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Original Article

Azimuthal auditory localization of gunshots in a realistic field environment: Effects of open-ear versus hearing protection-enhancement devices (HPEDs), military vehicle noise, and hearing impairment

Kristen A. Talcott*, John G. Casali*, John P. Keady† & Mead C. Killion‡

*Auditory Systems Laboratory, Virginia Tech, Blacksburg, Virginia, USA, †Innovation R&D Labs, Fairfax Station, Virginia, USA, ‡Etymotic Research, Inc., Elk Grove Village, Illinois, USA

Abstract

Objective: A controlled field experiment was conducted to evaluate localization of suprathreshold gunshot reports (from blank cartridges) with four hearing protection-enhancement devices (HPEDs) in comparison to the open ear with ambient outdoor noise and in 82 dBA diesel military heavy truck noise. *Design:* Five measures of localization accuracy and response time for eight shooter positions in azimuth were measured. *Study sample:* Nine normal-hearing and four impaired-hearing participants were tested. *Results:* Statistical analysis showed worse accuracy and response time performance with the electronic earmuffs (Peltor Com-Tac II™ in full gain position) than with the other tested HPEDs (Etymotic EB 1 and EB 15 High-Fidelity Electronic BlastPLG™ electronic earplugs, both set to Lo gain positions; and 3M Single-Ended Combat Arms™ passive earplug in level-dependent, "open" position). Performance with all HPEDs was worse than that with the open ear, except on right-left confusions, in which the 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 related to localization generally corroborated objective localization performance. *Conclusions:* None of the tested HPEDs preserved "normal" localization performance.

Key Words: Hearing protection-enhancement device; electronic hearing protector; level dependent hearing protector; sound localization; impulse noise localization; localization in noise; firearm noise; gunshot; sniper; auditory localization; azimuth

Noise-induced hearing loss is the most common military service-related disability. Over $1.2 billion was spent on hearing injuries in fiscal year 2006 and in fiscal year 2007, the Veteran's Administration dispensed approximately 350 000 hearing aids at a cost of $141 million (Saunders & Griest, 2009). About one third of soldiers returning from Iraq and Afghanistan combat zones have noise-induced hearing loss (Ahroon, 2007). Military hearing loss is a debilitating injury that degrades the warfighter's personal quality of life. In addition, hearing-impaired warfighters may pose a liability to themselves and others in combat operations, because if their auditory sense is compromised, so too is their survivability, lethality, and ability to function in team environments where communication is key. Finally, military personnel who lose their auditory fitness-for-duty (AFFD) due to hearing loss represent a huge monetary investment lost, based on the expenses accrued in training prior to service deployment, as well as in-service training.

While it is possible to protect against noise-induced hearing damage by using properly-selected hearing protection devices (HPDs) and hearing protection-enhancement devices (HPEDs), military personnel have little confidence in, and will likely not use protectors that compromise their situational awareness, as evidenced in actual operational field effectiveness research (Casali et al, 2009). In the combat environment, military personnel require the ability to detect, discriminate, recognize, and localize signals associated with mission tactics, communications, and enemy threats in order to maintain their all-important objectives of survival and lethality (Casali et al, 2009). Failure to hear and further auditorially process these signals poses a threat to their maintenance of stealth and situational awareness and will likely compromise safety (Ahroon, 2007; Casali et al, 2009).

Research has shown that sound localization is often negatively affected by the use of traditional, conventional passive HPDs as well as active HPDs (Abel et al, 1996; Bolia et al, 2001; Borg et al, 2008; Simpson et al, 2005; Takimoto et al, 2007; Vause & Grantham, 1999). In some cases, earmuff-style HPDs with enhanced signal-pass-through circuits have not demonstrated any improvements in localization over standard passive earmuffs,

Correspondence: John G. Casali, Auditory Systems Laboratory, Department of Industrial & Systems Engineering, Virginia Tech, Blacksburg, VA 24061, USA. E-mail: jcasali@vt.edu

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Abbreviations

AFFD	Auditory fitness-for-duty
ANOVA	Analysis of variance
ANSI	American National Standards Institute
dB	Decibel
HPD	Hearing protection device
HPED	Hearing protection-enhancement device
NRR	Noise reduction rating

while certain flat-attenuation earplugs have shown measurable advantages over other passive HPDs (Alali & Casali, 2011). However, pass-through communications modes have also shown an advantage over passive modes (Abel et al, 2007).

Manufacturers of a new generation of "pass-through" level-dependent HPEDs claim these devices preserve normal or near-normal hearing while protecting the user against high-level noise exposure, such as from sudden gunfire. If such claims are true, these devices have the potential to gain user acceptance, improve long-term quality of life of users, and save the government money provided as compensation to hearing-damaged veterans. As the first in-field experiment of this type with gunshots as the auditory threat stimulus, it was not the objective of this research (nor possible in a factorial experiment) to evaluate all classes and models of augmented protectors. A representative sample of two of the most common devices in military deployment (both commercially available at the time of the experiment), and two new devices (both in the final stages of production circa mid-2010), were selected for this study. Recent reviews of all augmented HPED technologies of the passive and active (electronic) types may be found in Casali (2010a, b).

The purpose of the experiment was to evaluate auditory localization with level-dependent, pass-through HPEDs in an outdoor experimental site and scenario designed to simulate a combat environment. The listener stands in an open clearing and shots are fired at and from around him or her from visually-obstructed locations in a lightly-forested perimeter. Three questions were addressed in this controlled field experiment:

1. Is there an effect of the Etymotic EB 1 and EB 15 electronic earplugs, the 3M Combat Arms™ passive level-dependent earplug, and the Peltor Com-Tac II™ electronic earmuff, versus the open ear, on objective measures of azimuthal localization accuracy and response time, as well as on subjective measures relating to user acceptance (i.e. comfort, confidence in localization ability)?
2. Is there an effect of a representative background noise common to the combat environment (a diesel truck at idle, 82 dBA) on the localization performance with the HPEDs and open ear?
3. Is there an effect of hearing impairment on localization performance while using the HPEDs compared to the open ear?

Experimental Methodology

An overview of the experimental methodology is provided here. Detailed descriptions of all aspects of the methodology, along with extensive photographs of the experimental site, are available in an earlier technical report by Casali & Keady (2010).

Experimental design

A 5 (listening condition) × 2 (noise level) completely within-subjects design was employed, having 13 participants (Figure 1).

Independent variables

LISTENING CONDITION

Listening condition was a within-subjects variable with four levels of HPEDs: (1) Etymotic EB 1 High-Fidelity Electronic BlastPLG™ EB 1 earplugs set to the "Lo" gain switch position with triple-flange polymer eartips, (2) Etymotic EB 15 High-Fidelity Electronic BlastPLG™ earplugs set to the "Lo" switch position with triple-flange polymer eartips, (3) 3M Single-Ended Combat Arms™ earplugs in open/weapons fire mode, and (4) Peltor Com-Tac II™ electronic earmuff set to the maximum gain setting; and a fifth listening condition comprised of the open ear (no HPED).

Each of these HPEDs is designed to protect a user's hearing from loud impulse noises (i.e. gunfire in the military sense), but also to minimize interference with normal hearing. The EB 1 and EB 15 are newly developed electronic earplugs that were being evaluated for military use at the time of the experiment. The "Lo" position on both was selected because it more closely replicates normal hearing and

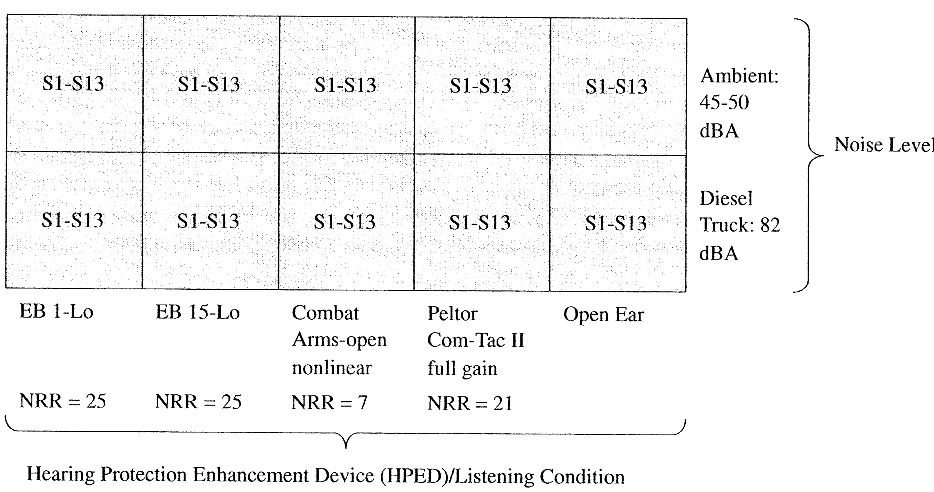

Figure 1. Experimental design with independent variables and subject assignment.

also provides circuit clamp-down protection during close proximity gunfire. The EB 1 in the "Lo" position is essentially acoustically transparent from 0–115 dB. The EB 15 in the "Lo" position is acoustically transparent for sounds below 60 dB, provides 15 dB of attenuation for sounds 85–155 dB, and blast protection for sounds 120–180 dB. The input-output gain profiles for the EB 1 and EB 15 in the "Lo" position are available at http://www.etymotic.com/pro/ebp.html. The Combat Arms earplug and Com-Tac II earmuff were selected because they are commonly deployed by various branches of the U.S. military, have been assessed in prior studies (Casali et al, 2009), and are sold with specific recommendation to military settings. According to the manufacturer's website (http://www.peltormilitary.com/sites/military/hearing_protection.aspx), the Combat Arms earplug "Allows wearers to hear low-level sounds critical to mission safety: conversation, footsteps, rifle bolts. When needed, the plug's "filter" reacts to provide instant protection from high level noises like weapons fire and explosions." According to the sales literature, the Com-Tac II electronic earmuff limits amplification of impact noises to 82 dBA, and amplifies ambient noise/voices up to 18 dB. At the juncture of the experiment in mid-2010, the Combat Arms and Com-Tac II were covered at http://www.peltormilitary.com. Attenuation data for all HPEDs tested appear on the manufacturers' websites noted above.

Noise level

Two noise levels were used in this study: ambient (rural, outdoor, lightly forested) and a 20-ton diesel military truck noise at 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 0.5-inch microphone, used for all daily site masking noise and gunshot calibration checks) at 45–50 dBA, with sources primarily consisting of occasional wind noise, though this was minimal because the site was surrounded by trees in the middle of a forest. 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 (Figure 2).

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 foot (1.83 m) height and 10 foot (3.05 m) from the participant. The input signal to the loudspeakers was generated from a Panasonic CD player and amplified with a Pioneer 100-W receiver-amplifier. In-field electrical power was provided by a Honda EU-2000i generator having an emitted sound output level at 10 feet (3.05 m) of 53–59 dBA, thus it was a non-contributory source in the 82 dBA truck masking noise and it was located at 40-feet (12.2 m) from the subject's position. The generator was turned off during the rural ambient noise conditions.

Hearing ability

Although hearing level was a variable of interest, a smaller number of hearing-impaired participants were recruited than normal-hearing participants. Given the smaller sample size, hearing ability could not be analysed as an independent variable in the main analysis. Normal hearing was defined as pure-tone thresholds, bilaterally, of 25 dBHL or better at 500, 1000, 2000, 4000, and 6000 Hz. Hearing-impaired participants were those that did not meet the threshold for normal hearing and furthermore had a pure-tone threshold greater than 30 dBHL at one or more test frequencies in at least one ear. Nine participants had normal hearing and four had impaired hearing, based on these operationally-defined criteria. Average hearing thresholds in each ear for normal and impaired participants are shown in Table 1.

Study participants

The study had thirteen participants: ten males and three females, age 22 to 54 years, with a mean age of 35 years. Participants were recruited from Virginia Tech and the surrounding area. Three participants had military experience.

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: seven had experience using both earplugs and earmuffs and five had experience with earplugs only. Participants who had used earplugs reported using foam and/or triple-flange plugs only (i.e. no HPEDs), except for one participant who had used a Peltor electronic earmuff for hunting. No participants had ever used hearing aids. Five participants had a history of exposure to loud noises either while working or during leisure time.

One participant had participated in informal auditory localization experiments. No other participants had previously participated in an auditory localization experiment. None of the participants had prior experience wearing any of the tested HPEDs.

Dependent measures

Six measures of localization performance were calculated: five measures of sound localization accuracy and one of localization response time. The measures of localization accuracy were: (1) mean absolute deviation (degrees) between the response target sign and the actual shooter location; (2) percent correct response: exact, the percentage of responses in which the participant responded with the exact target sign corresponding to the location of the shooter with no deviation; (3) percent correct response: within 22.5 degrees, the percentage of responses in which the participant responded with the exact target sign corresponding to the location of the shooter or a target sign 22.5 degrees to the left or right of the shooter; (4) percent of right-left errors, the percent of gunshots within ±45° (inclusive) directly to

Table 1. Participants' average hearing thresholds (dBHL).

			125	*250*	*500*	*1000*	*2000*	*3000*	*4000*	*6000*	*8000*
Right Ear	Normal	Mean	5.0	3.9	3.3	5.6	1.7	5.0	6.7	9.4	12.2
		S.D.	8.7	7.0	5.6	5.3	6.1	8.3	8.3	6.3	7.1
	Impaired	Mean	6.3	6.3	8.8	11.3	20.0	23.8	41.3	43.8	42.5
		S.D.	6.3	13.1	7.5	9.5	23.8	30.1	45.0	37.5	22.2
Left Ear	Normal	Mean	6.1	5.0	6.7	5.6	4.4	6.7	7.2	11.7	12.8
		S.D.	6.5	5.0	6.6	7.7	6.3	6.6	5.1	7.9	10.3
	Impaired	Mean	5.0	5.0	11.3	13.8	31.3	40.0	53.8	56.3	50.0
		S.D.	10.8	10.8	14.4	8.5	30.9	37.0	31.2	33.3	24.2

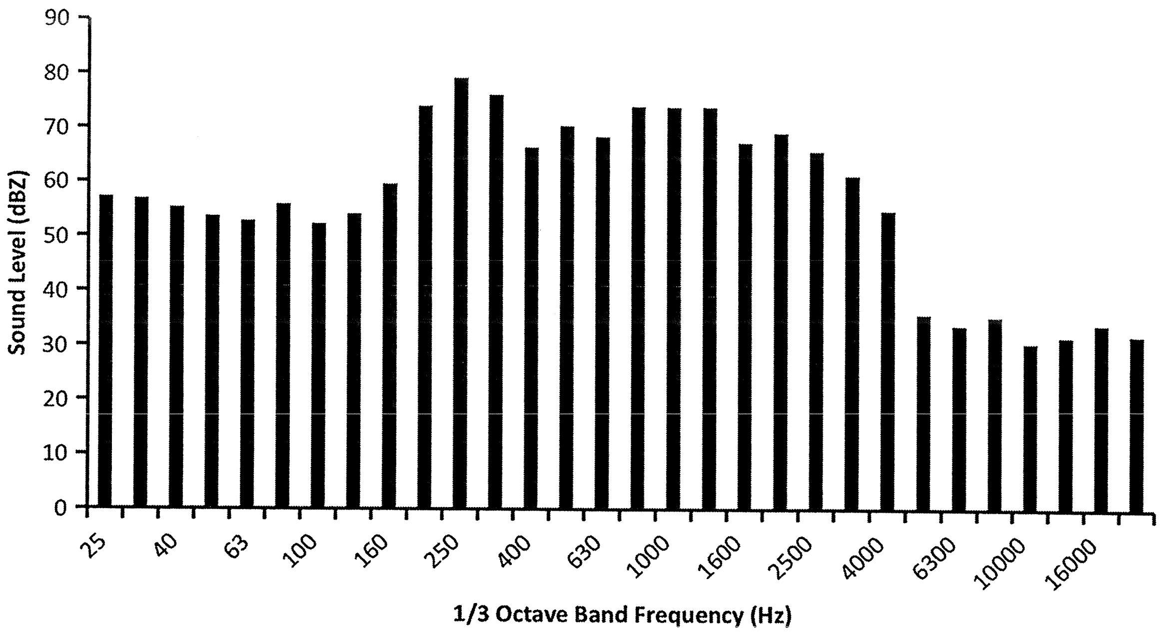

Figure 2. Twenty-ton diesel truck noise spectrum, as presented at 82 dBA overall level.

the left of the participant that were perceived to be in the same arc to the right of the participant and vice-versa; (5) percent of front-rear errors, the percent of gunshots within ± 45° (inclusive) directly to the front of the participant that were perceived to be in the same arc to the back of the participant and vice-versa. Response time was the time between when the shot was fired and the response from the participant, measured by the experimenter with a stopwatch, with samples of this time verified for accuracy from a digital recording of the gunshots followed by the subject's responses.

Participants completed a seven-interval, semantic differential rating scale with six impressions comprising the scale: interference with localization, confidence in localization, difficulty in judging location of gunshots, perceived protection, comfort, and ease of communication with experimenter. The participant completed the form immediately following the conclusion of all trials associated with a particular listening condition, while still wearing the device (or with ears unoccluded in the open ear condition).

Experiment site

An in-field test site was created especially for this study in a lightly-forested area of a farm located in a rural area in Pulaski County, Virginia. The experiment site was selected because it had a relatively level central plateau area with a gradual drop in elevation on all sides. This gradual drop in elevation helped ensure the lack of visual detection of the shooters. Trees and brush were removed in the central area to create a clearing of 50 feet (15.25 m) radius. The center of this area was the participant location. The woods outside of the clearing contained small and large trees with a density of about 1 tree per 60 square foot (5.58 m^2) of land. Eight shooter positions were created within the wooded area, lying on a circle 150 feet (45.75 m) 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 feet (15.25 m) from the participant position and at 22.5° increments of separation. The odd numbered target signs represented the exact eight actual shooter directions and eight "distracter" directions were numbered with even numbered signs, Figure 3.

The gunshot signal was generated by a single 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. 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 [0.125 s] 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 500–1000 feet (152.5–305 m). 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 analyser. 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 from 1200 Hz to 12500 Hz. Each of the shooters wore earplugs for hearing protection.

On each gunshot trial, the designated shooter fired a single blank aimed to avoid any trees or other obstructions at an umbrella 3 feet (0.91 m) above the participant's head position. The shooters and experimenter communicated via two-way radios. Shooters moved between the eight designated shooting positions on a cleared path. Brush was piled in the line-of sight at strategic shooter hiding positions, and camouflage netting was installed at the edge of the clearing to further obscure the participants' view of the shooter positions and the shooters' movements. 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

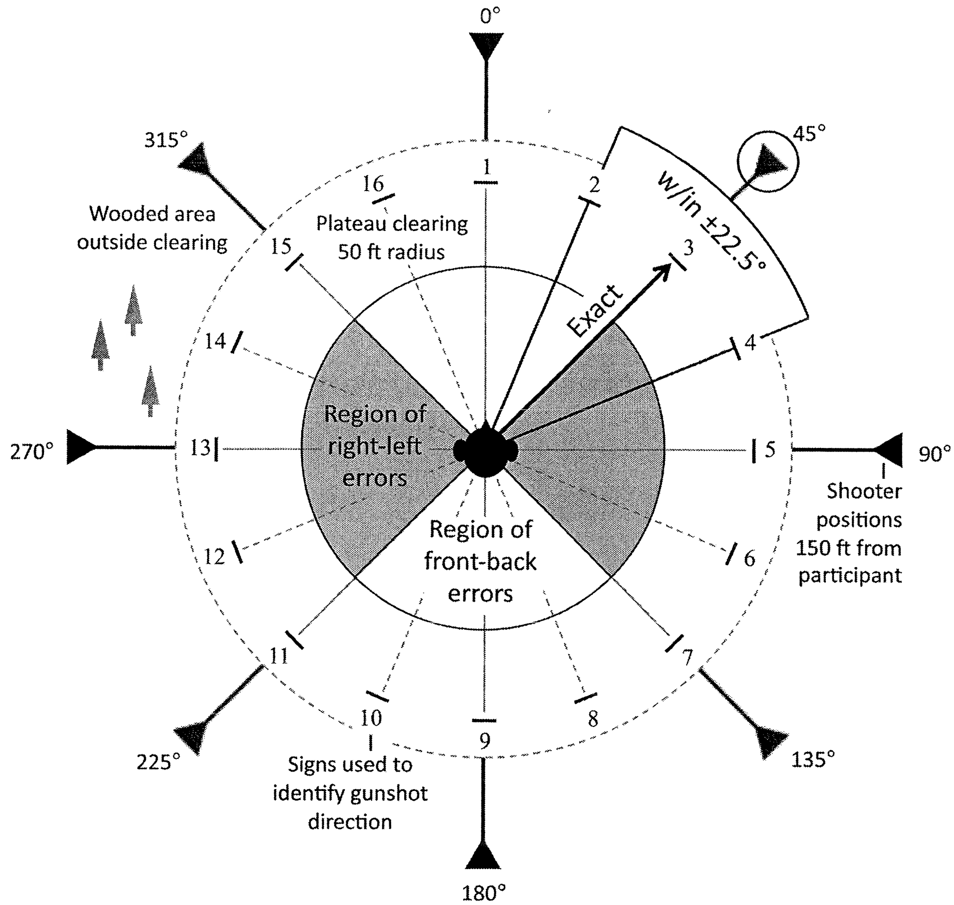

Figure 3. Experiment site layout showing the eight shooter positions, the 16 target signs (labeled 1–16) that participants used to identify shot location (with only odd-numbered signs corresponding to actual shooter positions, and even-numbered signs posing as distracters), and exact, "ballpark" (within 22.5°), front-back error, and right-left error regions for measures of localization accuracy.

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.

Introductory session

During the introductory session, participants first read and signed the informed consent form and then underwent audiometric screening. This screening consisted of 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 disqualify a participant from further participation in the study, and a pure-tone audiogram using a standard Hughson-Westlake manual test procedure. No participants had otoscopic problems that precluded them from participating in the study.

Auditory screening was done in the Auditory Systems Laboratory at Virginia Tech (11 participants) or near the experiment site in a quiet indoor test room that had been set up for the experiment (two participants). At Virginia Tech, participants' hearing was evaluated with a Beltone Model 114 manual pure-tone audiometer in the anechoic chamber in the Auditory Systems Laboratory. At the experiment site, participants' hearing was evaluated with a Beltone 119 manual portable pure-tone audiometer in a 25 dBA environment.

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 16 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."

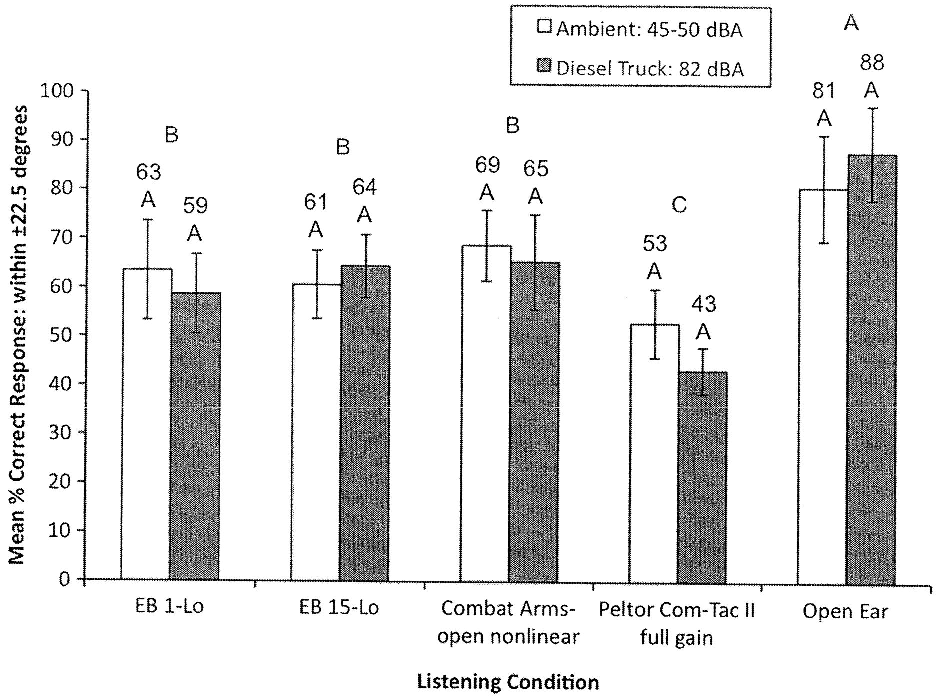

Figure 4. The effect of listening condition by noise level on percent correct response within ± 22.5 degrees ("ballpark"). Error bars are the 95% confidence interval about the mean. Numbers above the error bars are means. Letters are the results from Tukey's multiple comparisons test where different letters represent a significant difference at $p < 0.05$. The top letters are the main effect of listening condition, the lower letters are the comparison of noise conditions for individual HPEDs.

The experimenter fitted 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 fitted 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 fitted 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) the experimenter fitted the participant with the HPED, the participant stood on the mat facing sign 1 and the experimenter sat behind; (2) the experimenter turned the truck noise on or off (with generator as appropriate), (3) the participant donned occlusion glasses; (4) the experimenter turned on 75 dBA pink noise to mask the shooters' movements in the woods, the experimenter radioed the shooters to move to positions, and the shooters confirmed upon arrival; (5) the experimenter turned the pink noise off, yelled "ready," and the participant removed the vision-occlusion goggles; (6) the designated shooter fired the gun and the experimenter started the stopwatch; (7) the participant verbalized the target sign number as quickly and accurately as possible and the experimenter stopped the stopwatch; (8) steps 3 to 7 were repeated for all 8 shooter positions × 2 gunshot trials at each position; (9) the experimenter changed the noise condition and steps 3 to 7 were repeated; (10) the 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. The experiment was delayed during heavy rain and lightning, but was conducted if there was very light rain. If the wind speed exceeded about 8 mph gusting, the experiment was suspended.

Data analysis

The five dependent variables for listening condition and noise were analysed with five separate two-way within subjects analysis of variances (ANOVAs) in JMP™ software. Responses to each question on the subjective scale were analysed 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 analysed 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 as the criterion for a statistically-significant decision.

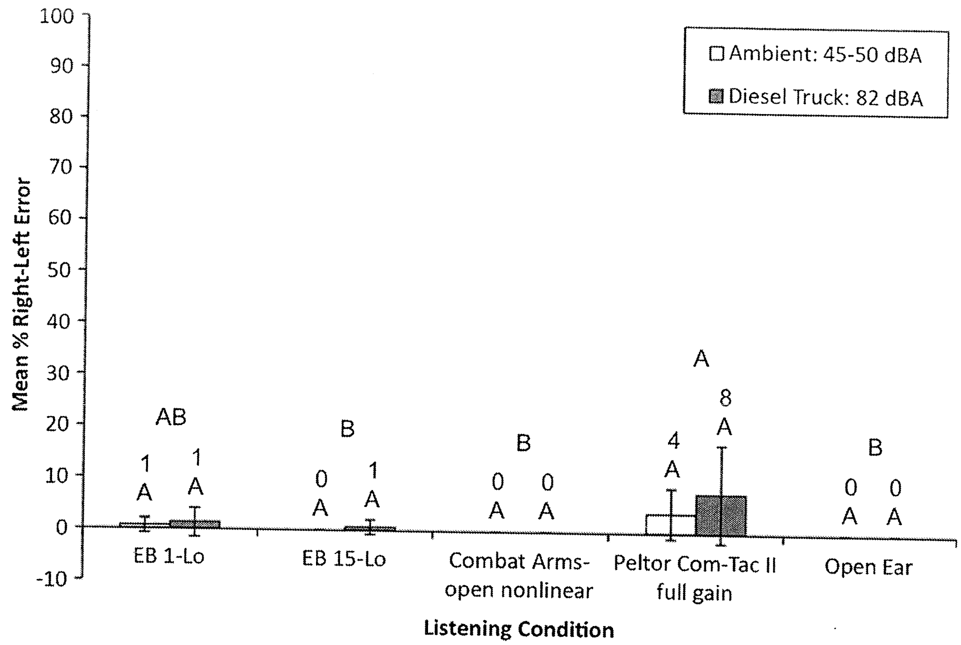

Figure 5. The effect of listening condition on percent of right-left errors. Error bars are the 95% confidence interval about the mean. Numbers above the error bars are means. Letters are the results from Tukey's multiple comparisons test where different letters represent a significant difference at $p < 0.05$. The top letters are the main effect of listening condition, the lower letters are the comparison of noise conditions for individual HPEDs.

Results

Listening condition and noise level: Objective measures

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.

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 ± 10 degrees deviation) than all other listening conditions, and significantly lower for the open ear condition (22 ± 14 degrees) than all other listening conditions. There was no significant difference between any of the three electronic or passive earplugs (EB 1 [44 ± 10 degrees], EB 15 [45 ± 10 degrees], and Combat Arms [41 ± 12 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 I 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 ± 10%) than all listening conditions and significantly greater for the open ear (55 ± 17%) than all listening conditions. There was no significant difference between the earplugs (EB 1 [34 ± 13%], EB 15 [35 ± 11%], and Combat Arms [35 ± 12%]). There was no significant main effect of noise level or significant interaction effect between listening condition and noise level.

Percent correct response within ± 22.5 degrees ("ballpark")

The ANOVA for percent correct response within ± 22.5 degrees ("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 ± 8%) than all other listening conditions and significantly greater for the open ear (84 ± 16%) than all HPED conditions. There was no significant difference between the earplugs (EB 1 [61 ± 13%], EB 15 [63 ± 9%], and Combat Arms [67 ± 13%]) 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

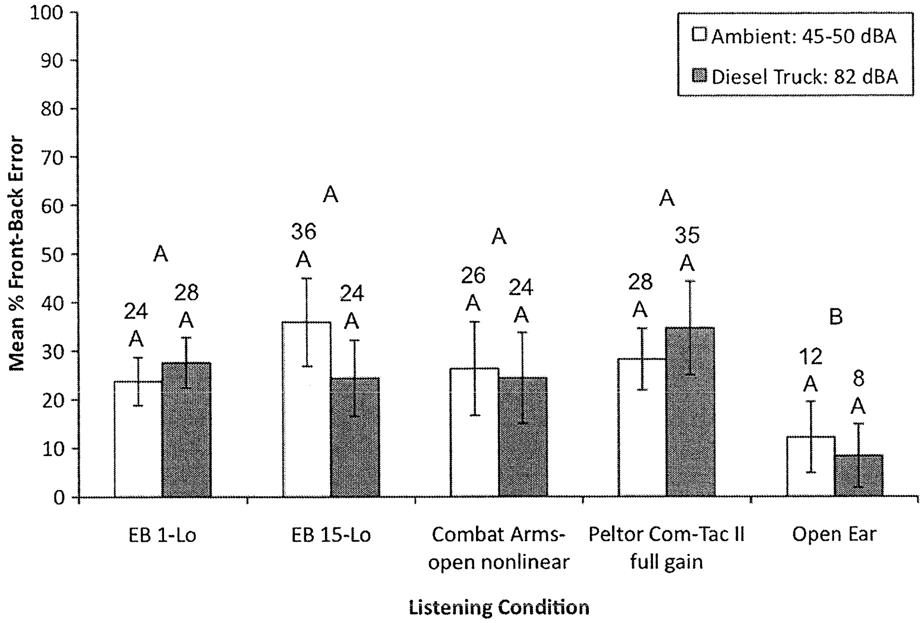

Figure 6. The effect of listening condition on percent of front-back errors. Error bars are the 95% confidence interval about the mean. Numbers above the error bars are means. Letters are the results from Tukey's multiple comparisons test where different letters represent a significant difference at $p < 0.05$. The top letters are the main effect of listening condition, the lower letters are the comparison of noise conditions for individual HPEDs.

worse and the open ear was significantly better. These effects are depicted in Figure 4.

Percent of 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 ± 10%) than the EB 15 (0 ± 1%), Combat Arms (0 ± 0%) earplugs, and the open ear (0 ± 0%) (Figure 5). There was no statistically-significant difference in percent of right-left errors between the EB 1 (1 ± 3%), EB 15 (0 ± 1%), and Combat Arms earplugs (0 ± 0%) and the open ear (0 ± 0%). There was no significant main effect of noise level or interaction effect between listening condition and noise level.

Percent of 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 ± 7% for the EB 1, 30 ± 11% for the EB 15, 25 ± 13% for the Combat Arms, 31 ± 9% for the Com-Tac II, and 10 ± 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 6).

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.

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 ± 1.4 s) than all other HPEDs (EB 1 [2.3 ± 1.0 s], EB 15 [2.5 ± 1.2 s], and Combat Arms [2.4 ± 1.2 s]) and the open ear (2.0 ± 1.2 s) (Figure 7). 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. The half-second difference found between the worst-performing HPED, the Com-Tac II earmuff, and the best performing HPED, the Combat Arms earplug, has practical significance in a combat environment: a half second could afford a warfighter sufficient time to take evasive action or return fire.

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 ± 1.8) than with

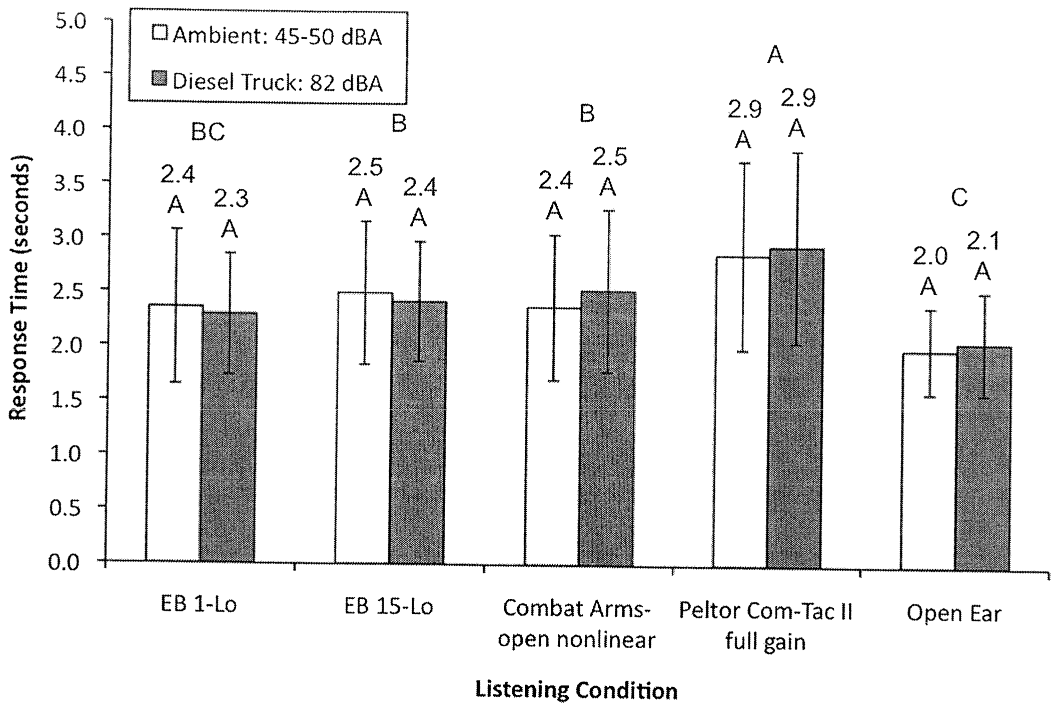

Figure 7. The effect of listening condition on mean response time. Error bars are the 95% confidence interval about the mean. Numbers above the error bars are means. Letters are the results from Tukey's multiple comparisons test where different letters represent a significant difference at $p < 0.05$. The top letters are the main effect of listening condition, the lower letters are the comparison of noise conditions for individual HPEDs.

the earplugs (EB 1 [4.8 ± 1.5], EB 15 [4.7 ± 1.5], and Combat Arms [4.4 ± 1.2]), and the open ear (6.2 ± 1.1). 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 ± 1.9) than for the EB 1 (4.5 ± 1.6) and the open ear (4.8 ± 1.6). There was no statistically-significant difference in rating of confidence in ability to localize between the open ear (4.8 ± 1.6) and any of the earplugs (EB 1 [4.5 ± 1.6], EB 15 [3.9 ± 1.6], Combat Arms [3.7 ± 1.5]). This is a very important finding because a 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 ± 1.7) than for any other listening condition (EB 1 [4.3 ± 1.5], EB 15 [4.1 ± 1.6], Combat Arms [3.9 ± 1.3], and open ear [4.9 ± 1.3]).

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 ± 1.1], EB 15 [4.8 ± 1.2], and Combat Arms [5.1 ± 1.3], and Com-Tac II [4.8 ± 2.0]) than with the open ear condition (6.8 ± 0.5). 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 ± 0.9], EB 15 [4.9 ± 0.9], and Combat Arms [5.1 ± 1.3], and Com-Tac II [4.4 ± 1.8]) than with the open ear condition (1.5 ± 1.0). 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.

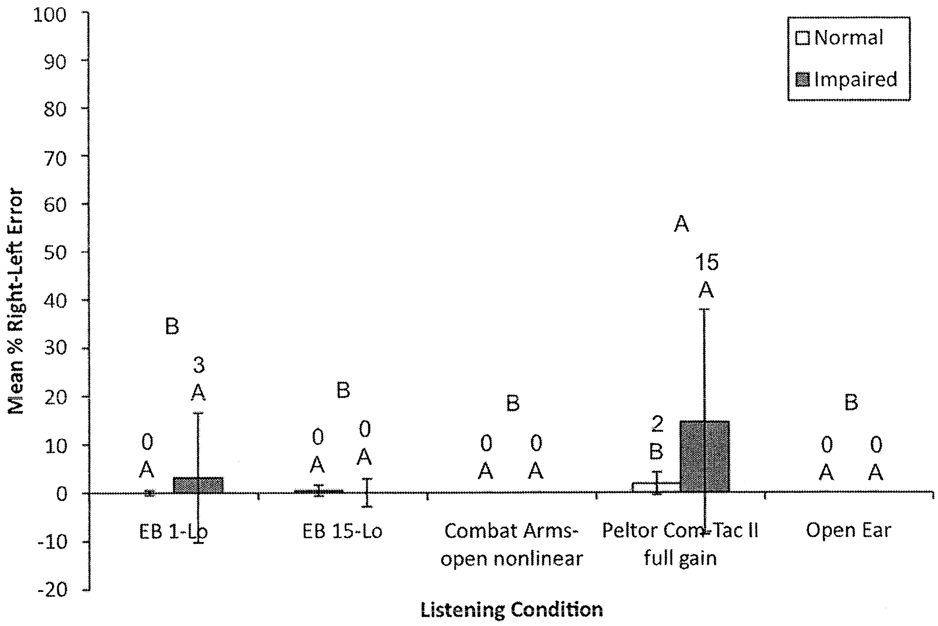

Figure 8. The effect of listening condition by hearing ability on percent of right-left errors. Error bars are the 95% confidence interval about the mean. Numbers above the error bars are means. Letters are the results from Tukey's multiple comparisons test where different letters represent a significant difference $p < 0.05$. The top letters are the main effect of listening condition, the lower letters are the comparison of hearing abilities for individual HPEDs.

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 ± 1.4), Combat Arms (4.8 ± 1.9), and Com-Tac II (4.4 ± 1.6) than for the open ear condition (6.5 ± 0.7). There was no statistically-significant differences between any of the HPEDs (EB 1 [5.4 ± 1.2], EB 15 [4.8 ± 1.4], Combat Arms [4.8 ± 1.9], and Com-Tac II [4.4 ± 1.6]), 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: Objective measures

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). This is an important result to consider in light of the fact that since the Com-Tac II, perhaps based on its 18 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, caution is suggested when recommending the Com-Tac II for use with hearing-impaired warfighters, and additional testing is recommended.

Discussion

On most measures, localization with the HPEDs was worse than that with the open ear. There was no significant difference between the earplugs (EB 1, EB 15, and Combat Arms), despite the difference in these earplug designs (electronic vs. mechanical). On most accuracy as well as the response time measures, localization with the Com-Tac II earmuff was significantly worse than that with the earplug-style HPEDs. Possible reasons for the poor performance with the Com-Tac II are the earmuff's full coverage of the pinnae, the microphone position (to the front of the earcup), the directionality (or lack thereof) of the microphones, and/or its particular dynamic gain/compression behavior. Based on these data, the Com-Tac II cannot be recommended for use in military situations where localization of gunshots is of importance to the soldier.

The presence of 82 dBA truck noise, as a main effect, did not significantly effect localization performance; however for some localization measures, there was a significant interaction of listening condition and noise. Where there was a significant interaction, the presence of this broadband, common military masking noise, appeared to accentuate the differences between HPEDs.

Somewhat surprisingly, hearing-impaired participants did not perform significantly worse than normal-hearing participants for all measures, except for right-left errors. Hearing-impaired participants had 13% more right-left errors with the Com-Tac II than did normal-hearing participants, and the Com-Tac II demonstrated a negative effect on right-left localization as compared to all other HPED and open ear conditions. These results should be interpreted with care, for several reasons. One is due to the specific audiometric profile of hearing loss in these individual subjects, as well as the small number of hearing-impaired subjects. However, given the rather consistently low ranking of the Com-Tac II's results amongst the HPEDs in this study, on realistic, situation-awareness-relevant measures of localization accuracy and response time, serious caution is advisable when selecting the Com-Tac II for combat situations where localization is of importance. The same may be true of other muff-type or even earplug-type HPEDs that provide dichotic sound pass-through capabilities, but each individual product must be evaluated prior to such a determination.

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. The results have applications for the military, as well as law enforcement, first responders, and recreational firearm users.

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. In addition, it should be noted that only about five minutes of accommodation time was allowed with each of the various HPEDs and that the influence of adaptation time on localization performance may be of interest for future research. However, in many examples of rapid deployment, soldiers are given the devices and must use them immediately, precluding adaptation.

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