX1102 power amplifier and 4 JBL SoundPower SP215-6 speakers were used to form background noise system. A TDT RP2.1 real time processor and a PA5 programmable attenuator were used to create detection test signals. A response switch with custom-made adapter was used to capture subject response.
- Larson Davis 2800 real time spectrum analyzer with ½" microphone and a QC20 calibrator was used to do the calibration task.

B. Experimenter's test protocol for single test session of Recognition/Identification test

1. Turn on all equipment: Background noise system, PC and signal speakers.
2. Before a subject arrives at the lab, check calibration of each signal speakers by playing 1/3 octave band with center frequency of 1000 Hz and adjust each speaker output as 70 dBA.
3. Greet the subjects and present informed consent form document and get signature if it's not done previously.
4. Place the subject at the center of the room.
5. Fit the subject with test device and gain setting to be tested.
6. Start the main test program and set all test relevant information: subject ID, test device, gain setting, SNR.
7. Start the CD player and play correct pink noise file: 60, 70, and 80 dBA for SNR of 10,0, and -10 respectively.
8. Inform the subject that test will start soon and start the program for testing.
9. The program will run test with both 12 o'clock and 3 o'clock signal speakers.
10. Repeat 6-9 for the other two SNR.

- Programs used: Windows 7, LabView 2013, VT-ASL proprietary R/I test program.
- Equipment: Behritone C50A powered speakers were used as signal speakers. A QSC CX1102 power amplifier and 4 JBL SoundPower SP215-6 speakers were used to form background noise system. A second monitor and a mouse were used to capture subject response.
- Larson Davis 2800 real time spectrum analyzer with ½" microphone and a QC20 calibrator was used to do the calibration task.

C. Experimenter's test protocol for single test session of Localization test

1. Turn on all equipment: background noise system, PC and signal speakers.
2. Before a subject arrives at the lab, check calibration of each signal speaker by playing 1/3 octave band with center frequency of 1000 Hz and adjust each speaker output as 70 dBA.
3. Greet the subjects and present informed consent form document and get signature if it's not done previously.
4. Place the subject at the center of the room.
5. Fit the subject with test device and gain setting to be tested.
6. Start the LabView localization test program
7. Set all test relevant information: subject id, test device, gain setting, test type (azimuth, elevation), signal level.
8. Inform the subject that test will start soon.
9. Start background noise (low or high) per test signal level.
10. Start the localization testing in the LabView program and move the cursor to subject screen.
11. Wait for the subject to finish all test trials.
12. Repeat 7-11 for other test conditions of the device: azimuth, elevation, low and high signal level.

- Programs: Windows 7, LabView 2013, VT-ASL proprietary L test program.
- Equipment: Behritone C50A powered speakers were used as signal speakers. A QSC CX1102 power amplifier and 4 JBL SoundPower SP215-6 speakers were used to form background noise system. A second monitor and a mouse were used to capture subject response.
- Larson Davis 2800 real time spectrum analyzer with ½" microphone and a QC20 calibrator was used to do the calibration task.

D. Experimenter's test protocol for single test session of Communication test

1. Turn on all equipment: Beltone audiometer, CD player with QuickSIN™ CD, signal speakers, subject microphone connected to an earphone for the experimenter.
2. Before a subject arrives at the lab, check calibration of the system by playing the calibration tone from the QuickSIN™ CD through each signal speaker (12, 3,6, and 9 o'clock positions) and adjust gain on the audiometer to measure.
3. Greet the subjects and present informed consent form document and get signature if it's not done previously.
4. Place the subject at the center of the room.
5. Fit the subject with test device and gain setting to be tested.
6. Direct the test signal to one of the signal speaker.
7. Inform the subject that test will start soon.
8. Play one of the QuickSIN™ tests.
9. Record number of correct answers as the subject repeats played sentences.
10. Repeat 6-9 for the three other speaker directions.

- Program: QuickSIN™ test program by Etymotic.
- Equipment: Behritone C50A powered speakers were used as signal speakers. A Sony CD player and Beltone audiometer were used to create test speeches from a QuickSIN™ CD.
- Larson Davis 2800 real time spectrum analyzer with ½" microphone and a QC20 calibrator was used to do the calibration task.

E. Proof-of-Concept Experimental Results: Detection Test (means, upper and lower 90% confidence interval bounds, and statistically-significant differences at *p*<0.10 indicated by different letters)

Response 125, 250, 500, 1000, 2000, 4000, and 8000 means test signal of 1/3-OB with center frequency of 125, 250, 500, 1000, 2000, 4000, and 8000, respectively. Response BARC means bolt-action rifle cocking. Test direction of 3, 6, 9, and 12 means the signal speaker was located at the right (3), behind (6), left (9), and directly in front (12) of the subject.

Response 125 Test direction=3		Mean	Lower 90%	Upper 90%	Response 125 Test direction=6		Mean	Lower 90%	Upper 90%
QuietPro+_unity_	A	6.97	5.27	8.67	EB15LE_unity_	A	7.76	6.00	9.52
QuietPro+_max_	AB	4.77	3.07	6.47	QuietPro+_unity_	A	7.17	5.41	8.93
X50_max_	AB	4.34	2.64	6.04	QuietPro+_max_	AB	6.12	4.36	7.88
EB15LE_unity_	AB	4.28	2.58	5.98	X50_unity_	ABC	5.6	3.84	7.36
X50_unity_	ABC	4.04	2.34	5.74	X50_max_	ABCD	4.38	2.62	6.14
ComTac_III_unity_	BCD	1.57	-0.13	3.27	EB15LE_max_	BCD	2.63	0.87	4.39
EB15LE_max_	CD	1	-0.70	2.70	ComTac_III_unity_	CD	2.55	0.79	4.31
ComTac_III_max_	CD	0.83	-0.87	2.53	Combat_Arms_open	D	1.73	-0.03	3.49
Combat_Arms_open	D	0.36	-1.34	2.06	ComTac_III_max_	D	1.66	-0.10	3.42

Response 250 Test direction=3		Mean	Lower 90%	Upper 90%	Response 250 Test direction=6		Mean	Lower 90%	Upper 90%
QuietPro+_unity_	A	4.84	3.39	6.29	QuietPro+_unity_	A	5.52	3.63	7.41
X50_unity_	A	4.44	2.99	5.89	QuietPro+_max_	AB	5.33	3.44	7.22
QuietPro+_max_	AB	3.55	2.10	5.00	EB15LE_unity_	ABC	4.49	2.60	6.38
EB15LE_unity_	ABC	2.46	1.01	3.91	X50_unity_	ABC	4.29	2.40	6.18
X50_max_	BCD	1.15	-0.30	2.60	Combat_Arms_open	ABCD	2.76	0.87	4.65
Combat_Arms_open	CD	0.45	-1.00	1.90	X50_max_	BCDE	2.17	0.28	4.06
EB15LE_max_	CD	0.39	-1.06	1.84	EB15LE_max_	CDE	1.64	-0.25	3.53
ComTac_III_max_	D	-0.93	-2.38	0.52	ComTac_III_unity_	DE	-0 24	-2.13	1.65
ComTac_III_unity_	D	-1.71	-3.16	-0.26	ComTac_III_max_	E	-0.78	-2.67	1.11

Response 500 Test direction=3		Mean	Lower 90%	Upper 90%	Response 500 Test direction=6		Mean	Lower 90%	Upper 90%
QuietPro+_unity_	A	1.53	-0.15	3.21	QuietPro+_unity_	A	3.69	2.14	5.24
Combat_Arms_open	A	1.52	-0.16	3.20	QuietPro+_max_	A	3.65	2.10	5.20
QuietPro+_max_	AB	0.47	-1.21	2.15	Combat_Arms_open	A	3.54	1.99	5.09
EB15LE_unity_	AB	0.23	-1.45	1.91	EB15LE_unity_	AB	2.64	1.09	4.19
ComTac_III_unity_	ABC	-0.28	-1.96	1.40	ComTac_III_unity_	AB	1.74	0.19	3.29
ComTac_III_max_	ABC	-0.48	-2.16	1.20	ComTac_III_max_	AB	1.65	0.10	3.20
X50_unity_	ABC	-0.67	-2.35	1.01	EB15LE_max_	AB	1.23	-0.32	2.78
EB15LE_max_	BC	-1.46	-3.14	0.22	X50_unity_	B	-0 19	-1.74	1.36
X50_max_	C	-2.36	-4.04	-0.68	X50_max_	B	-0.44	-1.99	1.11

Response 1000 Test direction=3		Mean	Lower 90%	Upper 90%	Response 1000 Test direction=6		Mean	Lower 90%	Upper 90%
Combat_Arms_open	A	3.96	2.20	5.72	Combat_Arms_open	A	4.65	2.94	6.36
ComTac_III_max_	AB	1.1	-0.66	2.86	QuietPro+_unity_	B	1.19	-0.52	2.90
ComTac_III_unity_	B	0.69	-1.07	2.45	EB15LE_unity_	B	0.95	-0.76	2.66
EB15LE_unity_	B	0.28	-1.48	2.04	QuietPro+_max_	BC	0.44	-1.27	2.15
QuietPro+_unity_	B	-0.7	-2.46	1.06	ComTac_III_max_	BC	0.4	-1.31	2.11
X50_max_	B	-0.73	-2.49	1.03	ComTac_III_unity_	BC	-0.48	-2.19	1.23
EB15LE_max_	B	-0.81	-2.57	0.95	EB15LE_max_	BC	-0.73	-2.44	0.98
QuietPro+_max_	B	-0.89	-2.65	0.87	X50_max_	BC	-1.6	-3.31	0.11
X50_unity_	B	-0.99	-2.75	0.77	X50_unity_	C	-2.01	-3.72	-0.30

Response 2000 Test direction=3		Mean	Lower 90%	Upper 90%	Response 2000 Test direction=6		Mean	Lower 90%	Upper 90%
Combat_Arms_open	A	9.5	7.10	11.90	Combat_Arms_open	A	9.39	7.71	11.07
QuietPro+_unity_	B	2.8	0.40	5.20	ComTac_III_max_	B	2.64	0.96	4.32
ComTac_III_unity_	B	2.73	0.33	5.13	QuietPro+_unity_	B	1.77	0.09	3.45
ComTac_III_max_	B	2.09	-0.31	4.49	ComTac_III_unity_	B	1.22	-0.46	2.90
EB15LE_unity_	B	1.51	-0.89	3.91	QuietPro+_max_	B	1.06	-0.62	2.74
QuietPro+_max_	B	1.38	-1.02	3.78	EB15LE_unity_	B	0.96	-0.72	2.64
EB15LE_max_	B	1.22	-1.18	3.62	X50_unity_	B	0.63	-1.05	2.31
X50_max_	B	0.57	-1.83	2.97	EB15LE_max_	B	0.19	-1.49	1.87
X50_unity	B	0.51	-1.89	2.91	X50_max	B	-0.01	-1.69	1.67

Response 4000 Test direction=3		Mean	Lower 90%	Upper 90%	Response 4000 Test direction=6		Mean	Lower 90%	Upper 90%
Combat_Arms_open	A	11.7	9.85	13.55	Combat_Arms_open	A	12.41	10.57	14.25
QuietPro+_max_	B	4.6	2.75	6.45	ComTac_III_unity_	B	5.61	3.77	7.45
QuietPro+_unity_	B	4.06	2.21	5.91	QuietPro+_max_	B	4.68	2.84	6.52
X50_unity_	BC	3.13	1.28	4.98	ComTac_III_max_	BC	3.99	2.15	5.83
EB15LE_unity_	BCD	2.34	0.49	4.19	QuietPro+_unity_	BC	3.62	1.78	5.46
X50_max_	BCD	1.25	-0.60	3.10	X50_max_	BC	2.73	0.89	4.57
ComTac_III_unity_	BCD	1.06	-0.79	2.91	X50_unity_	BC	2.72	0.88	4.56
ComTac_III_max_	CD	-0.79	-2.64	1.06	EB15LE_unity_	C	1.53	-0.31	3.37
EB15LE_max	D	-0.88	-2.73	0.97	EB15LE_max	C	1.34	-0.50	3.18

Response 8000 Test direction=3		Mean	Lower 90%	Upper 90%	Response 8000 Test direction=6		Mean	Lower 90%	Upper 90%
Combat_Arms_open	A	27.74	24.88	30.60	Combat_Arms_open	A	22.68	18.88	26.48
QuietPro+_unity_	B	21	18.14	23.86	QuietPro+_unity_	B	13.67	9.87	17.47
QuietPro+_max_	BC	17.87	15.01	20.73	QuietPro+_max_	B	11.92	8.12	15.72
ComTac_III_unity_	BC	15.58	12.72	18.44	ComTac_III_max_	B	10.04	6.24	13.84
ComTac_III_max_	C	13.92	11.06	16.78	ComTac_III_unity_	B	9.94	6.14	13.74
EB15LE_unity_	D	7.21	4.35	10.07	EB15LE_unity_	C	2.84	-0.96	6.64
X50_unity_	D	6.32	3.46	9.18	EB15LE_max_	CD	1.43	-2.37	5.23
EB15LE_max_	D	3.18	0.32	6.04	X50_unity_	CD	-0.63	-4.43	3.17
X50_max	D	2.72	-0.14	5.58	X50_max	D	-2.71	-6.51	1.09

Response AK-47 Burst Test direction=3		Mean	Lower 90%	Upper 90%	Response AK-47 Burst Test direction=6		Mean	Lower 90%	Upper 90%
Combat_Arms_open	A	2.83	-3.61	9.27	Combat_Arms_open	A	2.62	-4.15	9.39
ComTac_III_max_	B	-2.16	-8.60	4.28	EB15LE_unity_	B	-2 19	-8.96	4.58
ComTac_III_unity_	B	-2.42	-8.86	4.02	QuietPro+_unity_	BC	-2.62	-9.39	4.15
QuietPro+_unity_	B	-3.22	-9.66	3.22	QuietPro+_max_	BC	-2.88	-9.65	3.89
X50_unity_	BC	-3.91	-10.35	2.53	ComTac_III_unity_	BC	-2 91	-9.68	3.86
EB15LE_unity_	BC	-4.06	-10.50	2.38	ComTac_III_max_	BC	-3 38	-10.15	3.39
QuietPro+_max_	BC	-4.56	-11.00	1.88	X50_unity_	BC	-3.66	-10.43	3.11
EB15LE_max_	BC	-5.16	-11.60	1.28	X50_max_	BC	-5.02	-11.79	1.75
X50_max	C	-6.57	-13.01	-0.13	EB15LE_max	C	-5.89	-12.66	0.88

Response BARC Test direction=3		Mean	Lower 90%	Upper 90%	Response BARC Test direction=6		Mean	Lower 90%	Upper 90%
Combat_Arms_open	A	16.38	8.50	24.26	Combat_Arms_open	A	9.57	1.60	17.54
QuietPro+_unity_	B	8.14	0.26	16.02	ComTac_III_unity_	B	2.73	-5.24	10.70
QuietPro+_max_	B	6.83	-1.05	14.71	ComTac_III_max_	B	2.22	-5.75	10.19
ComTac_III_unity_	BC	6.4	-1.48	14.28	QuietPro+_max_	BC	2.06	-5.91	10.03
ComTac_III_max_	BCD	4.43	-3.45	12.31	QuietPro+_unity_	BC	1.66	-6.31	9.63
EB15LE_unity_	BCD	3.98	-3.90	11.86	EB15LE_unity_	BCD	0.53	-7.44	8.50
X50_unity_	CD	1.61	-6.27	9.49	EB15LE_max_	CD	-1 3	-9.27	6.67
X50_max_	D	0.87	-7.01	8.75	X50_unity_	D	-2 34	-10.31	5.63
EB15LE_max	D	0.61	-7.27	8.49	X50_max	D	-2.85	-10.82	5.12

Response 125 Test direction=9		Mean	Lower 90%	Upper 90%	Response 125 Test direction=12		Mean	Lower 90%	Upper 90%
QuietPro+_unity_	A	9.31	7.79	10.83	QuietPro+_unity_	A	7.67	5.96	9.38
QuietPro+_max_	A	9.07	7.55	10.59	QuietPro+_max_	AB	6.03	4.32	7.74
EB15LE_unity_	AB	6.77	5.25	8.29	EB15LE_unity_	ABC	5.44	3.73	7.15
X50_max_	BC	5.26	3.74	6.78	X50_unity_	BCD	3.81	2.10	5.52
ComTac_III_unity_	BC	5.07	3.55	6.59	X50_max_	BCD	3.47	1.76	5.18
X50_unity_	BC	4.91	3.39	6.43	ComTac_III_unity_	CDE	2.48	0.77	4.19
ComTac_III_max_	BC	4.3	2.78	5.82	ComTac_III_max_	DE	1.26	-0.45	2.97
Combat_Arms_open	BC	3.92	2.40	5.44	EB15LE_max_	DE	0.88	-0.83	2.59
EB15LE_max_	C	3.46	1.94	4.98	Combat_Arms_open	E	-0.26	-1.97	1.45

Response 250 Test direction=9		Mean	Lower 90%	Upper 90%	Response 250 Test direction=12		Mean	Lower 90%	Upper 90%
QuietPro+_max_	A	5.3	3.57	7.03	QuietPro+_unity_	A	5.24	3.66	6.82
QuietPro+_unity_	AB	4.9	3.17	6.63	QuietPro+_max_	A	5.01	3.43	6.59
X50_unity_	AB	4.51	2.78	6.24	X50_unity_	AB	3.23	1.65	4.81
Combat_Arms_open	ABC	3.44	1.71	5.17	EB15LE_unity_	BC	2.3	0.72	3.88
EB15LE_unity_	ABCD	2.66	0.93	4.39	Combat_Arms_open	BC	2.26	0.68	3.84
X50_max_	BCD	2.08	0.35	3.81	X50_max_	BC	2.15	0.57	3.73
EB15LE_max_	CD	1.19	-0.54	2.92	EB15LE_max_	C	0.52	-1.06	2.10
ComTac_III_max_	D	0.03	-1.70	1.76	ComTac_III_unity_	C	0.09	-1.49	1.67
ComTac_III_unity_	D	-0.2	-1.93	1.53	ComTac_III_max_	C	-0.02	-1.60	1.56

Response 500 Test direction=9		Mean	Lower 90%	Upper 90%	Response 500 Test direction=12		Mean	Lower 90%	Upper 90%
Combat_Arms_open	A	2.74	1.22	4.26	QuietPro+_unity_	A	3.13	2.12	4.14
QuietPro+_unity_	A	2.53	1.01	4.05	QuietPro+_max_	AB	2.29	1.28	3.30
ComTac_III_max_	AB	1.94	0.42	3.46	Combat_Arms_open	ABC	1.93	0.92	2.94
QuietPro+_max_	AB	1.93	0.41	3.45	X50_unity_	BCD	0.48	-0.53	1.49
ComTac_III_unity_	AB	1.21	-0.31	2.73	EB15LE_unity_	BCD	0.42	-0.59	1.43
X50_unity_	AB	0.68	-0.84	2.20	ComTac_III_unity_	CD	-0.18	-1.19	0.83
EB15LE_max_	AB	0.63	-0.89	2.15	X50_max_	D	-0.34	-1.35	0.67
X50_max_	AB	-0.36	-1.88	1.16	EB15LE_max_	D	-0.35	-1.36	0.66
EB15LE_unity_	B	-1.16	-2.68	0.36	ComTac_III_max_	D	-0.92	-1.93	0.09

Response 1000 Test direction=9		Mean	Lower 90%	Upper 90%	Response 1000 Test direction=12		Mean	Lower 90%	Upper 90%
Combat_Arms_open	A	2.61	0.86	4.36	Combat_Arms_open	A	4.53	2.77	6.29
ComTac_III_unity_	AB	1.8	0.05	3.55	QuietPro+_max_	B	1.47	-0.29	3.23
QuietPro+_unity_	AB	0.8	-0.95	2.55	EB15LE_unity_	B	1.33	-0.43	3.09
EB15LE_max_	AB	0.53	-1.22	2.28	QuietPro+_unity_	B	1.27	-0.49	3.03
X50_unity_	AB	0.31	-1.44	2.06	X50_unity_	B	1.12	-0.64	2.88
ComTac_III_max_	AB	0.21	-1.54	1.96	X50_max_	B	0.3	-1.46	2.06
EB15LE_unity_	AB	-0.21	-1.96	1.54	EB15LE_max_	B	0.29	-1.47	2.05
QuietPro+_max_	AB	-0.32	-2.07	1.43	ComTac_III_max_	B	0.13	-1.63	1.89
X50_max_	B	-1.36	-3.11	0.39	ComTac_III_unity_	B	-0.58	-2.34	1.18

Response 2000 Test direction=9		Mean	Lower 90%	Upper 90%	Response 2000 Test direction=12		Mean	Lower 90%	Upper 90%
Combat_Arms_open	A	8.72	7.24	10.20	Combat_Arms_open	A	8.52	6.51	10.53
QuietPro+_unity_	B	2.25	0.77	3.73	QuietPro+_unity_	B	2	-0.01	4.01
X50_unity_	B	1.17	-0.31	2.65	X50_unity_	BC	1.59	-0.42	3.60
QuietPro+_max_	B	0.92	-0.56	2.40	EB15LE_unity_	BCD	0.39	-1.62	2.40
X50_max_	B	0.77	-0.71	2.25	QuietPro+_max_	BCD	0.19	-1.82	2.20
EB15LE_max_	B	0.7	-0.78	2.18	X50_max_	BCD	-0.07	-2.08	1.94
ComTac_III_max_	B	0.69	-0.79	2.17	EB15LE_max_	BCD	-0.21	-2.22	1.80
ComTac_III_unity_	B	0.62	-0.86	2.10	ComTac_III_unity_	CD	-1.25	-3.26	0.76
EB15LE_unity_	B	-0.21	-1.69	1.27	ComTac_III_max_	D	-1.88	-3.89	0.13

Response 4000 Test direction=9		Mean	Lower 90%	Upper 90%	Response 4000 Test direction=12		Mean	Lower 90%	Upper 90%
Combat_Arms_open	A	9.19	7.38	11.00	Combat_Arms_open	A	14.13	12.34	15.92
X50_unity_	AB	5.32	3.51	7.13	QuietPro+_unity_	B	4.68	2.89	6.47
QuietPro+_max_	BC	4.18	2.37	5.99	QuietPro+_max_	B	4.6	2.81	6.39
X50_max_	BC	3.95	2.14	5.76	X50_unity_	BC	3.41	1.62	5.20
QuietPro+_unity_	BC	3.56	1.75	5.37	EB15LE_unity_	BCD	1.94	0.15	3.73
ComTac_III_unity_	BC	2.31	0.50	4.12	X50_max_	BCD	1.9	0.11	3.69
ComTac_III_max_	BC	1.98	0.17	3.79	ComTac_III_unity_	BCD	1.46	-0.33	3.25
EB15LE_unity_	BC	1.58	-0.23	3.39	EB15LE_max_	CD	-0.4	-2.19	1.39
EB15LE_max	C	0.42	-1.39	2.23	ComTac_III_max	D	-1 38	-3.17	0.41

Response 8000 Test direction=9		Mean	Lower 90%	Upper 90%	Response 8000 Test direction=12		Mean	Lower 90%	Upper 90%
Combat_Arms_open	A	22.04	19.60	24.48	Combat_Arms_open	A	18.68	15.83	21.53
QuietPro+_unity_	B	17.21	14.77	19.65	QuietPro+_unity_	B	11.21	8.36	14.06
QuietPro+_max_	B	15.62	13.18	18.06	QuietPro+_max_	BC	6.8	3.95	9.65
ComTac_III_unity_	C	7.66	5.22	10.10	ComTac_III_unity_	CD	4.64	1.79	7.49
ComTac_III_max_	C	6.25	3.81	8.69	ComTac_III_max_	CDE	3.14	0.29	5.99
X50_unity_	C	5.69	3.25	8.13	EB15LE_unity_	DEF	1.14	-1.71	3.99
EB15LE_unity_	C	5.37	2.93	7.81	X50_unity_	EF	-1.6	-4.45	1.25
X50_max_	C	5.17	2.73	7.61	EB15LE_max_	EF	-1.76	-4.61	1.09
EB15LE_max	C	4.16	1.72	6.60	X50_max	F	-3 17	-6.02	-0.32

Response AK-47 Burst Test direction=9		Mean	Lower 90%	Upper 90%	Response AK-47 Burst Test direction=12			Lower 90%	Upper 90%
Combat_Arms_open	A	1.79	-4.88	8.46	Combat_Arms_open	A	3.21	-3.78	10.20
QuietPro+_unity_	B	-1.9	-8.57	4.77	QuietPro+_unity_	B	-2 18	-9.17	4.81
QuietPro+_max_	B	-2.09	-8.76	4.58	X50_unity_	BC	-2.46	-9.45	4.53
ComTac_III_max_	B	-2.71	-9.38	3.96	EB15LE_unity_	BCD	-2 99	-9.98	4.00
ComTac_III_unity_	B	-2.95	-9.62	3.72	QuietPro+_max_	BCD	-3.09	-10.08	3.90
EB15LE_max_	B	-3.08	-9.75	3.59	EB15LE_max_	BCD	-4 51	-11.50	2.48
X50_max_	B	-3.37	-10.04	3.30	X50_max_	CDE	-4 57	-11.56	2.42
EB15LE_unity_	B	-3.84	-10.51	2.83	ComTac_III_unity_	DE	-5 19	-12.18	1.80
X50_unity	B	-3.95	-10.62	2.72	ComTac_III_max	E	-6 93	-13.92	0.06

Response BARC Test direction=9		Mean	Lower 90%	Upper 90%	Response BARC Test direction=12		Mean	Lower 90%	Upper 90%
Combat_Arms_open	A	11.83	3.10	20.56	Combat_Arms_open	A	10.26	0.93	19.59
QuietPro+_max_	B	5.17	-3.56	13.90	QuietPro+_unity_	B	0.23	-9.10	9.56
QuietPro+_unity_	B	5.02	-3.71	13.75	QuietPro+_max_	BC	-1.64	-10.97	7.69
X50_unity_	C	1.59	-7.14	10.32	ComTac_III_unity_	BC	-2 54	-11.87	6.79
X50_max_	C	1.39	-7.34	10.12	X50_unity_	BCD	-3.43	-12.76	5.90
ComTac_III_unity_	C	1.06	-7.67	9.79	EB15LE_unity_	CD	-4.82	-14.15	4.51
EB15LE_unity_	C	0.37	-8.36	9.10	ComTac_III_max_	CD	-5 12	-14.45	4.21
EB15LE_max_	C	-0.14	-8.87	8.59	EB15LE_max_	D	-6.46	-15.79	2.87
ComTac_III_max	C	-0.33	-9.06	8.40	X50_max	D	-6.86	-16.19	2.47

F. Proof-of-Concept Experimental Results: Recognition/Identification Test (means, upper and lower 90% confidence interval bounds, and statistically-significant differences at *p*<0.10 indicated by different letters)

Speaker = 3 means that the signal speaker was located at 3 o'clock or right of the subject.

Speaker = 12 means that the signal speaker was located at 12 o'clock or right of the subject.

Response Time

Response Time wind=0, S/N Ratio=-10, Speaker=3

Level		Mean	Lower 90%	Upper 90%
QuietPro unity	A	1.89	1.563	2.210
Combat Arms	AB	1.35	1.027	1.674
ComTac III unity	AB	1.35	1.024	1.672
QuietPro+ max	AB	1.30	0.974	1.621
EB15LE unity	B	1.26	0.937	1.584
X50 unity	B	1.21	0.882	1.529
OPEN EAR	B	1.11	0.790	1.437
ComTac III max	B	1.09	0.769	1.417
EB15LE max	B	1.07	0.751	1.398
X50 max	B	1.01	0.688	1.335

Response Time wind=0, S/N Ratio=-10, Speaker=12

Level		Mean	Lower 90%	Upper 90%
QuietPro unity	A	1.56	1.310	1.814
EB15LE unity	AB	1.45	1.200	1.704
ComTac III unity	AB	1.35	1.096	1.601
Combat Arms	AB	1.34	1.085	1.589
X50 max	AB	1.31	1.055	1.560
QuietPro+ max	AB	1.29	1.035	1.539
OPEN EAR	AB	1.28	1.030	1.534
X50 unity	AB	1.19	0.935	1.440
EB15LE max	B	1.06	0.809	1.314
ComTac III max	B	1.04	0.793	1.297

Response Time wind=0, S/N Ratio=0, Speaker=3

Level		Mean	Lower 90%	Upper 90%
Combat Arms	A	1.25	0.938	1.564
QuietPro+ max	A	1.24	0.928	1.554
QuietPro unity	A	1.24	0.926	1.551
ComTac III unity	A	1.22	0.905	1.530
EB15LE max	A	1.21	0.893	1.518
X50 unity	A	1.12	0.810	1.435
X50 max	A	1.09	0.775	1.400
EB15LE unity	A	1.06	0.743	1.368
OPEN EAR	A	1.03	0.717	1.343
ComTac III max	A	0.96	0.646	1.272

Response Time wind=0, S/N Ratio=0, Speaker=12

Level		Mean	Lower 90%	Upper 90%
QuietPro unity	A	1.34	1.067	1.610
EB15LE max	A	1.24	0.965	1.508
ComTac III unity	A	1.20	0.929	1.472
Combat Arms	A	1.15	0.883	1.426
EB15LE unity	A	1.15	0.883	1.426
X50 max	A	1.11	0.842	1.385
QuietPro+ max	A	1.08	0.808	1.351
OPEN EAR	A	1.06	0.788	1.330
X50 unity	A	1.03	0.762	1.304
ComTac III max	A	0.96	0.693	1.235

Correct Answers

Result wind=0, S/N Ratio=-10, Speaker=3

Level		Mean	Lower 90%	Upper 90%
EB15LE unity	A	9.80	9.256	10.344
ComTac III max	A	9.70	9.156	10.244
ComTac III unity	A	9.50	8.956	10.044
EB15LE max	A	9.50	8.956	10.044
QuietPro+ max	A	9.50	8.956	10.044
X50 max	A	9.40	8.856	9.944
OPEN EAR	A	9.30	8.756	9.844
QuietPro unity	A	9.30	8.756	9.844
X50 unity	A	9.20	8.656	9.744
Combat Arms	A	8.90	8.356	9.444

Result wind=0, S/N Ratio=-10, Speaker=12

Level		Mean	Lower 90%	Upper 90%
ComTac III max	A	9.70	9.168	10.232
ComTac III unity	AB	9.50	8.968	10.032
OPEN EAR	AB	9.50	8.968	10.032
QuietPro+ max	AB	9.50	8.968	10.032
EB15LE max	AB	9.40	8.868	9.932
EB15LE unity	AB	9.40	8.868	9.932
Combat Arms	AB	9.10	8.568	9.632
X50 unity	AB	8.90	8.368	9.432
QuietPro unity	AB	8.80	8.268	9.332
X50 max	B	8.30	7.768	8.832

Result wind=0, S/N Ratio=0, Speaker=3

Level		Mean	Lower 90%	Upper 90%
Combat Arms	A	9.50	8.575	10.425
ComTac III max	A	9.40	8.475	10.325
ComTac III unity	A	9.40	8.475	10.325
OPEN EAR	A	9.40	8.475	10.325
X50 max	A	9.40	8.475	10.325
EB15LE unity	A	9.00	8.075	9.925
X50 unity	A	9.00	8.075	9.925
EB15LE max	A	8.90	7.975	9.825
QuietPro+ max	A	8.90	7.975	9.825
QuietPro unity	A	8.90	7.975	9.825

Result wind=0, S/N Ratio=0, Speaker=12

Level		Mean	Lower 90%	Upper 90%
ComTac III unity	A	9.50	8.566	10.434
OPEN EAR	A	9.50	8.566	10.434
Combat Arms	A	9.40	8.466	10.334
X50 max	A	9.40	8.466	10.334
ComTac III max	A	9.20	8.266	10.134
EB15LE unity	A	9.10	8.166	10.034
EB15LE max	A	8.90	7.966	9.834
QuietPro unity	A	8.90	7.966	9.834
X50 unity	A	8.90	7.966	9.834
QuietPro+ max	A	8.80	7.866	9.734

Response Time wind=0, S/N Ratio=10, Speaker=3				
Level		Mean	Lower 90%	Upper 90%
ComTac III unity	A	1.20	0.955	1.446
EB15LE unity	A	1.07	0.822	1.313
EB15LE max	A	1.06	0.812	1.303
QuietPro+ unity	A	1.04	0.799	1.290
ComTac III max	A	1.04	0.792	1.282
X50 max	A	1.03	0.786	1.276
OPEN EAR	A	1.02	0.775	1.266
X50 unity	A	0.98	0.733	1.224
QuietPro+ max	A	0.97	0.727	1.217
Combat Arms	A	0.97	0.721	1.212

Result wind=0, S/N Ratio=10, Speaker=3				
Level		Mean	Lower 90%	Upper 90%
Combat Arms	A	9.40	8.395	10.405
ComTac III max	A	9.30	8.295	10.305
ComTac III unity	A	9.20	8.195	10.205
OPEN EAR	A	9.20	8.195	10.205
EB15LE unity	A	8.70	7.695	9.705
EB15LE max	A	8.60	7.595	9.605
QuietPro+ max	A	8.60	7.595	9.605
X50 max	A	8.60	7.595	9.605
X50 unity	A	8.60	7.595	9.605
QuietPro+ unity	A	8.50	7.495	9.505

Response Time wind=0, S/N Ratio=10, Speaker=12				
Level		Mean	Lower 90%	Upper 90%
QuietPro+ max	A	1.44	1.138	1.737
QuietPro+ unity	A	1.39	1.092	1.691
EB15LE max	A	1.11	0.812	1.411
EB15LE unity	A	1.10	0.800	1.399
Combat Arms	A	1.10	0.799	1.398
X50 max	A	1.04	0.745	1.344
OPEN EAR	A	1.00	0.703	1.302
ComTac III max	A	1.00	0.700	1.299
ComTac III unity	A	0.99	0.689	1.288
X50 unity	A	0.91	0.612	1.211

Result wind=0, S/N Ratio=10, Speaker=12				
Level		Mean	Lower 90%	Upper 90%
Combat Arms	A	9.60	8.597	10.603
ComTac III max	A	9.00	7.997	10.003
ComTac III unity	A	9.00	7.997	10.003
OPEN EAR	A	9.00	7.997	10.003
X50 max	A	8.80	7.797	9.803
EB15LE max	A	8.70	7.697	9.703
QuietPro+ unity	A	8.70	7.697	9.703
QuietPro+ max	A	8.60	7.597	9.603
EB15LE unity	A	8.50	7.497	9.503
X50 unity	A	8.40	7.397	9.403

Response Time wind=5, S/N Ratio=-10, Speaker=3				
Level		Mean	Lower 90%	Upper 90%
X50 max	A	1.31	1.013	1.615
ComTac III unity	A	1.27	0.972	1.575
QuietPro+ unity	A	1.27	0.965	1.568
EB15LE max	A	1.20	0.902	1.504
OPEN EAR	A	1.18	0.880	1.483
QuietPro+ max	A	1.18	0.877	1.479
EB15LE unity	A	1.14	0.839	1.441
ComTac III max	A	1.05	0.747	1.350
X50 unity	A	1.03	0.726	1.328
Combat Arms	A	1.02	0.716	1.318

Result wind=5, S/N Ratio=-10, Speaker=3				
Level		Mean	Lower 90%	Upper 90%
EB15LE unity	A	9.80	9.362	10.238
X50 unity	A	9.70	9.262	10.138
EB15LE max	A	9.60	9.162	10.038
ComTac III max	A	9.50	9.062	9.938
ComTac III unity	A	9.50	9.062	9.938
QuietPro+ unity	A	9.50	9.062	9.938
OPEN EAR	A	9.40	8.962	9.838
QuietPro+ max	A	9.40	8.962	9.838
X50 max	A	9.40	8.962	9.838
Combat Arms	A	9.20	8.762	9.638

Response Time wind=5, S/N Ratio=-10, Speaker=12				
Level		Mean	Lower 90%	Upper 90%
X50 max	A	1.43	1.160	1.692
OPEN EAR	A	1.40	1.132	1.663
EB15LE max	A	1.34	1.070	1.602
QuietPro+ max	A	1.32	1.055	1.587
EB15LE unity	A	1.27	1.008	1.539
Combat Arms	A	1.24	0.975	1.507
ComTac III unity	A	1.24	0.971	1.503
ComTac III max	A	1.23	0.962	1.494
X50 unity	A	1.04	0.772	1.304
QuietPro+ unity	A	1.03	0.765	1.297

Result wind=5, S/N Ratio=-10, Speaker=12				
Level		Mean	Lower 90%	Upper 90%
ComTac III max	A	9.60	9.034	10.166
ComTac III unity	A	9.60	9.034	10.166
EB15LE unity	A	9.60	9.034	10.166
QuietPro+ max	A	9.50	8.934	10.066
X50 unity	A	9.40	8.834	9.966
EB15LE max	A	9.30	8.734	9.866
OPEN EAR	A	9.20	8.634	9.766
QuietPro+ unity	A	9.20	8.634	9.766
Combat Arms	A	8.60	8.034	9.166
X50 max	A	8.50	7.934	9.066

Response Time wind=5, S/N Ratio=0, Speaker=3				
Level		Mean	Lower 90%	Upper 90%
Combat Arms	A	1.29	1.008	1.563
EB15LE unity	A	1.28	0.999	1.554
ComTac III unity	A	1.27	0.997	1.551
X50 max	A	1.26	0.978	1.532
QuietPro+ max	A	1.19	0.914	1.468
QuietPro+ unity	A	1.15	0.874	1.429
ComTac III max	A	1.05	0.774	1.329
EB15LE max	A	1.01	0.735	1.290
OPEN EAR	A	1.00	0.719	1.273
X50 unity	A	0.92	0.647	1.202

Result wind=5, S/N Ratio=0, Speaker=3				
Level		Mean	Lower 90%	Upper 90%
ComTac III max	A	9.50	8.567	10.433
OPEN EAR	A	9.50	8.567	10.433
ComTac III unity	A	9.40	8.467	10.333
X50 max	A	9.30	8.367	10.233
Combat Arms	A	9.20	8.267	10.133
X50 unity	A	9.10	8.167	10.033
EB15LE max	A	9.00	8.067	9.933
EB15LE unity	A	9.00	8.067	9.933
QuietPro+ unity	A	8.90	7.967	9.833
QuietPro+ max	A	8.70	7.767	9.633

Response Time wind=5, S/N Ratio=0, Speaker=12				
Level		Mean	Lower 90%	Upper 90%
ComTac III unity	A	1.29	1.014	1.575
EB15LE unity	A	1.29	1.013	1.574
Combat Arms	A	1.29	1.013	1.574
X50 max	A	1.25	0.973	1.534
QuietPro+ max	A	1.17	0.894	1.456
QuietPro+ unity	A	1.14	0.856	1.417
EB15LE max	A	1.09	0.812	1.374
X50 unity	A	1.08	0.797	1.359
OPEN EAR	A	1.00	0.716	1.278
ComTac III max	A	0.97	0.692	1.254

Result wind=5, S/N Ratio=0, Speaker=12				
Level		Mean	Lower 90%	Upper 90%
ComTac III max	A	9.50	8.543	10.457
OPEN EAR	A	9.50	8.543	10.457
X50 max	A	9.40	8.443	10.357
ComTac III unity	A	9.30	8.343	10.257
X50 unity	A	9.10	8.143	10.057
Combat Arms	A	9.00	8.043	9.957
EB15LE max	A	8.90	7.943	9.857
EB15LE unity	A	8.90	7.943	9.857
QuietPro+ unity	A	8.90	7.943	9.857
QuietPro+ max	A	8.80	7.843	9.757

Response Time wind=5, S/N Ratio=10, Speaker=3				
Level		Mean	Lower 90%	Upper 90%
EB15LE max	A	1.30	0.990	1.611
QuietPro+ max	A	1.21	0.897	1.518
Combat Arms	A	1.19	0.879	1.500
ComTac III max	A	1.15	0.841	1.462
X50 max	A	1.14	0.826	1.447
ComTac III unity	A	1.13	0.820	1.441
QuietPro+ unity	A	1.06	0.749	1.370
OPEN EAR	A	1.06	0.749	1.370
X50 unity	A	0.97	0.657	1.278
EB15LE unity	A	0.86	0.554	1.175

Result wind=5, S/N Ratio=10, Speaker=3				
Level		Mean	Lower 90%	Upper 90%
Combat Arms	A	9.60	8.634	10.566
OPEN EAR	A	9.30	8.334	10.266
X50 max	A	9.30	8.334	10.266
ComTac III unity	A	9.10	8.134	10.066
ComTac III max	A	9.00	8.034	9.966
EB15LE max	A	8.80	7.834	9.766
EB15LE unity	A	8.70	7.734	9.666
X50 unity	A	8.70	7.734	9.666
QuietPro+ max	A	8.60	7.634	9.566
QuietPro+ unity	A	8.50	7.534	9.466

Response Time wind=5, S/N Ratio=10, Speaker=12				
Level		Mean	Lower 90%	Upper 90%
Combat Arms	A	1.33	1.031	1.629
X50 max	A	1.25	0.955	1.553
ComTac III unity	A	1.20	0.905	1.503
QuietPro+ max	A	1.15	0.856	1.454
OPEN EAR	A	1.10	0.796	1.394
EB15LE max	A	1.09	0.794	1.392
EB15LE unity	A	1.09	0.793	1.391
QuietPro+ unity	A	1.04	0.743	1.341
ComTac III max	A	1.02	0.725	1.323
X50 unity	A	1.01	0.708	1.306

Result wind=5, S/N Ratio=10, Speaker=12				
Level		Mean	Lower 90%	Upper 90%
Combat Arms	A	9.50	8.531	10.469
ComTac III unity	A	9.30	8.331	10.269
ComTac III max	A	9.20	8.231	10.169
OPEN EAR	A	9.10	8.131	10.069
X50 max	A	9.00	8.031	9.969
QuietPro+ unity	A	8.70	7.731	9.669
EB15LE max	A	8.50	7.531	9.469
EB15LE unity	A	8.50	7.531	9.469
QuietPro+ max	A	8.40	7.431	9.369
X50 unity	A	8.40	7.431	9.369

Response Time wind=10, S/N Ratio=-10, Speaker=3				
Level		Mean	Lower 90%	Upper 90%
QuietPro+ max	A	1.52	1.201	1.841
Combat Arms	A	1.32	0.996	1.636
EB15LE max	A	1.21	0.892	1.531
EB15LE unity	A	1.21	0.887	1.526
X50 max	A	1.19	0.872	1.511
ComTac III unity	A	1.17	0.850	1.490
QuietPro+ unity	A	1.17	0.850	1.490
ComTac III max	A	1.15	0.827	1.466
OPEN EAR	A	1.08	0.759	1.398
X50 unity	A	1.04	0.721	1.361

Result wind=10, S/N Ratio=-10, Speaker=3				
Level		Mean	Lower 90%	Upper 90%
EB15LE max	A	9.70	9.210	10.190
EB15LE unity	A	9.70	9.210	10.190
OPEN EAR	A	9.70	9.210	10.190
ComTac III max	A	9.60	9.110	10.090
ComTac III unity	A	9.60	9.110	10.090
QuietPro+ max	A	9.60	9.110	10.090
X50 max	AB	9.50	9.010	9.990
QuietPro+ unity	AB	9.30	8.810	9.790
X50 unity	AB	9.30	8.810	9.790
Combat Arms	B	8.30	7.810	8.790

Response Time wind=10, S/N Ratio=-10, Speaker=12				
Level		Mean	Lower 90%	Upper 90%
QuietPro+ unity	A	1.42	1.107	1.733
Combat Arms	A	1.35	1.039	1.666
OPEN EAR	A	1.32	1.005	1.631
X50 max	A	1.31	0.997	1.623
EB15LE max	A	1.29	0.977	1.603
QuietPro+ max	A	1.26	0.949	1.575
EB15LE unity	A	1.25	0.937	1.563
ComTac III unity	A	1.22	0.909	1.535
ComTac III max	A	1.21	0.894	1.520
X50 unity	A	1.02	0.710	1.336

Result wind=10, S/N Ratio=-10, Speaker=12				
Level		Mean	Lower 90%	Upper 90%
EB15LE unity	A	9.70	9.077	10.323
ComTac III unity	AB	9.50	8.877	10.123
ComTac III max	AB	9.30	8.677	9.923
EB15LE max	AB	9.30	8.677	9.923
QuietPro+ max	AB	9.30	8.677	9.923
QuietPro+ unity	AB	9.10	8.477	9.723
OPEN EAR	AB	8.90	8.277	9.523
X50 max	AB	8.90	8.277	9.523
X50 unity	AB	8.70	8.077	9.323
Combat Arms	B	8.10	7.477	8.723

Response Time wind=10, S/N Ratio=0, Speaker=3				
Level		Mean	Lower 90%	Upper 90%
QuietPro+ unity	A	1.17	0.890	1.456
QuietPro+ max	A	1.17	0.889	1.454
X50 unity	A	1.14	0.861	1.426
OPEN EAR	A	1.10	0.819	1.385
X50 max	A	1.08	0.795	1.360
EB15LE max	A	1.07	0.786	1.352
Combat Arms	A	1.07	0.783	1.348
EB15LE unity	A	1.00	0.719	1.285
ComTac III max	A	0.98	0.692	1.258
ComTac III unity	A	0.90	0.618	1.183

Result wind=10, S/N Ratio=0, Speaker=3				
Level		Mean	Lower 90%	Upper 90%
ComTac III max	A	9.50	8.498	10.502
ComTac III unity	A	9.50	8.498	10.502
OPEN EAR	A	9.30	8.298	10.302
EB15LE max	A	9.10	8.098	10.102
EB15LE unity	A	9.00	7.998	10.002
QuietPro+ max	A	9.00	7.998	10.002
X50 max	A	9.00	7.998	10.002
X50 unity	A	9.00	7.998	10.002
Combat Arms	A	8.90	7.898	9.902
QuietPro+ unity	A	8.90	7.898	9.902

Response Time wind=10, S/N Ratio=0, Speaker=12				
Level		Mean	Lower 90%	Upper 90%
QuietPro+ max	A	1.35	1.068	1.642
ComTac III max	A	1.19	0.899	1.473
QuietPro+ unity	A	1.16	0.875	1.449
EB15LE unity	A	1.15	0.868	1.442
X50 max	A	1.13	0.846	1.420
ComTac III unity	A	1.09	0.802	1.376
Combat Arms	A	1.08	0.789	1.364
X50 unity	A	1.04	0.751	1.326
OPEN EAR	A	0.99	0.700	1.274
EB15LE max	A	0.94	0.648	1.223

Result wind=10, S/N Ratio=0, Speaker=12				
Level		Mean	Lower 90%	Upper 90%
ComTac III max	A	9.50	8.502	10.498
ComTac III unity	A	9.50	8.502	10.498
OPEN EAR	A	9.50	8.502	10.498
EB15LE max	A	9.10	8.102	10.098
EB15LE unity	A	9.10	8.102	10.098
X50 max	A	9.10	8.102	10.098
X50 unity	A	9.00	8.002	9.998
Combat Arms	A	8.90	7.902	9.898
QuietPro+ max	A	8.90	7.902	9.898
QuietPro+ unity	A	8.90	7.902	9.898

Response Time wind=10, S/N Ratio=10, Speaker=3				
Level		Mean	Lower 90%	Upper 90%
QuietPro+ max	A	1.17	0.915	1.424
OPEN EAR	A	1.16	0.907	1.416
Combat Arms	A	1.15	0.893	1.402
ComTac III max	A	1.07	0.818	1.327
EB15LE max	A	1.06	0.802	1.311
ComTac III unity	A	1.04	0.790	1.299
QuietPro+ unity	A	1.03	0.780	1.289
X50 max	A	1.02	0.767	1.276
X50 unity	A	0.99	0.738	1.247
EB15LE unity	A	0.97	0.714	1.223

Result wind=10, S/N Ratio=10, Speaker=3				
Level		Mean	Lower 90%	Upper 90%
Combat Arms	A	9.60	8.622	10.578
ComTac III max	A	9.20	8.222	10.178
OPEN EAR	A	9.10	8.122	10.078
ComTac III unity	A	9.00	8.022	9.978
QuietPro+ max	A	8.80	7.822	9.778
X50 unity	A	8.70	7.722	9.678
EB15LE max	A	8.60	7.622	9.578
QuietPro+ unity	A	8.60	7.622	9.578
X50 max	A	8.60	7.622	9.578
EB15LE unity	A	8.40	7.422	9.378

Response Time wind=10, S/N Ratio=10, Speaker=12				
Level		Mean	Lower 90%	Upper 90%
EB15LE unity	A	1.12	0.863	1.376
X50 max	A	1.11	0.854	1.366
QuietPro+ unity	A	1.11	0.852	1.364
ComTac III unity	A	1.06	0.806	1.318
ComTac III max	A	1.03	0.772	1.284
X50 unity	A	1.02	0.759	1.272
Combat Arms	A	1.01	0.757	1.269
EB15LE max	A	1.00	0.745	1.257
QuietPro+ max	A	0.97	0.709	1.221
OPEN EAR	A	0.96	0.701	1.213

Result wind=10, S/N Ratio=10, Speaker=12				
Level		Mean	Lower 90%	Upper 90%
Combat Arms	A	9.80	8.832	10.768
ComTac III max	AB	9.30	8.332	10.268
OPEN EAR	AB	9.30	8.332	10.268
ComTac III unity	AB	9.20	8.232	10.168
EB15LE max	AB	8.80	7.832	9.768
X50 max	AB	8.70	7.732	9.668
X50 unity	AB	8.70	7.732	9.668
EB15LE unity	AB	8.60	7.632	9.568
QuietPro+ max	AB	8.60	7.632	9.568
QuietPro+ unity	B	8.30	7.332	9.268

G. Proof-of-Concept Experimental Results: Localization Tests, Azimuth and Frontal Elevation (means, upper and lower 90% confidence interval bounds, and statistically-significant differences at *p*<0.10 indicated by different letters)

The low noise means 50 dBA signal with 40 dBA background pink noise and the high noise means 85 dBA signal with 75 dBA background pink noise.

Azimuth

Correct rate, low noise

Level		Mean	Lower 90%	Upper 90%
Open Ear	A	54.7	47.1	62.3
EB15 Unity	AB	46.1	38.5	53.7
EB15 Max	AB	45.3	37.7	52.9
X50 Unity	BC	38.1	30.5	45.6
X50 Max	BC	36.7	29.1	44.3
Combat Arms Open	BC	36.4	28.8	44.0
QuietPro+ Unity	BC	36.4	28.8	44.0
ComTac III Unity	BC	35.6	28.0	43.1
ComTac III Max	BC	35.0	27.4	42.6
QuietPro+ Max	C	31.4	23.8	39.0

Correct rate, high noise

Level		Mean	Upper 90%
Open Ear	A	36.9	43.1
EB15 Unity	AB	33.9	40.1
Combat Arms Open	AB	33.1	39.2
EB15 Max	AB	32.5	38.7
ComTac III Max	ABC	25.8	32.0
QuietPro+ Unity	BC	25.0	31.2
QuietPro+ Max	BC	25.0	31.2
ComTac III Unity	BC	24.4	30.6
X50 Unity	BC	24.2	30.3
X50 Max	C	15.3	21.5

ballpark rate, low noise

Level		Mean	Lower 90%	Upper 90%
Open Ear	A	89.2	80.8	97.5
EB15 Unity	B	72.5	64.1	80.9
EB15 Max	BC	71.7	63.3	80.0
Combat Arms Open	BCD	67.8	59.4	76.2
QuietPro+ Unity	BCDE	64.4	56.1	72.8
X50 Unity	BCDE	64.2	55.8	72.5
X50 Max	BCDE	63.6	55.2	72.0
QuietPro+ Max	CDE	60.6	52.2	68.9
ComTac III Max	DE	58.3	50.0	66.7
ComTac III Unity	E	55.8	47.5	64.2

ballpark rate, high noise

Level		Mean	Lower 90%	Upper 90%
Open Ear	A	63.3	55.7	71.0
EB15 Unity	AB	60.0	52.4	67.6
Combat Arms Open	ABC	55.8	48.2	63.5
EB15 Max	ABC	55.6	47.9	63.2
ComTac III Max	BCD	48.9	41.3	56.5
QuietPro+ Max	BCD	47.5	39.9	55.1
QuietPro+ Unity	CD	45.6	37.9	53.2
ComTac III Unity	CD	44.7	37.1	52.3
X50 Unity	DE	41.4	33.8	49.0
X50 Max	E	31.4	23.8	39.0

response time, low noise

Level		Mean	Lower 90%	Upper 90%
X50 Unity	A	1.48	1.31	1.65
Combat Arms Open	A	1.46	1.28	1.63
EB15 Max	A	1.43	1.26	1.60
EB15 Unity	A	1.42	1.25	1.59
X50 Max	A	1.42	1.25	1.59
Open Ear	A	1.40	1.23	1.57
ComTac III Max	A	1.40	1.23	1.57
QuietPro+ Unity	A	1.39	1.22	1.56
ComTac III Unity	A	1.36	1.19	1.53
QuietPro+ Max	A	1.34	1.17	1.51

response time, high noise

Level		Mean	Lower 90%	Upper 90%
EB15 Unity	A	1.55	1.36	1.73
X50 Max	A	1.53	1.35	1.72
X50 Unity	A	1.50	1.31	1.68
Combat Arms Open	A	1.49	1.31	1.67
ComTac III Max	A	1.48	1.30	1.66
EB15 Max	A	1.46	1.28	1.64
Open Ear	A	1.44	1.26	1.63
ComTac III Unity	A	1.42	1.24	1.61
QuietPro+ Unity	A	1.40	1.22	1.58
QuietPro+ Max	A	1.33	1.15	1.52

Frontal Elevation

Correct rate, low noise

Level		Mean	Lower 90%	Upper 90%
Open Ear	A	54.4	42.9	66.0
X50 Unity	AB	42.4	30.8	53.9
EB15 Max	AB	38.9	27.4	50.4
EB15 Unity	AB	38.3	26.8	49.9
ComTac III Max	AB	36.7	25.1	48.2
QuietPro+ Max	AB	36.7	25.1	48.2
QuietPro+ Unity	AB	36.7	25.1	48.2
X50 Max	B	32.3	20.8	43.8
Combat Arms Open	B	30.0	18.5	41.5
ComTac III Unity	B	29.4	17.9	41.0

ballpark rate, high noise

Level		Mean	Lower 90%	Upper 90%
EB15 Max	A	50.0	37.5	62.5
QuietPro+ Unity	AB	37.8	25.3	50.3
Combat Arms Open	AB	37.2	24.7	49.7
Open Ear	AB	35.6	23.1	48.0
X50 Unity	AB	34.4	22.0	46.9
QuietPro+ Max	AB	34.4	22.0	46.9
EB15 Unity	AB	32.2	19.7	44.7
ComTac III Max	B	28.9	16.4	41.4
ComTac III Unity	B	26.7	14.2	39.1
X50 Max	B	20.0	7.5	32.5

ballpark rate, low noise

Level		Mean	Lower 90%	Upper 90%
Open Ear	A	92.8	86.2	99.4
X50 Unity	AB	82.1	75.5	88.7
EB15 Max	AB	79.4	72.8	86.1
ComTac III Max	AB	77.8	71.2	84.4
X50 Max	AB	77.1	70.5	83.7
EB15 Unity	B	76.7	70.1	83.3
Combat Arms Open	B	76.1	69.5	82.7
QuietPro+ Unity	B	75.0	68.4	81.6
QuietPro+ Max	B	75.0	68.4	81.6
ComTac III Unity	B	68.9	62.3	75.5

ballpark rate, high noise

Level		Mean	Lower 90%	Upper 90%
Open Ear	A	87.2	80.2	94.3
QuietPro+ Unity	AB	78.9	71.9	85.9
EB15 Max	AB	76.1	69.1	83.1
QuietPro+ Max	AB	74.4	67.4	81.5
Combat Arms Open	AB	74.4	67.4	81.5
EB15 Unity	AB	72.8	65.7	79.8
ComTac III Unity	BC	70.0	63.0	77.0
ComTac III Max	BC	67.8	60.7	74.8
X50 Unity	BC	66.1	59.1	73.1
X50 Max	C	55.6	48.5	62.6

response time, low noise

Level		Mean	Lower 90%	Upper 90%
X50 Max	A	1.52	1.34	1.71
X50 Unity	A	1.49	1.30	1.67
EB15 Unity	A	1.47	1.28	1.65
Combat Arms Open	A	1.46	1.28	1.65
EB15 Max	A	1.44	1.26	1.63
QuietPro+ Max	A	1.43	1.25	1.62
Open Ear	A	1.42	1.23	1.60
ComTac III Unity	A	1.41	1.23	1.59
ComTac III Max	A	1.41	1.22	1.59
QuietPro+ Unity	A	1.39	1.20	1.57

response time, high noise

Level		Mean	Lower 90%	Upper 90%
X50 Max	A	1.52	1.33	1.72
EB15 Unity	A	1.50	1.30	1.69
X50 Unity	A	1.46	1.26	1.65
ComTac III Unity	A	1.44	1.24	1.64
Open Ear	A	1.43	1.23	1.63
Combat Arms Open	A	1.41	1.21	1.61
QuietPro+ Max	A	1.41	1.21	1.60
ComTac III Max	A	1.41	1.21	1.60
QuietPro+ Unity	A	1.39	1.19	1.59
EB15 Max	A	1.39	1.19	1.58

H. Proof-of-Concept Experimental Results: Communication Test (means, upper and lower 90% confidence interval bounds, and statistically-significant differences at *p*<0.10 indicated by different letters)

Speaker loc of 3, 6, 9, and 12 means the signal speaker was located at the right (3), behind (6), left (9), and directly in front (12) of the subject.

no wind

Response SNR loss wind speed=0, speaker loc=3

		Mean	Lower 90%	Upper 90%
QuietPro+ unity	A	0.40	-0.50	1.30
ComTac III max	AB	0.10	-0.80	1.00
X50 max	AB	0.00	-0.90	0.90
Combat Arms	AB	-0.30	-1.20	0.60
QuietPro+ max	AB	-0.40	-1.30	0.50
EB15LE max	AB	-0.50	-1.40	0.40
open ear	AB	-0.60	-1.50	0.30
EB15LE unity	AB	-1.00	-1.90	-0.10
X50 unity	AB	-1.40	-2.30	-0.50
ComTac III unity	B	-1.90	-2.80	-1.00

Response SNR loss wind speed=0, speaker loc=6

		Mean	Lower 90%	Upper 90%
ComTac III max	A	0.70	-0.39	1.79
ComTac III unity	A	0.40	-0.69	1.49
EB15LE max	A	0.20	-0.89	1.29
QuietPro+ max	A	0.10	-0.99	1.19
X50 unity	A	-0.20	-1.29	0.89
open ear	A	-0.30	-1.39	0.79
X50 max	A	-0.40	-1.49	0.69
Combat Arms	A	-0.70	-1.79	0.39
EB15LE unity	A	-1.10	-2.19	-0.01
QuietPro+ unity	A	-1.20	-2.29	-0.11

Response SNR loss wind speed=0, speaker loc=9

		Mean	Lower 90%	Upper 90%
ComTac III unity	A	0.90	-0.06	1.86
X50 max	A	0.70	-0.26	1.66
QuietPro+ unity	A	0.50	-0.46	1.46
open ear	A	0.00	-0.96	0.96
Combat Arms	A	0.00	-0.96	0.96
ComTac III max	A	-0.20	-1.16	0.76
EB15LE max	A	-0.30	-1.26	0.66
X50 unity	A	-0.40	-1.36	0.56
EB15LE unity	A	-0.70	-1.66	0.26
QuietPro+ max	A	-0.70	-1.66	0.26

Response SNR loss wind speed=0, speaker loc=12

		Mean	Lower 90%	Upper 90%
open ear	A	0.80	-0.26	1.86
EB15LE max	A	0.60	-0.46	1.66
ComTac III max	A	0.40	-0.66	1.46
X50 unity	A	0.20	-0.86	1.26
QuietPro+ max	A	-0.60	-1.66	0.46
X50 max	A	-0.60	-1.66	0.46
Combat Arms	A	-0.80	-1.86	0.26
QuietPro+ unity	A	-1.00	-2.06	0.06
ComTac III unity	A	-1.10	-2.16	-0.04
EB15LE unity	A	-1.40	-2.46	-0.34

5 MPH wind

Response SNR loss wind speed=5, speaker loc=3

		Mean	Lower 90%	Upper 90%
X50 unity	A	0.50	-0.57	1.57
ComTac III unity	A	0.10	-0.97	1.17
QuietPro+ unity	A	-0.10	-1.17	0.97
open ear	A	-0.30	-1.37	0.77
Combat Arms	A	-0.30	-1.37	0.77
EB15LE unity	A	-0.60	-1.67	0.47
QuietPro+ max	A	-0.70	-1.77	0.37
X50 max	A	-0.70	-1.77	0.37
EB15LE max	A	-0.80	-1.87	0.27
ComTac III max	A	-1.30	-2.37	-0.23

Response SNR loss wind speed=5, speaker loc=6

		Mean	Lower 90%	Upper 90%
X50 unity	A	0.40	-0.62	1.42
ComTac III max	A	0.30	-0.72	1.32
X50 max	A	0.20	-0.82	1.22
QuietPro+ Max	A	0.20	-0.82	1.22
QuietPro+ unity	A	0.00	-1.02	1.02
Combat Arms	A	-0.10	-1.12	0.92
EB15LE max	A	-0.40	-1.42	0.62
EB15LE unity	A	-0.60	-1.62	0.42
ComTac III unity	A	-0.70	-1.72	0.32
open ear	A	-0.80	-1.82	0.22

Response SNR loss wind speed=5, speaker loc=9

		Mean	Lower 90%	Upper 90%
X50 max	A	1.00	0.04	1.96
Combat Arms	A	0.20	-0.76	1.16
X50 unity	A	0.00	-0.96	0.96
open ear	A	-0.20	-1.16	0.76
ComTac III max	A	-0.20	-1.16	0.76
ComTac III unity	A	-0.30	-1.26	0.66
QuietPro+ unity	A	-0.40	-1.36	0.56
QuietPro+ max	A	-0.60	-1.56	0.36
EB15LE max	A	-0.80	-1.76	0.16
EB15LE unity	A	-0.90	-1.86	0.06

Response SNR loss wind speed=5, speaker loc=12

		Mean	Lower 90%	Upper 90%
EB15LE max	A	0.10	-0.73	0.93
X50 max	A	0.00	-0.83	0.83
EB15LE unity	A	0.00	-0.83	0.83
ComTac III max	A	-0.20	-1.03	0.63
open ear	A	-0.40	-1.23	0.43
ComTac III unity	A	-0.40	-1.23	0.43
QuietPro+ max	A	-0.40	-1.23	0.43
X50 unity	A	-0.70	-1.53	0.13
Combat Arms	A	-1.00	-1.83	-0.17
QuietPro+ unity	A	-1.00	-1.83	-0.17

10 MPH wind

Response SNR loss wind speed=10, speaker loc=3

		Mean	Lower 90%	Upper 90%
ComTac III max	A	0.80	-0.15	1.75
X50 unity	A	0.60	-0.35	1.55
ComTac III unity	A	0.00	-0.95	0.95
X50 max	A	-0.30	-1.25	0.65
Combat Arms	A	-0.30	-1.25	0.65
open ear	A	-0.60	-1.55	0.35
EB15LE unity	A	-0.80	-1.75	0.15
QuietPro+ max	A	-0.90	-1.85	0.05
QuietPro+ unity	A	-1.20	-2.15	-0.25
EB15LE max	A	-1.30	-2.25	-0.35

Response SNR loss wind speed=10, speaker loc=6

		Mean	Lower 90%	Upper 90%
open ear	A	-0.10	-1.13	0.93
X50 unity	A	-0.10	-1.13	0.93
EB15LE unity	A	-0.20	-1.23	0.83
QuietPro+ unity	A	-0.20	-1.23	0.83
Combat Arms	A	-0.60	-1.63	0.43
ComTac III unity	A	-0.60	-1.63	0.43
ComTac III max	A	-0.70	-1.73	0.33
QuietPro+ max	A	-0.70	-1.73	0.33
EB15LE max	A	-0.80	-1.83	0.23
X50 max	A	-1.00	-2.03	0.03

Response SNR loss wind speed=10, speaker loc=9

		Mean	Lower 90%	Upper 90%
X50 max	A	1.00	0.05	1.95
QuietPro+ max	A	0.60	-0.35	1.55
QuietPro+ unity	A	0.60	-0.35	1.55
Combat Arms	A	0.50	-0.45	1.45
open ear	A	0.10	-0.85	1.05
ComTac III unity	A	0.00	-0.95	0.95
ComTac III max	A	-0.10	-1.05	0.85
EB15LE unity	A	-0.10	-1.05	0.85
X50 unity	A	-0.30	-1.25	0.65
EB15LE max	A	-0.50	-1.45	0.45

Response SNR loss wind speed=10, speaker loc=12

		Mean	Lower 90%	Upper 90%
EB15LE max	A	1.40	0.51	2.29
ComTac III max	AB	0.50	-0.39	1.39
ComTac III unity	AB	0.30	-0.59	1.19
QuietPro+ max	AB	0.20	-0.69	1.09
EB15LE unity	AB	0.00	-0.89	0.89
X50 unity	AB	-0.10	-0.99	0.79
open ear	AB	-0.50	-1.39	0.39
Combat Arms	AB	-0.60	-1.49	0.29
X50 max	AB	-0.70	-1.59	0.19
QuietPro+ unity	B	-1.10	-1.99	-0.21