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LABORATORY PERFORMANCE OF THE SINGLE-SIDED E-A-R® COMBAT ARMS HEARING PROTECTIVE EARPLUG

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ABSTRACT

The objective of this study was to compare the effect of wearing conventional and passive level-dependent hearing protection earplugs on hearing and horizontal plane sound source identification, in quiet. A single device was tested that incorporated these as separate modes of operation. Ten males and ten females with normal hearing participated. Each was tested with the ears unoccluded and fitted binaurally with the device in each mode. Measurements were made of free-field hearing thresholds for one-third octave noise bands with centre frequencies ranging from 250 Hz to 8000 Hz and the ability to discriminate among eight speakers surrounding the subject at a distance of 1 metre. The stimulus was a 300-ms, 75-dB SPL white noise burst. The sound attenuation was derived from the hearing thresholds. With the device in the conventional mode, mean thresholds were in the range of 36.2 dB to 53.3 dB SPL, signifying an induced mild hearing loss. In the level-dependent mode, thresholds were at most 37.9 dB SPL. Mean attenuation values were generally similar to the manufacturer's specifications. There was no effect of gender. Percent correct for sound source identification decreased by 40% with the conventional mode and by 20% with the level-dependent mode. Degree of attention, then appears to be a key factor for outcome. However, an analysis of error types showed that the level-dependent mode of operation resulted in a frontward bias that was similar to that observed previously with a device incorporating external microphones for enhanced communication.

SOMMAIRE

Le but de cet article est de comparer l'effet du port de bouchons conventionnels à celui de bouchons passifs avec atténuation dépendante du niveau acoustique sur l'audition et l'identification de sources sonores dans le plan horizontal dans le silence. Un protecteur permettant ces deux modes d'opération a été étudié auprès de dix hommes et dix femmes ayant une audition normale. Chaque individu a été évalué sans protection auditive et avec port binaural du protecteur dans chacun des deux modes. Les seuils auditifs en champ libre ont été mesurés pour des bandes de bruits tiers d'octave centrées sur des fréquences entrent 250 Hz et 8000 Hz, ainsi que la capacité à discriminer huit haut-parleurs placés à un mètre autour des participants. Le stimulus était d'une durée de 300 ms et était présenté à 75 dB SPL. Le degré d'atténuation a été déduit à partir des seuils auditifs. En mode conventionnel, des seuils moyens entre 36.2 et 53.3 dB SPL ont été obtenus, équivalent à une perte auditive de degré léger. En mode avec atténuation dépendante du niveau, les seuils auditifs n'ont pas dépassés 37.9 dB SPL. Les valeurs moyennes d'atténuation obtenues étaient en général similaires aux données fournies par le fabricant. Aucun effet du genre n'a été observé. Comparativement à la condition sans protection auditive, le pourcentage d'identifications correctes de la source sonore avec port du protecteur a chuté par 40% en mode conventionnel et par 20% en mode avec atténuation dépendante du niveau. Le degré d'atténuation semble donc être un facteur clé pour expliquer les résultats obtenus. Par contre, une analyse du type d'erreurs commises en mode avec atténuation dépendante du niveau a démontré un biais pour des réponses vers l'avant similaire à celui obtenu antérieurement avec un protecteur incorporant des microphones externes pour améliorer la communication.

1. INTRODUCTION

Continuous unprotected exposure to continuous noise levels in excess of 85 dBA or impulse noise exceeding 140 dB peak will result in a hearing loss (ISO, 1990; Abel, 2005). Hearing impairment may be reduced either by reducing the level of the noise at the source or by using personal hearing protection devices. Since sound reduction at the source is difficult and costly to achieve (Sheen and Hsiao, 2007), the cornerstone of hearing conservation programs, in both civilian and military occupational settings, is the wearing of hearing protective earplugs and earmuffs. Conventional passive level-independent plugs and muffs reduce sounds by the same amount regardless of their level. High frequencies

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14. ABSTRACT
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are reduced more than low frequencies. For muffs, sound attenuation typically increases from about 10 dB at 250 Hz to 35 dB at 1000 Hz and then remains fairly constant. In general, plugs provide more low-frequency attenuation than muffs. However, the outcome varies widely, depending on the particular device chosen and the goodness of the fit in individual users (Berger, 2000).

By comparison, the attenuation provided by level-dependent devices will vary depending on the ambient noise in which they are worn (Abel et al., 1993). Passive level-dependent hearing protectors do not impede sound at low to moderate intensities but do protect against exposure to high-level impulse noise (Abel and Lam, 2004). Such devices incorporate a precision orifice in an acoustical duct which improves transmission of low-level sounds. High-level impulses in the range of 120 dB will create turbulent air flow in the orifice which restricts their passage. There are two types of active level-dependent hearing protectors. The first type provides limited amplification for low-level sounds and conventional attenuation at higher levels. The second type samples the incoming waveform and adds it out of phase to the original with the goal of noise cancellation. While no devices currently available provide complete cancellation, these may increase the attenuation at frequencies below 1000 Hz by as much as 20 dB (McKinley et al., 1996).

Regardless of the hearing protector selected, users express concern that the device will interfere with the detection and localization of warning sounds and the ability to communicate, thereby compromising performance and increasing personal risk (Abel, 2008; Casali et al., 2009). This have been confirmed by laboratory studies which show that the sound attenuation afforded by the hearing protector will add to the user's hearing threshold. Thus, a mild hearing loss may become moderate to severe, with the consequence that environmental sounds may become distorted or will have to be much louder to be heard (Abel et al., 1993). In both normal and hearing impaired individuals, the wearing of plugs and muffs has been shown to obstruct spectral cues derived from the filtering effect of the outer ear. These normally enable the discrimination of front from rearward sound sources (Musicant and Butler, 1984; Blauert, 1997; Abel et al., 2007).

In a previous research study, the sound attenuation of the E-A-R® Combat Arms earplug was investigated (Abel and Lam, 2004). This device is comprised of two separate plugs attached stem-to-stem. One plug (olive colour) is a conventional level-independent device that is worn in steady-state noise. The other (yellow colour) is a passive level-dependent device that is meant to be worn in environments characterized by a relatively low ambient with sporadic high-level impulses (e.g., weapons fire). It provides significantly less attenuation than its conventional pair mate, thereby promoting communication while minimizing exposure to impulsive sounds. Results of the study showed that the attenuation of both devices, 21-40 dB for the conventional plug and 5-22 dB for the level-dependent plug, closely matched the manufacturer's specifications.

A single-sided version of the E-A-R® Combat Arms earplug has recently been marketed (see Figure 1). This device comprises one plug with a selector dial that enables the user to choose the mode of operation, conventional or level-dependent for steady-state noise and impulse (weapons fire) noise, respectively. An advantage of this updated version is that it is available in three sizes enabling a better fit for individual users. The aim of the present study was to assess the real-ear attenuation at threshold of this device in each of its two modes of operation, in men and women, and also to test the effect of each mode on auditory detection and horizontal plane sound source identification. The objective was the generation of new information that would help individuals employed in military combat arms trades to understand the relative benefits and drawbacks of this device for active combat, in terms of both its ability to protect hearing and its effect on situational awareness (Abel et al., 2009).

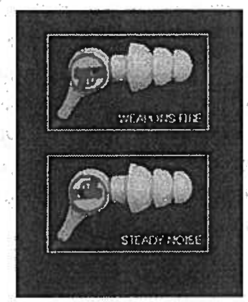

Figure 1. The single-sided E-A-R® Combat Arms earplug. The top panel shows the dial in the level-dependent mode, with the image of the weapon pointing towards the plug. The bottom panel shows the dial in the conventional mode, with the weapon pointing away from the plug.

2. METHOD AND MATERIALS

2.1 Experimental Design

The study protocol was approved in advance by the Human Research Ethics Committee, Defence Research and Development Canada. Two groups of 10 males and 10 females (military and/or civilian), aged 18-60 years, with normal hearing were tested. In each individual, hearing thresholds and sound source identification were assessed under three experimental conditions in which the ears were: unoccluded (Unocclud), fitted binaurally with the single-sided version of the Combat Arms earplug in the steady state noise mode (CAE SS), and fitted binaurally with the single-sided version of the Combat Arms earplug in the weapons fire mode (CAE WF). The unoccluded condition was presented first, followed by the CAE SS and then the CAE WF. Presentation of the unoccluded condition first ensured that subjects would have a good understanding of the procedures before preceding to the occluded conditions where hearing would be compromised. Previous studies have shown that learning effects for sound source identification are less than 5% (Abel et al., 2009).

The selection of size of the earplug for each subject was made by a trained technician after inspection of the ear canals. Subjects were then given verbal instructions for inserting the device prior to doing so themselves. The fits were checked by the technician to insure that the plugs were well seated in the ear canal. This protocol is a variation of Method A (Experimenter-Supervised Fit) described in ANSI Standard S12.6-1997 for measuring the real-ear attenuation of hearing protectors. If necessary, other sizes were tried. In the CAE SS mode, the subject's free-field hearing threshold was measured first at 4000 Hz and compared with the unoccluded threshold at the same frequency, as a way to ensure that a good fit had been achieved with the size selected before proceeding.

Hearing thresholds were measured once for each of eight one-third octave noise bands, centred at 250, 500, 1000, 2000, 3150, 4000, 6300 and 8000 Hz. The sound attenuation provided by the earplug in each mode of operation, the real-ear attenuation at threshold (REAT), was derived by subtracting the hearing threshold obtained for the ears unoccluded (control) condition from the hearing thresholds obtained for the hearing protector in each of its two modes of operation, at each sound frequency tested (Berger, 2000).

Sound source identification was assessed using a horizontal array of eight loudspeakers positioned at the following azimuth angles: 15°, 75°, 105°, 165°, 195° (-165°), 255° (-105°), 285° (-75°) and 345° (-15°). Two speakers were placed in each of the four spatial quadrants at azimuths that would allow an examination of right-left and front-back confusions among mirror image azimuths close to the midline and interaural axes of the head. These were positioned at a distance of 1 m from the subject's centre head position, at ear height. The stimulus was a 75 dB SPL, 300-ms white noise burst with a 50-ms rise/decay time to minimize onset transients. Broadband noise allows the observer access to binaural (ITD and ILD) and spectral cues in combination (Blauert, 1997).

2.2 Subjects

Subjects were recruited by means of an email sent to employees of Defence Research and Development Canada – Toronto (DRDC Toronto). Prior to inclusion in the study, volunteers were screened by telephone for a history of ear disease, hearing loss and tinnitus, excessive wax in the outer ear canal, claustrophobia and difficulty concentrating over a 2-hour period. Those who passed these screening criteria underwent a hearing test conducted by a trained technician to ensure that pure-tone air conduction thresholds were no greater than 20 dB HL (i.e., no more than a mild hearing loss) at 500, 1000, 2000 and 4000 Hz (Yantis, 1985), and that the interaural difference at each of these frequencies was no greater than 15 dB. The latter requirement was meant to minimize a possible left/right bias in sound localization. Those who passed the hearing test were scheduled for participation in the study.

2.3 Apparatus

Subjects were tested individually while seated in the centre of a double-walled, semi-reverberant sound proof booth (Series 1200; IAC, Bronx, NY) with inner dimensions of 3.5 (L) × 2.7 (W) × 2.3 (H) metres that met the requirements for hearing protector testing specified in American National Standard S12.6-1997 (ANSI, 1997). The ambient noise was less than the maximum permissible for audiometric test rooms specified in American National Standard S3.1-1999 (ANSI, 1999). Reverberation times were 0.6s at 125 Hz and 250 Hz, 0.4 s from 500 Hz to 4000 Hz, and 0.3 s at 6000 Hz and 8000 Hz. The instrumentation and calibration methods have been described previously (Giguère and Abel, 1990; Giguère and Abel, 1993).

The one-third octave noise bands for the hearing threshold measurements were produced using a white noise generator (B&K 1405; Brüel and Kjaer Instruments, Norcross, GA) and band pass filter (B&K 1617; Brüel and Kjaer Instruments, Norcross, GA). Outputs were fed to a manual range attenuator (HP 350-D; Hewlett-Packard, Palo Alto, CA) and receiver (RX-V620; Yamaha, Buena Park, CA) and presented free-field over a set of three loudspeakers (DL10; Celestion, Maidstone, Kent, UK), positioned to create a uniform sound field. Subjects used a hand held push-button switch to indicate that they had heard the stimulus.

For the sound source identification test, subjects were seated in the centre of a circular array of eight loudspeakers (Minimus 3.5; Radio Shack Corp, Fort Worth, Tx), closely balanced with respect to output levels (1.5 dB) and frequency response from 125-12000 Hz (2.5 dB). The stimulus was produced by a noise generator (Type 1405; Brüel and Kjaer Instruments, Norcross, GA). Level was set using a programmable attenuator (S85-08; Coulbourn Instruments, Lehigh Valley, PA) and a set of integrated stereo amplifiers (Realistic SA-150; Radio Shack Corp, Fort Worth, Tx). Subjects signified their spatial judgments by means of a specially designed laptop response box consisting of a set of eight micro switches in the same configuration as the speaker array, both in number of elements and azimuth angles.

For both paradigms, the timing of events, including stimulus duration and envelope shape, and logging of responses were accomplished using a modular system (Coulbourn Instruments, Lehigh Valley, PA). Devices were controlled by a personal computer via IEEE-488 (Institute of Electrical and Electronics Engineers, Inc., New York, NY) and Lablinc interfaces (Coulbourn Instruments, Lehigh Valley, PA), and digital I/O lines.

2.4 Procedure

Hearing thresholds were measured using a variation of Békésy tracking (Brunt, 1985). For each threshold determination, the stimulus was pulsed continuously at a rate of 2.5 per second. The pulse duration was 250 ms including a rise/decay time of 50 ms. Subjects were instructed to depress an on/off push-button switch whenever the pulses were audible, and to release the switch when they could no longer be heard. The sound level of consecutive pulses was increased in steps of 1 dB until the switch was depressed and then decreased at the same rate of change until the switch was released. The tracking trial was terminated after a minimum of eight alternating intensity excursions with a range of 4 to 20 dB. Hearing threshold was defined as the average sound level of the eight final peaks and valleys.

For sound source identification, one block of forced-choice loudspeaker identification trials was given for each of the three experimental conditions. The trial block comprised 15 random presentations of the stimulus through each of the eight loudspeakers, in randomized sets of eight, giving a total of 120 trials. The rate of presentation of trials was approximately one every seven seconds. Each trial began with a ½-sec warning light on the response box, followed by a ½-sec delay and the presentation of the 300-msec broadband noise stimulus. When the warning light flashed, the subject focused on a straight-ahead visual target affixed to the wall of the booth. This ensured that the speaker array and coordinate system of the head were aligned. She/he was instructed to sit squarely and to try to minimize head movement, although the head was not restrained. Previous research has shown that head movements may help to resolve front/back confusions (Wightman and Kistler, 1999).

Following each stimulus presentation, the subject pushed the microswitch on the laptop response box corresponding to the loudspeaker that emitted the stimulus. She/he was advised to use both hands for responding, the right hand for buttons on the right and the left hand for buttons on the left, to eliminate the possibility of errors from crossing the hand to the contralateral side. Guessing, if uncertain, was encouraged and no feedback was given about the correctness of the judgments. A set of two practice trials/loudspeaker with feedback (i.e., 16 trials) was given at the start of the session with the ears unoccluded to provide the subject with a spatial sense of the loudspeaker array relative to the response buttons, and to ensure that instructions had been understood.

3.0 RESULTS

The dataset for each subject consisted of (1) hearing thresholds for each of eight frequencies, (2) derived attenuation scores, (3) the overall percentage (percent) correct sound localization judgments, (4) the percent correct for each of the four spatial quadrants, (5) the percent correct by azimuth and (6) the percent mirror image reversal errors for positions close to the midline and interaural axes, under each of the three ear conditions. Repeated measures analyses of variance, ANOVA (Daniel, 1983), were applied to each outcome measure to assess the effect of ear condition (unoccluded, CAE SS and CAE WF), gender (male vs female), and various test parameters. For each ANOVA, Mauchley's Test of Sphericity was applied to the data to test the hypothesis that the variances of the differences between the levels of the repeated measures factors were not significantly different (Howell, 2002). If they were different, then the Greenhouse-Geisser correction was applied. Post hoc pairwise comparisons between levels of significant factors were made using the Bonferroni correction (Miller, 1991).

The means of free-field hearing thresholds for the 20 subjects, averaged across gender groups, are shown in Figure 2. An ANOVA applied to the data indicated significant effects of ear condition, frequency, ear condition by frequency, and ear condition by frequency by gender ($p<0.02$ or better). There was no main effect of gender. Averaged across gender and frequency, mean thresholds for the unoccluded, CAE SS and CAE WF conditions were 10.1, 41.7 and 26.7 dB SPL, respectively. Post hoc comparisons indicated that these were significantly different from each other. For both unoccluded and CAE SS conditions, thresholds were at a minimum in the region of 3150 Hz to 4000 Hz. For the CAE WF, thresholds steadily increased from 500 Hz to 8000 Hz.

The attenuation provided by the earplug in each of its two modes of operation, derived from the threshold data, are presented in Table I. Regardless of the mode of operation, CAE SS or CAE WF, observed mean values were within 5 dB of the manufacturer's specification, except for the CAE WF at 250 Hz, where the observed value was 8 dB less. Standard deviations were also comparable at 6 dB or less, except for the CAE SS at 250, 500 and 1000 Hz where they ranged from 8-10 dB. An ANOVA applied to the observations showed significant effects of protector mode, frequency, protector mode by frequency, and protector mode by frequency by gender ($p<0.02$ or better). Across frequencies, attenuation values for the CAE SS were relatively stable at 27.0 dB to 34.7 dB. In contrast, attenuation values for the CAE WF increased from -2.9 dB at 250 Hz to 24.8 dB at 3150 Hz and then remained fairly stable at 23.6 dB, on average, from 4000 Hz to 8000 Hz. From 2000 Hz to 8000 Hz the CAE SS provided 8.9 dB to 10.6 dB more attenuation than the CAE WF. Differences in the same direction from 250 Hz to 1000 Hz decreased from 29.9 dB to 16.6 dB.

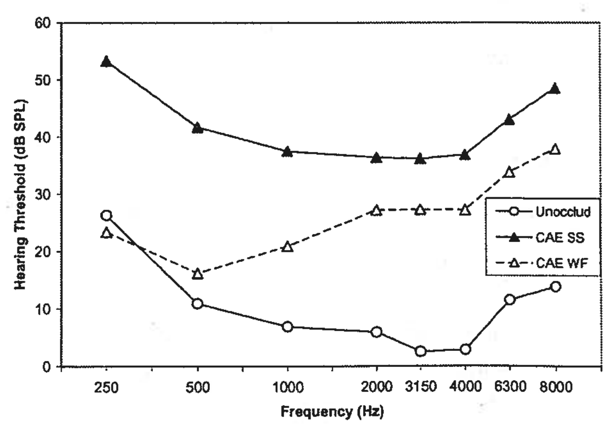

Figure 2. Free-field hearing thresholds with the ears unoccluded and fitted with single-sided E-A-R® Combat Arms earplugs.

Overall percent correct for sound source identification varied significantly across ear conditions but not gender, ranging from a mean of 90.4% for unoccluded listening to 70.1% with the CAE WF to 48.9% with the CAE SS ($p<0.0001$). Post hoc comparisons showed that these were significantly different from each other. Averaged across ear conditions, the change in accuracy from the first sixteen to the last sixteen trials which might show evidence of practice or fatigue was not significant. However, there were significant effects of ear condition and ear condition by change ($p<0.01$ or better). Observable gains were less than 1% for the unoccluded and CAE WF conditions, and 11.6% for the CAE SS.

Accuracy in discriminating the four spatial quadrants is shown in Figure 3. The data were averaged across gender groups. An ANOVA applied to these data indicated that there were significant effects of ear condition and side (right vs left) ($p<0.01$ or better) but not gender or quadrant (front vs back). In order to elucidate, ANOVAs were subsequently applied to the data for the three ear conditions, taken separately. The ANOVA for unoccluded listening showed a significant effect only of quadrant ($p<0.05$). Averaged across sides, frontal accuracy exceeded rearward accuracy by 7.5%, with 94.4% for the frontal quadrant and 86.9% for the rearward quadrant. There were no significant differences when the ears were fitted with the CAE SS. On average, quadrant accuracy was 54.4%. For the CAE WF, there were significant effects of side and quadrant ($p<0.04$ or better). Averaged across quadrants, the accuracy on the right side exceeded the left side by 3.6%. Averaged across sides, accuracy for the frontal quadrant exceeded that for the rearward quadrant by 24.5%, with 83.2% for the frontal quadrant and 58.7% for the rearward quadrant.

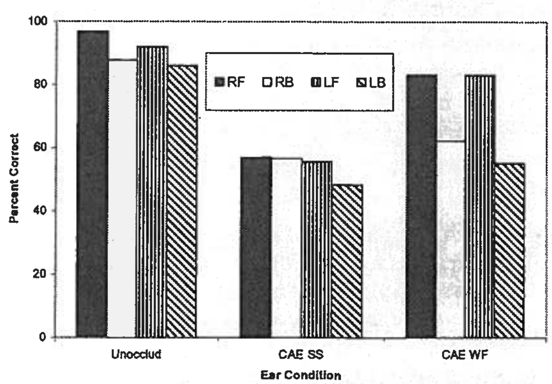

Figure 3. Quadrant discrimination with the ears unoccluded and fitted with single-sided E-A-R® Combat Arms earplugs.

Figure 4 shows the mean percent correct for each of the eight azimuths, averaged across gender groups. For all three conditions, outcomes appeared to be similar for mirror image azimuths on the right (15, 75, 105 and 165 deg) and left (345, 285, 255 and 195 deg) sides. An ANOVA applied to the data for the unoccluded condition showed that there was a significant effect of azimuth ($p<0.001$) but not side. Averaged across left and right sides, scores for the four azimuthal positions ranged from 75.2% to 99.5%. Pairwise comparisons among azimuths indicated that the results for the front and rearward azimuths close to the midline axis were no different, nor were those on either side of the interaural axis. Performance was significantly better for the former than the latter ($p<0.05$). A similar pattern was evident when subjects wore the CAE WF, although the scores were relatively lower. An ANOVA applied these data showed that for this condition both side and azimuth were significant ($p<0.02$ or better) but not their interaction. Averaged across azimuth, the difference due to side was relatively small at 4.4%, with an advantage for the right. Averaged across sides, azimuthal percent correct ranged from 45.7% to 88.2%. Pairwise comparisons indicated that again the results for the two azimuths close to the midline axis were no different nor were those on either side of the interaural axis. Only the frontal azimuth close to the midline axis (highest score) was significantly different from the rearward azimuth close to the interaural axis (lowest score). In the case of the CAE SS, neither side nor azimuth was a significant factor. Averaged across sides, accuracy scores for the ranged from 42.8% to 57.5%.

An analysis of mirror image reversal errors for positions close to the midline and interaural axes of the head revealed that the likelihood of a right-left (left response given right stimulus, L/R, and right response given left stimulus) confusion was less than 5%, except for the CAE SS rearward hemisphere midline positions, 195 deg/165 deg

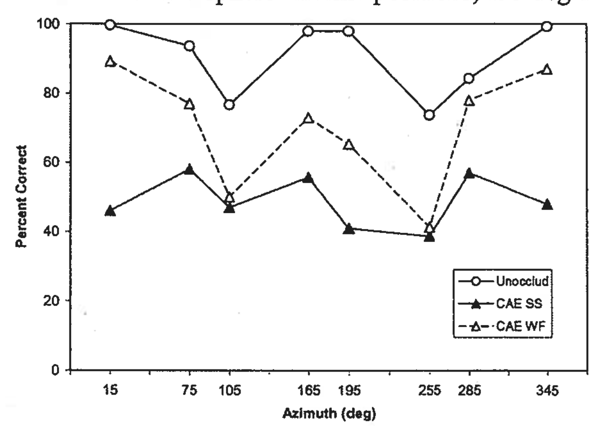

Figure 4. Azimuthal accuracy with the ears unoccluded and fitted with single-sided E-A-R® Combat Arms earplugs.

and 165deg/195deg, where the outcomes were 7.7% and 11.0%. As shown in Table II, the prevalence of front-back mirror image reversal errors (B/F and F/B) was substantially higher. ANOVAs applied to these data for each of the three ear conditions taken separately showed that in each case, position (midline vs interaural) was significant factor ($p<0.0001$) but side (right vs left) was not. In the unoccluded and CAE WF conditions, the type of error (B/F vs F/B) was also significant ($p<0.05$ or better). Averaged across right and left sides, the percentage of errors was more likely for the interaural position compared with the midline position, by 16-19% across the three ear conditions. At the interaural position, F/B errors were more likely than B/F by 14% and 34%, in the unoccluded and CAE WF conditions, respectively. For the CAE WF, the likelihood of a F/B mirror image error at the interaural position was 54% (about half the trials), compared with 49% for the CAE SS and 25% for unoccluded listening.

4.0 DISCUSSION

The single-sided E-A-R® Combat Arms earplug was designed to give users the option of reduced attenuation to promote communication, with the added guarantee of enhanced protection against sporadic impulsive weapons fire. A dial on the stem of the device allows the user to switch to conventional level-independent attenuation in case of high-level steady-state ambients. In the present study, the REAT method was used to derive the attenuation achieved in each of these two modes of operation (Berger, 2000). This method has the advantage of giving individual hearing thresholds at a wide range of test frequencies, with the ears unoccluded and protected. These values provide insight into the level of difficulty that the user will experience under these conditions. In the present study, the mean free-field hearing thresholds observed with the ears unoccluded from 250 Hz to 8000 Hz matched minimal audible field measurements reported in the literature (see Green, 1976). When subjects wore the device in the steady-state mode, their mean thresholds were in the range of 36.2 dB to 53.3 dB SPL, signifying an induced mild hearing loss. At the speech frequencies, 500 Hz, 1000 Hz and 2000 Hz, thresholds were 38.5 dB SPL, on average. These values suggest that even in normal-hearing listeners, there might be some difficulty with speech understanding when the device is worn, depending on the level of the speech. By comparison, in the weapons fire mode, thresholds were at most 37.9 dB SPL, with an average of 21.4 dB SPL at the speech frequencies. This value is well below the fence for hearing loss (Yantis, 1985).

The mean attenuation values derived from the free-field threshold measurements were similar to the manufacturer's specifications, except for the value observed for the weapons fire mode at 250 Hz. No differences were observed due to gender, although lesser attenuation has been previously reported for females (Abel et al., 1988). This may been due to the fact that the device was available in three sizes. Of the 10 males tested, seven were fitted with the large size, two with regular and one with small. Of the 10 females, three were fitted with large size, five with regular and two with small. The data obtained for the two modes of operation are compared in Figures 5 and 6, respectively, with data obtained in the same laboratory using the same methods but with different subjects for the double-sided EAR® Combat Arms earplug (Abel and Lam, 2004) and Surefire EP3 Sonic Ear Defender™ (Abel and Nakashima, 2008). The latter device consists of a single ear plug with an aperture that can be sealed. As shown in Figure 5, the single-sided EAR® Combat Arms earplug (CAE S) provides essentially the same conventional attenuation as its double-sided counterpart (CAE D), with about 6-dB more attenuation below 2000 Hz and about 6-dB less attenuation at 6300 Hz and 8000 Hz. The single-sided Combat Arms earplug provides relatively more attenuation than the Surefire EP3 (EP3 S) at all frequencies tested. The difference was highly variable with a minimum of 3.7 dB at 8000 Hz and a maximum of 14.9 at 4000 Hz. As shown in Figure 6, the passive level-dependent attenuation was highly similar for all three devices with differences less than 6 dB at all but 250 Hz, 4000 Hz and 8000 Hz, where differences of 9.6 dB, 7.8 dB and 7.4 dB were noted.

Recent field trials involving various types of hearing protection devices (Casali et al., 2009) and focus group discussions of experience with hearing protection during military operations (Abel, 2008) indicated that these devices may disrupt auditory performance enough to override their benefit for hearing conservation. In the present study the results for overall accuracy in horizontal plane sound source identification showed that percent correct decreased by 40% when the Combat Arms earplug was worn in its conventional mode of operation but only by 20% in its level-dependent mode, relative to unoccluded listening. These outcomes are similar to those observed previously in a study comparing muff and plug style electronic hearing protectors with conventional muffs and plugs (Abel et al., 2007). They suggest that sound reduction is a critical factor for sound source identification.

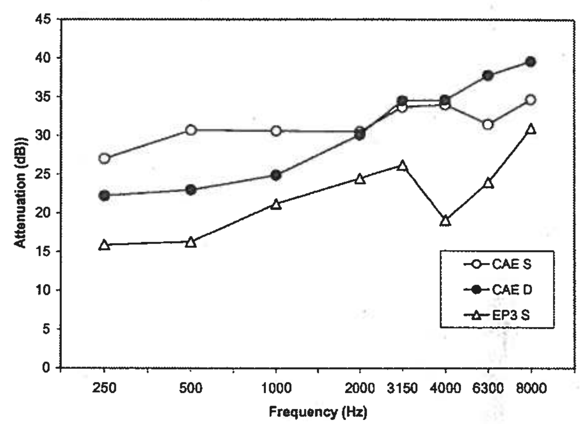

Figure 5. A comparison of sound reduction observed for three earplugs which provide both conventional and level-dependent passive attenuation: conventional attenuation.

Vause and Grantham (1999) debated the question of whether difficulties with sound location with hearing protection may instead be related to interference with spectral cues provided by the outer ears (pinnae). In line with previous studies of hearing protection, the present study showed that subjects had no difficulty distinguishing between speakers on the right and left sides of space. Front versus back discrimination which depends on spectral cues (Musicant and Butler, 1984) was more problematic, especially for azimuths located close to the interaural axis. For these azimuths, a frontal bias was evident for the unoccluded, as well as the protected conditions. The difference between the two types of mirror image reversal error, F/B and B/F, was significantly different only for the unoccluded and CAE WF conditions. For these, percentage of F/B errors exceeded B/F errors by about the same amount, 26%. However, the likelihood of a F/B error was substantially higher with the CAE fitted, in either mode, at 49% for the CAE SS, 54% for the CAE WF and 25% for unoccluded listening. Thus, it appears that both attenuation and spectrum have roles to play with respect to the impact of wearing hearing protection.

The direction of errors in

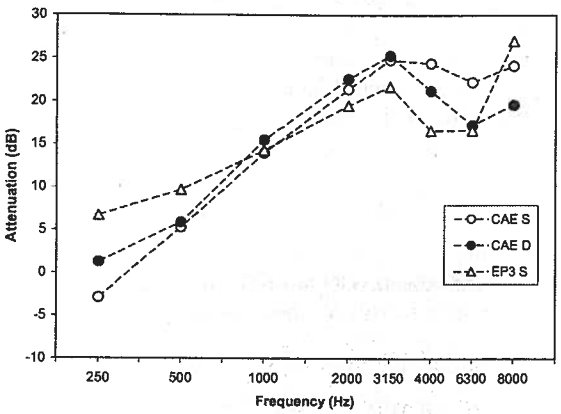

Figure 6. A comparison of sound reduction observed for three earplugs which provide both conventional and level-dependent passive attenuation: level-dependent attenuation.

sound localization when hearing protection is worn is not consistent across published studies. Russell and Noble (1976), for example, reported that the wearing of conventional plugs resulted in a rearward shift for a white noise stimulus, whereas the wearing of conventional muffs resulted in a frontward shift in perceived location. More recently, Abel et al. (2007) found that for speakers close to the midline axis, a rearward bias, i.e., a difference of 20% or more in B/F mirror image reversal errors compared with F/B mirror image reversal errors, was evident for both a conventional muff and plug but there was little difference for a muff or plug with advanced communications capability. In contrast, for speakers close to the interaural axis, a frontward bias where F/B errors exceeded B/F errors was observed only for a hearing protective earplug with enhanced communications capability. The error pattern demonstrated for the communications earplug was in the same direction as the pattern observed in the present study for the passive level-dependent plug. Taken together, these findings indicate that that (1) the greater the attenuation, the greater the difficulty overall for sound source identification, (2) with a conventional plug, averaged across azimuths, front and rearward accuracy are affected equally, and (3) a frontward mirror image reversal error is evident for positions in the vicinity of the ear when either active plugs incorporating external microphones or passive level-dependent plugs incorporating a small aperture are worn. The nature of real-world task requirements will determine whether and the degree to which these will impact situational awareness and safety.

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Table I. Attenuation (dB) achieved with single-sided E-A-R® Combat Arms earplugs (CAE) in two modes of operation, steady-state noise (SS) and weapons fire (WF), compared with the manufacturer's specifications.

	Ear Condition			
	CAE SS		CAE WF	
Freq (Hz)	Spec	Obs	Spec	Obs
250	30.6 (5.4)	27.0 (9.0)	4.9 (2.9)	-2.9 (6.2)
500	34.5 (5.6)	30.7 (10.1)	10.1 (2.9)	5.3 (3.9)
1000	31.4 (4.8)	30.6 (8.1)	17.0 (3.8)	14.0 (4.4)
2000	30.8 (4.6)	30.5 (5.0)	22.9 (5.1)	21.4 (4.4)
3150	37.3 (5.9)	33.7 (2.7)	29.9 (2.7)	24.8 (4.0)
4000	36.3 (6.5)	34.0 (4.7)	27.4 (3.4)	24.4 (5.2)
6300	34.1 (4.5)	31.5 (5.8)	24.4 (4.0)	22.2 (6.1)
8000	36.3 (3.8)	34.7 (4.8)	24.4 (5.0)	24.1 (4.5)

* N=20; Mean (SD)

Table II. Percentage of front-back reversal errors in sound source identification with the ears unoccluded and fitted with single-sided E-A-R® Combat Arms ear plugs (CAE) in two modes of operation, steady-state noise (SS) and weapons fire (WF).

				Ear Condition		
Side	Position	Error Type	Error	Unoccluded	CAE SS	CAE WF
R	Midline	B/F†	165/15	0.0 (0.0)*	25.7 (31.8)	8.7 (20.3)
		F/B	15/165	0.7 (3.0)	20.0 (32.7)	21.0 (35.5)
	Interaural	B/F	105/75	6.3 (16.4)	33.7 (32.0)	22.3 (31.7)
		F/B	75/105	23.0 (23.7)	45.3 (35.8)	50.0 (37.4)
L	Midline	B/F	195/345	0.0 (0.0)	24.7 (30.0)	10.7 (23.6)
		F/B	345/195	0.0 (0.0)	28.0 (39.9)	29.0 (35.8)
	Interaural	B/F	255/285	15.0 (20.3)	30.0 (34.7)	17.0 (27.1)
		F/B	285/255	26.3 (26.6)	53.0 (33.3)	58.0 (37.3)

*N=20; Mean (SD)
† B/F=back response given front stimulus