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Warfighter Auditory Situation Awareness: Locating the Shooter with and without Hearing Protection

ABSTRACT

A controlled field experiment was conducted using a specially-prepared, partially forested remote rural site to ascertain listeners' aural performance in locating the azimuthal direction of actual gunshots (blank cartridges) from hidden "snipers." Subjects were required to detect and localize the gunshots, which corresponded to eight shooter positions in 360-degrees around the their stationary listening position, by vocalizing target sign numbers.

The study had five listening conditions: four military hearing protection/enhancement devices (HPEDs) and an open ear (i.e., no HPED) condition presented in a randomized sequence with two noise levels: rural resting ambient of 45-50 dBA and 82 dBA military diesel truck high idle engine noise. Five objective measures of localization accuracy and an additional measure of response time for eight shooter positions were measured for nine normal hearing and four impaired hearing participants.

Statistical analysis showed worse accuracy and response time performance with the electronic earmuffs (Peltor Com-Tac II™) than with the other tested HPEDs (Etymotic EB 1 and EB 15 BlastPLG™, both set to the Lo gain positions and AEARO/3M Combat Arms™ earplug in its level-dependent, "open" position). Performance with all HPEDs was worse than that with the open ear, except on right-left confusions, in which the Com-Tac II™ earmuff stood alone as worst, and in response time, for which the EB 1 was equivalent to the open ear. There was no significant main effect of noise on performance. Hearing impairment increased right-left confusions. Subjective ratings generally corroborated objective localization performance.

These results show the importance of human factors input to HPED design, as well as application of realistic auditory tests relating to situational awareness of the user, especially for dangerous situations such as sniper localization. These results have certain applications for the military as well as law enforcement, first responders, and recreational firearm users.

INTRODUCTION

Human Systems Integration (HSI) is predicated on the fact that informational input to the human must be compatible with the parametric limitations of the sensory systems, one of the most important of which is hearing. The hearing sense, due to its role in detection and identification of signals, as well as its omnidirectionality and sound localization capabilities, is critical to the warfighter for maintaining situation awareness in conflict scenarios. For this reason, it is important that hearing remain as uncompromised as possible from such effects as occlusion with a hearing protection device or the occurrence of noise-induced hearing loss.

Without a doubt, noise-induced hearing loss in military soldiers is a staggering, rampant problem, as evidenced by estimates which indicate that since the Afghanistan war began in 2001 and the Iraq war in 2003, approximately 52% of combat soldiers experienced moderately severe hearing loss or worse, primarily attributable to combat-related exposures (DOEHRS-DR, 2007). Furthermore, the problem of noise-induced hearing loss is the *most common* military disability, as evidenced by over $1.2 billion spent on personnel hearing-related injuries in fiscal year 2006 alone (Saunders & Griest, 2009). In fiscal year 2010, hearing loss and tinnitus were the two most prevalent service-connected disabilities for veterans receiving

compensation, with 744,871 veterans receiving compensation related to tinnitus and 672,410 receiving compensation related to hearing loss (Department of Veterans Affairs, 2010, p. 5).

But not only is military hearing loss compensated at over a billion dollars per year, and is a debilitating injury that degrades the warfighter's personal quality of life, there are other major ramifications. Hearing impairments result in extreme losses in the investment of training dollars when the warfighter's hearing renders them incapable of duty, as well as a hindrance to the warfighters' operational performance, including both compromised survivability and lethality. The hearing-impaired soldier may in fact pose a liability in certain military circumstances, because their reduced sensory-perceptual aural capabilities inhibits their ability to detect and identify threats, gauge distances and localize sounds, and communicate/coordinate with other personnel for tactical purposes, all of which compromises HSI, especially in team situations (Hawkins & Wightman, 1980; McIlwain & Gates, 2008).

Somewhat ironically, the very hearing protection devices (HPDs) that are designed to protect and preserve soldiers' hearing may induce sensory-perceptual impairments in warfighters' performance, even if they possess normal hearing acuity (Casali et al., 2009; Casali, 2010a,b). This creates a loss of situational awareness, perhaps the most critical task of which is the soldier's ability, or inability, to locate the source of gunfire, the subject of this paper.

METHODOLOGY

A 5 (listening condition) x 2 (noise level) completely within-subjects design was employed

Participants

Ten males and 3 females, aged 22 to 54 years with a mean age of 35 years participated in the experiment.

Eight of the participants had experience with firearms, through both shooting and hunting activities. Twelve of the participants had used hearing protectors in the past, however only one participant had ever used an HPED (a Peltor electronic earmuff for hunting).

Independent Variables

The listening conditions were: (1) the third generation (i.e., rocker-switch, single-ended) version of the AEARO/3M Combat Arms™ earplug in its open, or level-dependent valve setting, (2) the Peltor Com-Tac II™ sound transmission earmuff, (3) the Etymotic Research EB 1 electronic BlastPLG™, (4) the Etymotic Research EB 15 electronic BlastPLG™, and (5) the open ear (i.e. no HPED). The Combat Arms™ and Com-Tac II™ HPEDs were selected because at the juncture of the experiment (Summer 2010) they were probably the most common augmented hearing protection devices deployed for military use, and the Com-Tac II™ was used in its maximum gain (i.e., about 15 dB) setting. The BlastPlg™ earplugs were selected because they represent newly developed products for the military, based on hearing aid amplification/compression technology, and both were operated in their low gain setting, at which the EB 1 yields "transparent" hearing at levels up to about 110 dB and the EB 15 yields "transparent" hearing below 60 dB, 15 dB attenuation about 90 dB, and a gradual transition from gain to attenuation in-between. The HPEDs used in the experiment are shown in Figure 1.
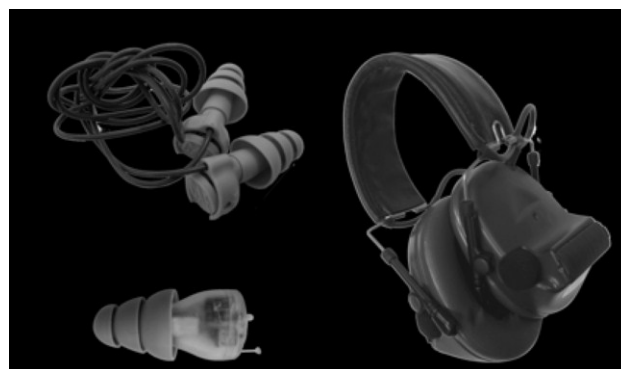

Figure 1. HPEDs used in the experiment.

The noise levels were: ambient (rural, outdoor, lightly forested) and a 20-ton diesel truck noise idle presented via loudspeakers at 82 dBA constant level. The rural ambient noise was measured with an ANSI Type 2 sound level meter (Quest Model 2200 with ½-in microphone, used for all daily site masking noise and gunshot calibration checks) at 45-50 dBA. The truck noise was chosen because it is representative of the type of vehicle noise common

to the combat environment. The truck noise had maximum spectral 1/3-octave band levels of 79 dBZ at the 250 Hz 1/3-octave band, falling to 55 dBZ at the 4000 Hz 1/3-octave band, with spectral rolloff above. The truck noise was presented from four Klipsch AW-650 outdoor loudspeakers, at 90-degree angles to the front, back, and sides of the participant, mounted on posts at a 6 ft height and 10 ft from the participant. The input signal to the loudspeakers was generated from a Panasonic CD player and a Pioneer 100-W receiver-amplifier.

A third variable, subject hearing level, was also used in certain data analyses. Subjects were audiometrically tested, and nine were categorized as normal hearing (< 25 dBHL bilaterally from 250-6000Hz) with good bilateral symmetry, and four were categorized as moderately hearing-impaired.

Dependent Variables
Objective measures of localization performance were: (1) mean absolute value degrees from the correct response, (2) percent correct response "exact," (3) percent correct response "ballpark" (i.e., within ±22.5 degrees), (4) percent of right-left errors, (5) percent of front-rear errors, and (6) mean response time in seconds to localize.

For each listening condition, participants also completed a 7-interval, semantic differential rating scale with six impressions: interference with localization, confidence in localization, difficulty in judging location of gunshots, perceived protection, comfort, and ease of communication with experimenter.

Experiment Site
An in-field test site was created in a lightly-forested area of a farm located in a rural area in Pulaski County, Virginia. The participant stood at the center of a level central plateau area with a 50 ft-radius clearing. Outside the clearing was a wooded area with a gradual drop in elevation on all sides and a tree density of about one tree per 60 square ft of land. Eight shooter positions were created within the wooded area, lying on a circle 150 ft away from the participant's location and at 45° increments of separation. Sixteen numbered target signs were positioned at the edge of the clearing at 50 ft from the participant and at 22.5 degree increments of separation. The odd-numbered target signs

represented the exact eight actual shooter directions and eight "distracter" directions were even-numbered, per Figure 2.
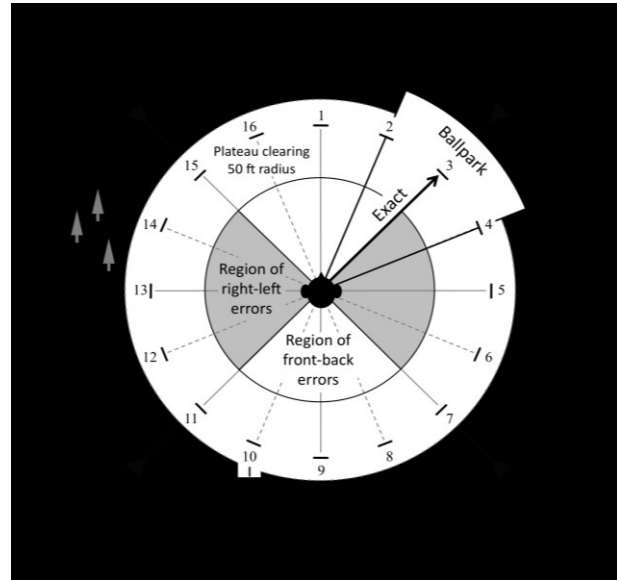

Figure 2. Experiment site layout showing the 8 shooter positions, the 16 signs (labeled 1-16) that participants used to identify shot location, and measures of localization accuracy.

The gunshot signal was generated by a blank cartridge shot by one of three persons ("shooters") shooting 22-caliber long rifle crimped blanks from 22-caliber pistols from one of the shooter positions and aimed at an umbrella 3 ft above the participant's head. The pistol and blank ammunition were selected because they produced gunshots with a peak level of about 100-104 dB(P) at the subject's ear (and about 97 dBA using a fast [1/8-second] time constant), which imposed a low enough gunshot level to avoid over-exposure of the participant in the open ear conditions, and moreover, to approximate the level of unsilenced larger caliber weapons, such as a rifle shot from distances of 500 to1000 ft. The gunshot level at the subject's ear was well above threshold (approximately +20 signal-to-noise ratio [gunshot peak dB(P) level used for comparison] for the 82 dBA truck noise) under occlusion by any of the HPEDs. In addition to the Quest 2200 sound level meter used for all calibrations of broadband and peak levels, the gunshot spectrum was also measured with a Larson Davis 3200D 1/3-octave band analyzer. The maximum sound level recorded was 116 dBA (fast) at the shooter's ear and 97 dBA (fast) at the participant's ear. The gunshot's acoustic signature

was broadband, with most of the energy ranging from 82 dBZ to 90 dBZ in 1/3 octave bands with centers from 1200 Hz to 12500 Hz.

On each gunshot trial, the designated shooter fired a single blank aimed to avoid any trees or other obstructions. The participant's view of the shooters positions and movements was obstructed with brush was piled in the line-of sight at strategic shooter hiding positions, and camouflage netting installed at the edge of the clearing. In addition, during shooter movements between gunshots, the subject's vision was occluded using hard plastic safety goggles that were blacked out using electrical tape. These goggles were removed immediately prior to each trial's gunshot so that the subject could quickly visually access the target signs for response.

Procedure
Participants completed two sessions: (1) an introductory session and (2) the experimental session at the rural farm site.

During the introductory session, participants first read and signed the informed consent form and then underwent audiometric screening with three parts: an audiometric history form that had questions about past noise exposures and experience with HPEDs, an otoscopic inspection to check for excessive cerumen or other conditions that would contraindicate the use of an earplug insert, and a pure-tone audiogram, using a standard Hughson-Westlake manual test procedure. No participants had exclusionary otoscopic problems.

For the experimental session, when the participant arrived at the experiment site, the experimenter briefed the participant on the purpose and procedures; showed him/her the guns, blanks, and other relevant equipment; and answered any questions asked. The participant was then fitted with a dosimeter to record sound exposure during the experiment and a digital recorder to record his/her responses, which served as a data collection accuracy back-up source to check the experimenter's hand-recorded responses and stopwatch-measured response times.

Next, the experimenter read specific instructions to the participant. The experimenter stated that the signs corresponded to sixteen possible shooting

positions from which a gunshot could be fired. Between trials and before the gunshot was fired, the participant was instructed to stand on a mat in the center of the site, facing target sign 1. After the shot, the participant was allowed to move his/her head and rotate the body to aid in localization and sign identification. On each trial, after each shot, the participant was asked to verbally identify the numbered target that corresponded most closely to the perceived shot location, and to do so "as quickly and accurately as possible, since both accuracy and speed were of importance."

The experimenter fit all hearing protectors on the participant in an effort to obtain an optimal, consistent fit. For the EB 1 and EB 15 earplugs, which were available in two eartip sizes (regular and large) and the Combat Arms™ earplug, which had three sizes (small, regular, and large), the experimenter first measured the ear canal with an AEARO EarGage™ and then selected the size that best fit the participant with the aim of getting a tight, but comfortable fit. The same size HPED eartip was used in both ears. The EB 1 and EB 15 were fit with the curve of the device towards the participant, as recommended by Etymotic's personnel.

For each listening condition, the following procedure was used: (1) experimenter fit participant with HPED, participant stood on the mat facing sign 1 and the experimenter sat behind; (2) experimenter turned truck noise on or off (with generator as appropriate), (3) participant donned occlusion glasses; (4) experimenter turned on 75 dBA pink noise to mask shooters' movements in woods, experimenter radioed shooters to move to positions, and shooters confirmed upon arrival; (5) experimenter turned pink noise off, yelled "ready," and participant removed vision-occlusion goggles; (6) designated shooter fired gun and experimenter started stopwatch; (7) participant verbalized target sign number as quickly and accurately as possible and experimenter stopped stopwatch; (8) steps 3 to 7 were repeated for all eight shooter positions with two gunshot trials at each; (9) experimenter changed noise condition and steps 3 to 7 were repeated; (10) participant filled out the subjective rating scale for the listening condition.

For each combination of listening condition and noise condition, a gunshot was fired from all of the

eight possible shooter locations two times (totaling 16 trials). Each participant thus responded to a total of 160 gunshot trials. The time between trials was approximately 0.5 to 1.5 minutes to allow time for the shooters to change locations. The presentation order of the listening conditions and noise conditions was randomized to avoid order effects, and the two gunshots at each of eight azimuthal positions were randomized with the constraint that no two trials occurred in succession from one position.

The experimental sessions took approximately 3-4 hours and were conducted in a single session. The study was conducted in May and June of 2010 during daylight hours.

Data Analysis
The five dependent variables for listening condition and noise were analyzed with five separate two-way within subjects analysis of variances (ANOVAs) in JMP™ software. Responses to each question on the subjective scale were analyzed with additional separate one-way, within-subjects ANOVAs. This parametric ANOVA was justified with the subjective data given that they were obtained from an equal-appearing interval scale. The dependent variables for listening condition (collapsed across noise, within subjects) and hearing ability (between subjects) were analyzed with separate two-way mixed design ANOVAs. Tukey's Honestly Significant Difference test was used for post-hoc comparisons. An α-level of 0.05 was selected a priori for as the criterion for a statistically-significant decision.

RESULTS
In the ensuing coverage of results, the discussion is separated into sections delineated by the five dependent measures, all of which were operationally-defined above. Due to journal space limitations, data figures are provided herein for only a few dependent measures; for data figures on all measures and effects, the reader is referred to the technical report by Casali & Keady (2010).

Listening Condition and Noise Level: Objective Measures
Mean Absolute Deviation: The ANOVA for mean absolute deviation showed a significant main effect of listening condition ($F = 24.35$, $p < 0.0001$). Post-hoc comparisons showed that the mean absolute deviation was significantly greater for the Com-Tac II™ (58 degrees deviation) than all other listening conditions and significantly lower for the open ear condition (22 degrees) than all other listening conditions. There was no significant difference between any of the three electronic or passive earplugs (EB 1 [44 degrees], EB 15 [45 degrees], and Combat Arms™ [41 degrees]). There was no significant main effect of noise, but there was a significant interaction between listening condition and noise level ($F = 3.45$, $p = 0.0148$). Mean absolute deviation for the open ear condition was significantly better (lower deviations) than all other listening conditions for both noise levels. However, mean absolute deviation for the Com-Tac II™ was significantly worse (higher deviations) than all other listening conditions in the diesel truck noise condition. For both noise conditions, there was no statistically-significant difference between the three earplug-style devices (EB 1, EB 15, and Combat Arms™), and for the ambient noise condition, there was no statistically-significant difference between any HPEDs.

Percent Correct Response Exact: The ANOVA for percent correct response exact showed a significant main effect of listening condition ($F = 17.22$, $p < 0.0001$). Post-hoc comparisons showed that the percent correct response exact was significantly lower for the Com-Tac II™ (21%) than all listening conditions and significantly greater for the open ear (55%) than all listening conditions. There was no significant difference between the earplugs (EB 1 [34%], EB 15 [35%], and Combat Arms™ [35%]). There was no significant main effect of noise level or significant interaction effect between listening condition and noise level.

Percent Correct Response Ballpark: The ANOVA for percent correct response "ballpark" showed a significant main effect of listening condition ($F = 23.43$, $p < 0.0001$). Post-hoc comparisons showed that the percent correct response ballpark was significantly lower for the Com-Tac II™ (48%) than all other listening conditions and significantly greater for the open ear (84%) than all HPED conditions. There was no significant difference between the earplugs (EB 1 [61%], EB 15 [63%],

and Combat Arms™ [67%]) on this ballpark accuracy measure. There was also no significant main effect of noise level. There was a significant interaction between listening condition and noise level ($F = 3.70$, $p = 0.0105$), wherein percent correct response ballpark for the open ear was significantly better than all other listening conditions in the truck noise condition, but it was only better than three HPEDs, the EB 1, EB 15 and Com-Tac II™, in the ambient noise condition. There was no statistically significant difference between percent correct response ballpark with the open ear and with the Combat Arms™ earplug in the ambient noise condition. Ballpark accuracy for the Com-Tac II™ was significantly worse than that for all other listening conditions in the truck noise condition, but was only lower than the open ear and Combat Arms™ conditions in the ambient noise condition. Collapsing across both noise conditions, there was no statistically significant difference between the earplugs (EB 1, EB 15, and Combat Arms™), but the Com-Tac II™ was significantly worse and the open ear was significantly better (Figure 3).
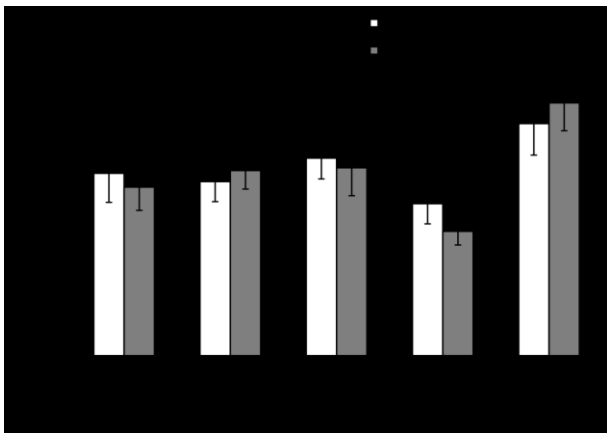

Figure 3. The effect of listening condition by noise level on percent correct response ballpark. Error bars are the 95% confidence interval about the mean. Numbers above the error bars are means. Letters are the results from Tukey's multiple comparisons test where different letters represent a significant difference. The top letters are the main effect of listening condition; the lower letters are the comparison of noise conditions under each listening condition.

Percent Right-Left Errors: The ANOVA for percent of right-left errors showed a significant main effect of listening condition ($F = 3.98$, $p = 0.0072$). Post-hoc comparisons showed that the percent of right-left errors was significantly higher with the Com-

Tac II™ (6%) than the EB 15 (1%), Combat Arms™ (0%) earplugs, and the open ear (0%, Figure 4).

Figure 4. The effect of listening condition on percent of right-left errors. Error bars are the 95% confidence interval about the mean. Numbers above the error bars are means. Letters are the results from Tukey's multiple comparisons test where different letters represent a significant difference. The top letters are the main effect of listening condition; the lower letters are the comparison of noise conditions under each listening condition.

There was no statistically-significant difference in percent of right-left errors between the EB 1 (2%), EB 15, and Combat Arms™ earplugs and the open ear. There was no significant main effect of noise level or interaction effect between listening condition and noise level.

Percent Front-Back Errors: The ANOVA for percent of front-back errors showed a significant main effect of listening condition ($F = 12.83$, $p < 0.0001$). The mean percent of front-back errors were 26% for the EB 1, 30% for the EB 15, 25% for the Combat Arms™, 31% for the Com-Tac II™, and 10% for the open ear. Post-hoc comparisons with Tukey's multiple comparison test showed that the percent of front-back errors was significantly lower in the open ear condition than with any of the HPEDs and there was no statistically-significant difference in percent of front-back errors between the HPEDs (Figure 5).
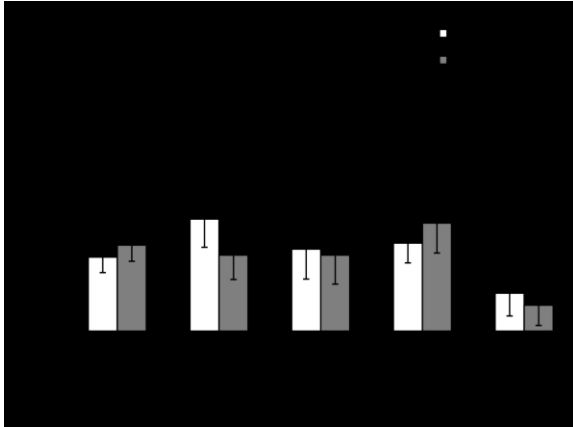
Figure 5. The effect of listening condition on percent of front-back errors. Error bars are the 95% confidence interval about the mean. Numbers above the error bars are means. Letters are the results from Tukey's multiple comparisons test where different letters represent a significant difference. The top letters are the main effect of listening condition; the lower letters are the comparison of noise conditions under each listening condition.
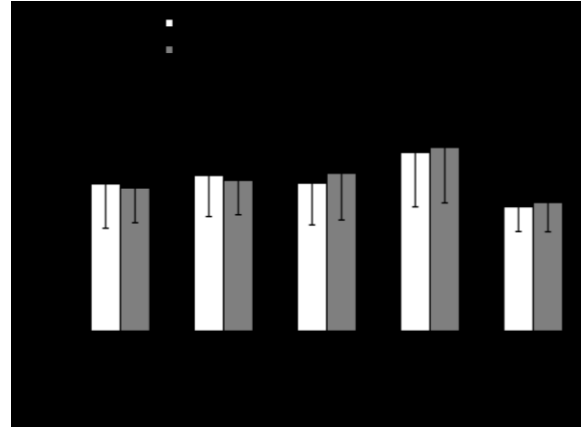

Figure 6. The effect of listening condition on mean response time. Error bars are the 95% confidence interval about the mean. Numbers above the error bars are means. Letters are the results from Tukey's multiple comparisons test where different letters represent a significant difference. The top letters are the main effect of listening condition; the lower letters are the comparison of noise conditions under each listening condition.

The ANOVA also showed a significant interaction between listening condition and noise level ($F = 2.62$, $p = 0.0464$). Post-hoc testing with Tukey's multiple comparison test showed that percent of front-back errors for the open ear condition was significantly lower than all other listening conditions in the truck noise, but was only better than the EB 15 and Com-Tac II™ in the ambient noise and equivalent to the EB 1 and Combat Arms™. Collapsed across both noise levels, there was no statistically-significant difference between any of the HPEDs on front-back errors.

Mean Response Time: The ANOVA for mean response time showed a significant main effect of listening condition ($F = 11.11$, $p < 0.0001$). Post-hoc comparisons showed that the mean response time was significantly higher for the Com-Tac II™ (2.9 seconds) than all other HPEDs (EB 1 [2.3 seconds], EB 15 [2.5 seconds], and Combat Arms™ [2.4 seconds]) and the open ear (2.0 seconds, Figure 6).

There was no significant difference in mean response time between the three earplug-type devices. The mean response time with the open ear was significantly lower than that with all HPEDs except the EB 1, which was equivalent in speed of response. There was no significant main effect of noise level and there was no significant interaction effect between listening condition and noise level.

Visual inspection of responses: In order to clarify the relationship between listening condition and participant response, counts of responses (sign identified) for each shooter position were graphed on polar plots. Results from all participants for the shooter positions behind signs 1, 3, 5, and 7 are shown in Figure 7. Space limitations do not allow the results to be displayed from all shooter positions, but the most relevant ones will be mentioned herein.

As suggested by the results from the accuracy measures, responses in the open ear conditions were consistently more accurate than responses in the HPED conditions. Most of the errors in the open ear condition were adjacent errors.
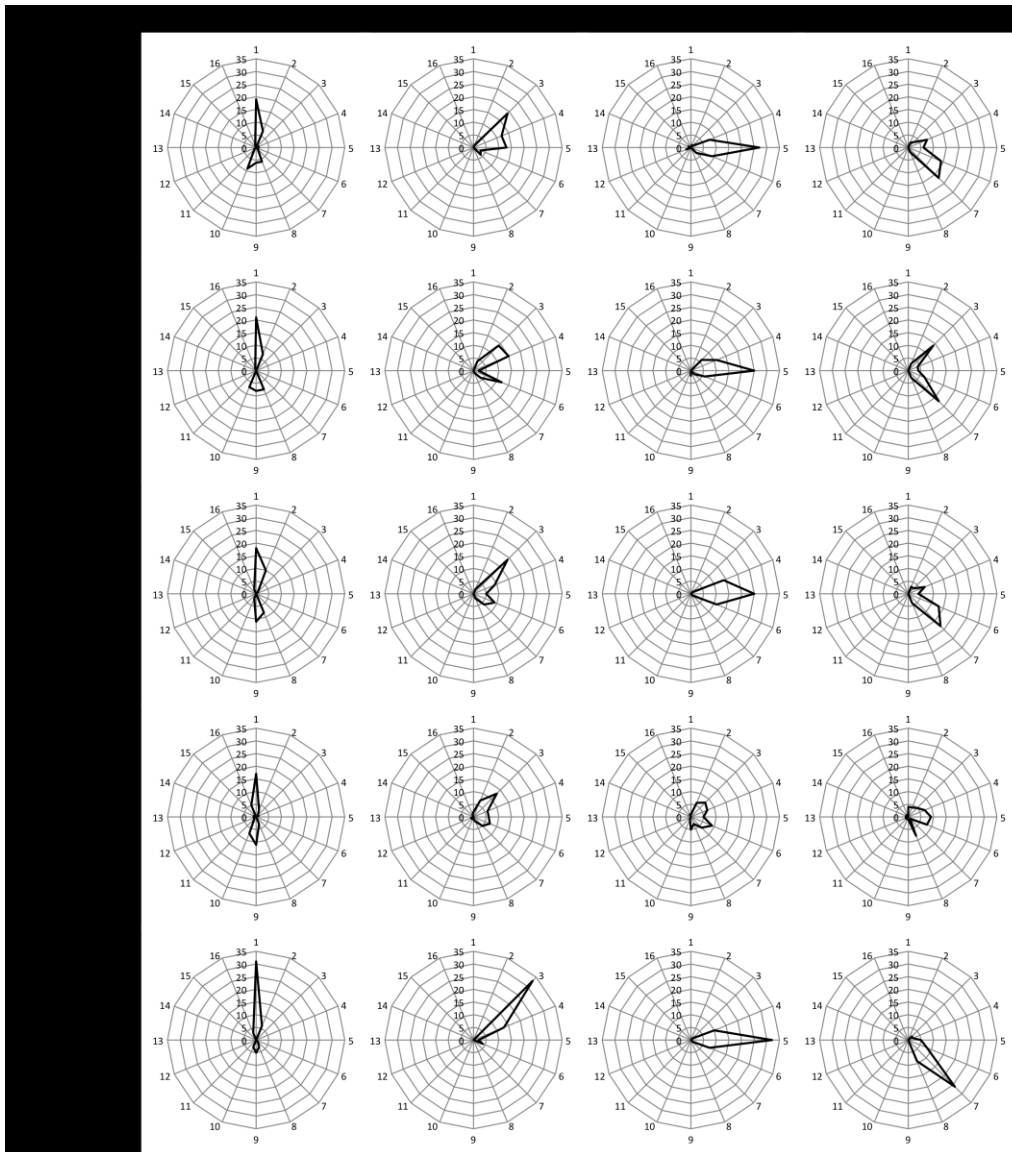
Figure 7. Responses by gunshot location and hearing protection enhancement device (HPED)/listening condition for all participants for shooter positions behind signs 1, 3, 5, and 7.

Front-back errors in all listening conditions were mostly limited to shooter positions 1 and 9, which were directly in front of and directly behind the participant, respectively. However, the polar charts also show a phenomenon not captured by the accuracy measures: for the gunshots originating from 45 degree angles to the front and rear of the participant (shooter positions behind signs 3 and 7), responses for the earplug conditions (EB 1, EB 15, and Combat Arms™) show a large number of errors where the response was flipped across the frontal plane from actual position. These errors could be called "cone of confusion errors" because they occur in the cone in which interaural time and level differences are identical. This suggests that the earplugs alter localization cues would allow disambiguation between points on the cone, possibly because they fill the concha and block the entrance to the ear canal.

In addition, the polar plots show a difficulty localizing with the Com-Tac II™. The spread of errors for the gunshot locations not directly to the front of the participant is greater than that for other devices, showing a significant disruption in

localization ability that was reflected in the accuracy measures.

Listening Condition: Subjective Rating Scales
Interference with ability to localize gunshots: Participants were asked to respond to the question, "Please rate how this hearing protection device (or open ear) condition interfered with your ability to localize the gunshots" on a bipolar, interval scale from 1 (worst interference) to 7 (no interference). The ANOVA yielded a significant effect of listening condition ($F = 16.12$, $p < 0.0001$). Post-hoc comparisons demonstrated that ratings for ability to localize were significantly lower for the Com-Tac II™ (2.8) than with the earplugs (EB 1 [4.8], EB 15 [4.7], and Combat Arms™ [4.4]) and the open ear (6.2). The ratings for ability to localize were significantly higher for the open ear condition than any HPED. There was no statistically-significant difference between the earplugs.

Confidence in ability to localize gunshots: Participants were asked to respond to the question, "Please rate how confident you were about your ability to locate the gunshots in this hearing protection device (or open ear) condition" on a bipolar, interval scale from 1 (no confidence) to 7 (extremely confident). The ANOVA showed a significant effect of listening condition ($F = 4.84$, $p = 0.0025$). Post-hoc comparisons showed that ratings for confidence in ability to localize were significantly lower for the Com-Tac II™ (2.9) than for the EB 1 (4.5) and the open ear (4.8). There was no statistically-significant difference in rating of confidence in ability to localize between the open ear (4.8) and any of the earplugs (EB 1 [4.5], EB 15 [3.9], Combat Arms™ [3.7]). This is a very important finding because a warfighter's lack of confidence in an HPED's ability to facilitate localization can lead to non-use of the protector.

Difficulty to judge location of gunshots: Participants were asked to respond to the question, "Please rate how difficult it was to judge the location of the gunshots in this hearing protection (or open ear) condition" on a bipolar, interval scale from 1 (extremely difficult) to 7 (extremely easy). The ANOVA showed a significant effect of listening condition ($F = 7.61$, $p < 0.0001$). Post-hoc comparisons showed that ratings for confidence in

difficulty to judge location of gunshots were significantly lower for the Com-Tac II™ (2.5) than for any other listening condition (EB 1 [4.3], EB 15 [4.1], Combat Arms™ [3.9], and open ear [4.9]).

Comfort: Participants were asked to respond to the question, "Please rate how comfortable this hearing protection device (or open ear) condition was while wearing it during the experiment" on a bipolar, interval scale from 1 (extremely uncomfortable) to 7 (extremely comfortable). The ANOVA showed a significant effect of listening condition ($F = 5.59$, $p = 0.0010$). Post-hoc comparisons showed that ratings for comfort were significantly lower for the HPEDs (EB 1 [4.8], EB 15 [4.8], and Combat Arms™ [5.1], and Com-Tac II™ [4.8]) than with the open ear condition (6.8). However, there was no statistically-significant difference in rated comfort between HPEDs.

Protection: Participants were asked to respond to the question, "Please rate how well-protected your hearing was in the presence of gunshots when using this hearing protection device (or open ear) condition" on a bipolar, interval scale from 1 (no protection) to 7 (extremely protected). The ANOVA showed a significant effect of listening condition ($F = 4.84$, $p = 0.0025$). Post-hoc comparisons showed that ratings for protection were significantly higher for the HPEDs (EB 1 [4.4], EB 15 [4.9], Combat Arms™ [5.1], and Com-Tac II™ [4.4]) than with the open ear (1.5). There was no statistically-significant difference between HPEDs, however. These results do evidence what was obvious to the subjects; that is, to be protected one of the HPEDs had to be worn.

Ease of communication. Participants were asked to respond to the question: "Please rate how easy it was to communicate with the experimenter while wearing this hearing protection device (or open ear) condition during the experiment" on a bipolar, interval scale from 1 (extremely difficult) to 7 (extremely easy). The ANOVA showed a significant effect of listening condition ($F = 4.84$, $p = 0.0025$). Post-hoc comparisons showed that ratings for ease of communication were significantly lower for the EB 15 (4.8), Combat Arms™ (4.8), and Com-Tac II™ (4.4) than for the open ear (6.5). There was no statistically-significant differences between any of the HPEDs (EB 1 [5.4], EB 15 [4.8], Combat

Arms™ [4.8], and Com-Tac II™ [4.4]); however, it is important to note that the EB 1 was the only HPED rated equal to the open ear on communications ease.

Listening Condition and Hearing Ability
The main effect of listening condition was significant at $p < 0.05$ for all six objective localization measures. Because these effects were discussed earlier, they will not be repeated here.

Turning to effects involving hearing ability, the main effect of hearing ability was significant ($F = 6.03$, $p = 0.0319$) for percent right-left error. The percent of right-left errors was lower for participants with normal hearing than those with impaired hearing (0% and 4%, respectively). The interaction of listening condition and hearing ability was also significant ($F = 6.24$, $p = 0.0005$) for percent right-left error. There was no statistically-significant difference between listening conditions for participants with normal hearing. However, when using the Com-Tac II™, hearing-impaired participants had significantly more right-left errors than in any other listening condition, and also poorer performance than did the normal hearers with the Com-Tac II™ (Figure 8).
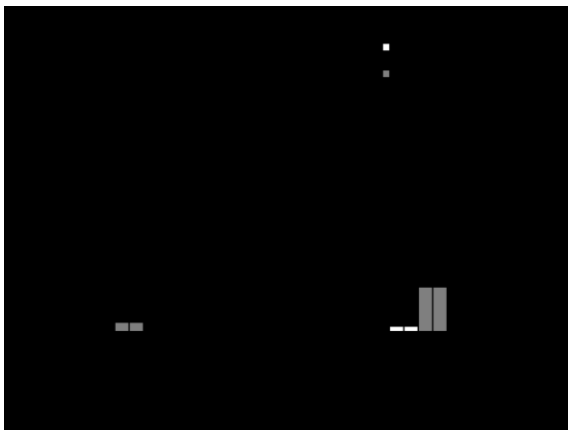

Figure 8. The effect of listening condition by hearing ability on percent of right-left errors. Error bars are the 95% confidence interval about the mean. Numbers above the error bars are means. Letters are the results from Tukey's multiple comparisons test where different letters represent a significant difference. The top letters are the main effect of listening condition; the lower letters are the comparison of hearing abilities under each listening condition.

This is an important result to consider in light of the fact that since the Com-Tac II™, perhaps based on its approximately 15 dB of pass-through gain, is sometimes applied for use by military personnel who have lost some hearing and need to return to duty. Based on these results, this practice is contraindicated due to its negative effects on localization.

CONCLUSIONS
On most accuracy measures and across the two noise conditions, both of the Etymotic BlastPLG™ devices exhibited localization performance that was close in line with the level-dependent end of the Combat Arms™ earplug, which is the most common "enhanced" hearing protector currently used by the U.S. military. In all cases, the open ear condition ranked as best in accuracy performance when compared to any of these three earplug-configuration devices. On all measures of localization accuracy performance, the Com-Tac II™ earmuff-based device ranked as lowest in localization performance among the four HPEDs and the open ear, except for front-rear errors where it was equivalent to the other HPEDs. Perhaps these detriments occurred due to the Com-Tac II™'s full coverage of the pinnae of the ear and/or its particular gain/compression behavior.

On the dependent measure of right-left errors, and across all HPEDs as well as the open ear, there were very few confusions of whether gunshots were coming from the right or left. Right-left confusions were substantially fewer than front-rear confusions when using almost any HPED, perhaps serving as evidence of the importance of interaural time and interaural level difference cues in localization, as well as the need for turning the head to aid in localization by employing these acoustical cues. There were no significant differences between the two noise conditions on any of the dependent measures; however, hearing-impaired individuals tended toward poorer localization performance than normal hearers but only on certain measures. It is noteworthy that the Com-Tac II™ earmuff resulted in significantly poorer (by 12-15%) right-left localization for impaired hearers when compared to other HPEDs, suggesting that despite that fact that this device provides about 15 dB of pass-through gain for moderate level sounds, it is not beneficial for certain hearing-impaired individuals for localizing.

Finally, the response time metric was very sensitive to HPED effects, with the Com-Tac II™ earmuff resulting in about 0.5 second longer response times than the other HPEDs, and about 0.9 seconds longer than the open ear. The EB 15 and Combat Arms™ also slowed response time by about 0.5 seconds compared to the open ear, but the EB 1 did not show any significant disadvantage on this measure.

For obvious reasons, degradation of either auditory localization decision response times, or auditory localization accuracy, or both can pose life-and-death consequences for the warfighter. Auditory threat localization is but one, albeit a very important, auditory task that is associated with maintaining or even enhancing the situational awareness of military personnel, and especially so for those involved in active combat and/or exercising special operational tactics.

These results provide evidence for the importance of human factors engineering in both the development and operational testing of HPEDs that closely mimic, or restore, the open ear's response in localization. More research is needed to determine the reasons for those decrements in performance associated with certain HPEDs as compared to the open ear that were revealed by this experiment, with the objective of optimization of future HPED designs to more closely replicate, and even eventually enhance "normal" hearing. Future research should include auditory signatures of gunshots, but also others as well, such as high-frequency signals including weapons preparation and human vocalizations. Furthermore, it is important to note that this experiment did not investigate accommodation time to the various HPEDs, and that may indeed be an important factor in the training process with warfighters who are to be deployed with such devices.

NOTE: A more extensive version of this paper with additional data presentation is in press for the *International Journal of Audiology.*

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