

**U.S. Marine Corps Level-Dependent Hearing Protector
Assessment: Objective Measures of Hearing Protection
Devices**

by Angelique A. Scharine and Rachel A. Weatherless

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14. ABSTRACT To characterize the effects of four level-dependent earplug-style hearing protection devices (HPDs), measurements were made of the passive attenuation of steady-state and impulsive noise, as well as the localization ability of listeners while they wore each HPD. Three HPDs were mechanical (Moldex BattlePlugs, 3M Combat Arms Earplugs, and the SureFire EP4 Sonic Defenders Plus). These triple-flange earplug-style HPDs provide level-dependent protection through the incorporation of a filter that allows the user to hear ambient sounds with minimal attenuation but protects against impulsive noises above about 105-dB peak. We tested the fourth HPD (Etymotic Electronic BlastPLG EB15) in the inactive condition only, but it can provide ambient environmental hearing via external microphones and uses electronic circuitry to limit or shut off the transmission of unsafe levels of noise. The three mechanical earplugs provided similar (8–14 dB) passive attenuation of steady-state pink noise presented at 105 dB A. One-third octave band analyses of this attenuation showed differences in the spectral profile at higher frequencies. The inactive EB15, tested with foam ACCU-Fit ER38-14F ear-tips, provided 28 dB of passive attenuation. The devices all provided in excess of 30-dB attenuation of an impulsive noise presented at approximately 157-dB peak; in particular, the inactive EB15 provided more than 34 dB of passive attenuation. All four devices caused an increase in average localization error—near 0° and 180°, most likely due to reversals. The average unsigned azimuth error did not differ significantly across the four earplugs, ranging from about 38 to 42. All four earplugs, as tested, provide sufficient protection against noise. The significance of the mechanical earplugs' differential effects on the spectral content of lower-level steady-state noise on spatial orientation and, ultimately, user acceptance are discussed. Similarly, we note the limitations of inferences made from tests of the EB15 in only a passive mode.					
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1. Objective

This effort was funded by the U.S. Marine Corps Program Manager Infantry Combat Equipment (PM ICE) as a part of its Marine Rifle Expeditionary Squad program. The objective was to determine the comparative attenuation performance characteristics of four level-dependent earplugs in impulsive and steady-state noise environments in order to assess how these differences might affect user acceptance (figure 1). As these attenuation characteristics can also affect a user's auditory spatial perception, auditory localization ability was also measured. Three of these were designed with a filter that prevents levels of noise exceeding approximately 105 dB from entering the ear. We tested the Moldex^{*} BattlePlugs[†] (Mx), the 3M[‡] Combat Arms[§] Earplugs (CAE), and the SureFire^{**} EP4 Sonic Defenders^{††} Plus (SF).

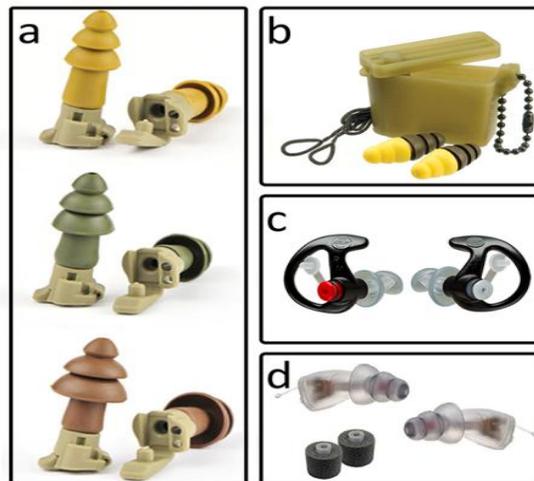


Figure 1. Hearing protectors tested: (a) Moldex BattlePlugs, (b) 3M Combat Arms Earplugs, (c) SureFire EP4 Sonic Defenders *Plus* (SF), and (d) Etymotic Electronic BlastPLG EB15 earplug.

*Moldex is a registered trademark of Moldex, Culver City, CA.

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‡3M is a registered trademark of The 3M Company, St. Paul, MN.

§Combat Arms is a registered trademarks of The 3M Company, St. Paul, MN.

**SureFire is a registered trademark of SureFire, LLC, Fountain Valley, CA.

††Sonic Defenders is a registered trademark of SureFire, LLC, Fountain Valley, CA.

The fourth item, the Etymōtic* Electronic BlastPLG† EB15‡ earplug (EB15) is an “active” device designed to use electronic limiters and compression to provide hearing of low-level ambient sounds while protecting against high-level noise; it was tested with ACCU-Fit§ ER38-14F foam ear-tips and with the batteries removed. Testing the EB15 without batteries makes it a passive hearing protector without level-dependent features. This was done by request from the customer, as active testing of the same device was planned for future testing. Without the level-dependent features, it is expected that the device will have higher levels of attenuation, both of steady-state and impulsive noise. Effects on localization will depend on the degree to which localization cues are audible. It is acknowledged that (as-tested) comparisons of the EB15 to the other earplugs are not reasonable and were not the intent of the study. Rather we report the objective data as observed.

2. Steady-State Attenuation Testing

One common criticism of level-dependent hearing protectors is that even at safe levels (below 85 dB A), they cause some attenuation, which may reduce the detection of, and impair auditory sensitivity to, desirable auditory information. If a user feels that this attenuation is too great, it may affect acceptance of a hearing protector and compliance with mandated hearing protector use. Therefore, while the primary function of these hearing protectors is to attenuate high-level impulse noise, we wish to document the steady-state attenuation introduced by wearing the protectors. Ideally, a level-dependent HPD will provide little attenuation of safe levels (less than 85 dB A) of steady-state noise and at least 25-dB attenuation of very intense (greater than 140 dB peak) impulsive noise.

2.1 Facilities and Instrumentation

2.1.1 Auditory Test Fixture (ATF), Reference Microphone, and Recording System

A G.R.A.S. Hearing-Protector Auditory Test Fixture (ATF) Type 45CA (see figure 2), fitted with IEC 60711 ear simulators and molded pinnae, was positioned in the center of the room and used to record the test signal. A PreSonus Firestudio** recording interface set to a sampling rate of 44.1 kHz was used for analog to digital conversion and to transmit the signal to a laptop computer where it was recorded using Adobe Audition 3.0.

*Etymōtic is a registered trademark of Etymōtic Research, Inc., Elk Grove Village, IL.

†BlastPLG is a registered trademark of Etymōtic Research, Inc., Elk Grove Village, IL.

‡EB15 is a registered trademark of Etymōtic Research, Inc., Elk Grove Village, IL.

§ACCU-Fit is a registered trademark of Etymōtic Research, Inc., Elk Grove Village, IL

**Firestudio is a registered trademark of PreSonus Audio Electronics, Inc., Baton Rouge, LA.

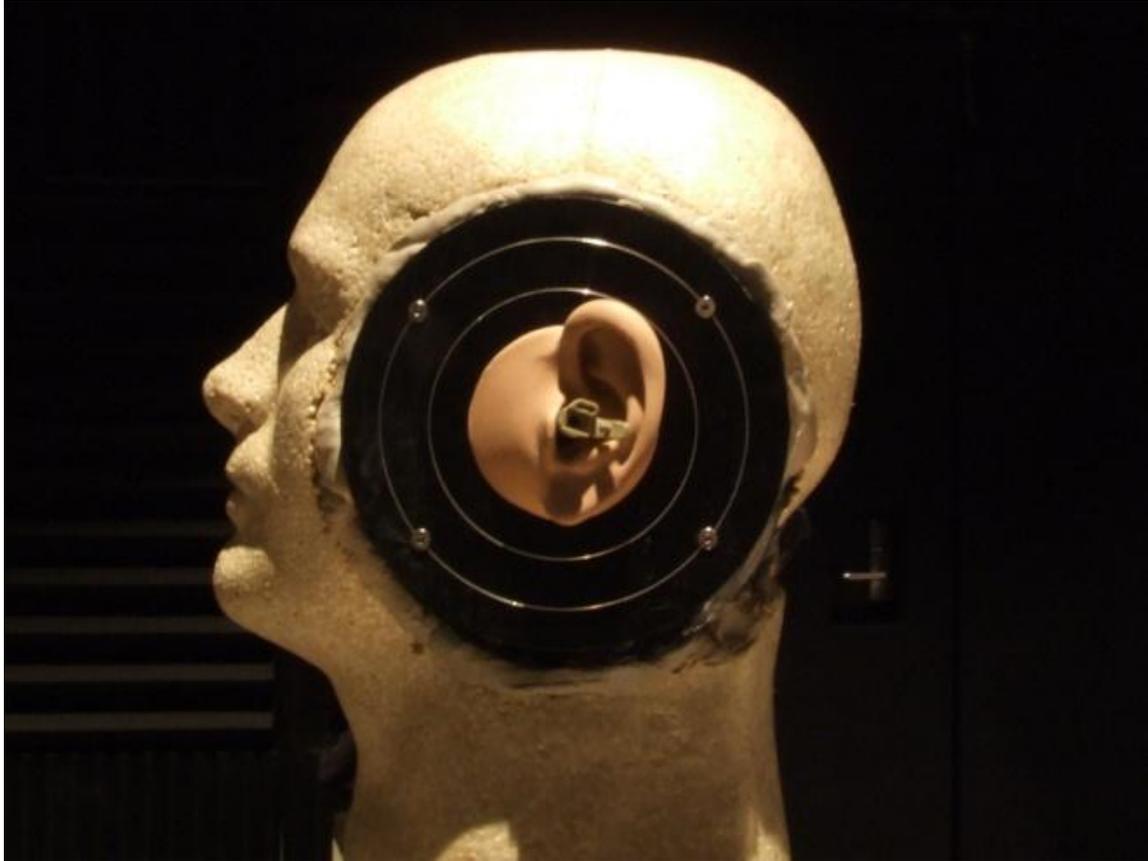


Figure 2. G.R.A.S. Hearing-Protector Test Fixture Type 45CA (shown with Mx inserted). (The Styrofoam headform was not on this ATF during testing.)

2.1.2 Research Facilities, Loudspeaker, and Test Signal

A pink-noise test signal was presented from four background loudspeakers placed in the corners of the U.S. Army Research Laboratory's Environment for Auditory Research (EAR) Dome Room (Henry et al., 2009) about 4 m from the center of the room (see figure 3). The noise was presented at 100 dB A, as measured with a Brüel & Kjær Sound Level Meter Type 2226 held at the location of the ATF. This level was chosen because it is within the range for which the microphones (inside the ears) of the ATF are designed and high enough to remain in that range when a HPD is in place. It is not expected that this level would be high enough to involve any significant increase in attenuation over the HP's attenuation at low sound levels.



Figure 3. Dome Room of the Environment for Auditory Research at the U.S. Army Research Laboratory. (Person and chair shown were not present during recordings and were replaced by the G.R.A.S. 45CA shown in figure 2.)

2.2 Variables

There were two independent variables investigated in the study: HPD condition and one-third octave frequency. The four HPD conditions were Mx, CAE, SF, and EB15. The dependent variable was attenuation, defined as the difference between the signal level, as measured by the ATF with and without the HPD.

2.3 Procedures

A G.R.A.S. 42AA sound calibrator with an adapter that allows it to be coupled to the ATF was used to generate a signal of 250 Hz at 114 dB. This signal was recorded through each channel (left and right ears) of the testing system and used as a calibrated reference for the other measurements.

The 100-dB pink-noise test signal was then played continuously from the loudspeakers. A reference measurement was made by recording the test signal with no hearing protection in place. Then the HPD under test was inserted into the ears of the ATF and a 5-s recording was made from both ATF ears (left-right channels) simultaneously. The HPD was then removed and reinserted and the recording process repeated. This procedure was repeated for each of the HPDs under test.

2.4 Data Analysis

Each set of recordings ($2 \times$ HPD) was processed using a custom MATLAB algorithm to compute the levels for each component octave and one-third octave band (ANSI/ASA S1.6-1984, 2011). This was also done for the reference set recorded with no HPD. A-weighting (ANSI/ASA S1.42-2001, 2011) was then applied and the A-weighted one-third octave, octave, and overall levels were obtained. A-weighted values were used for all analyses reported in this report. For each HPD, attenuation was calculated by computing the reduction in the overall A-weighted signal level when the device was in place compared to the level in the bare-head fixture. Attenuation, as a function of one-third octave and octave band frequency, was then calculated in the same manner. Figures 4–6 show overall attenuation and attenuation as a function of frequency for the HPDs under test. The error bars represent ± 1 standard deviation.

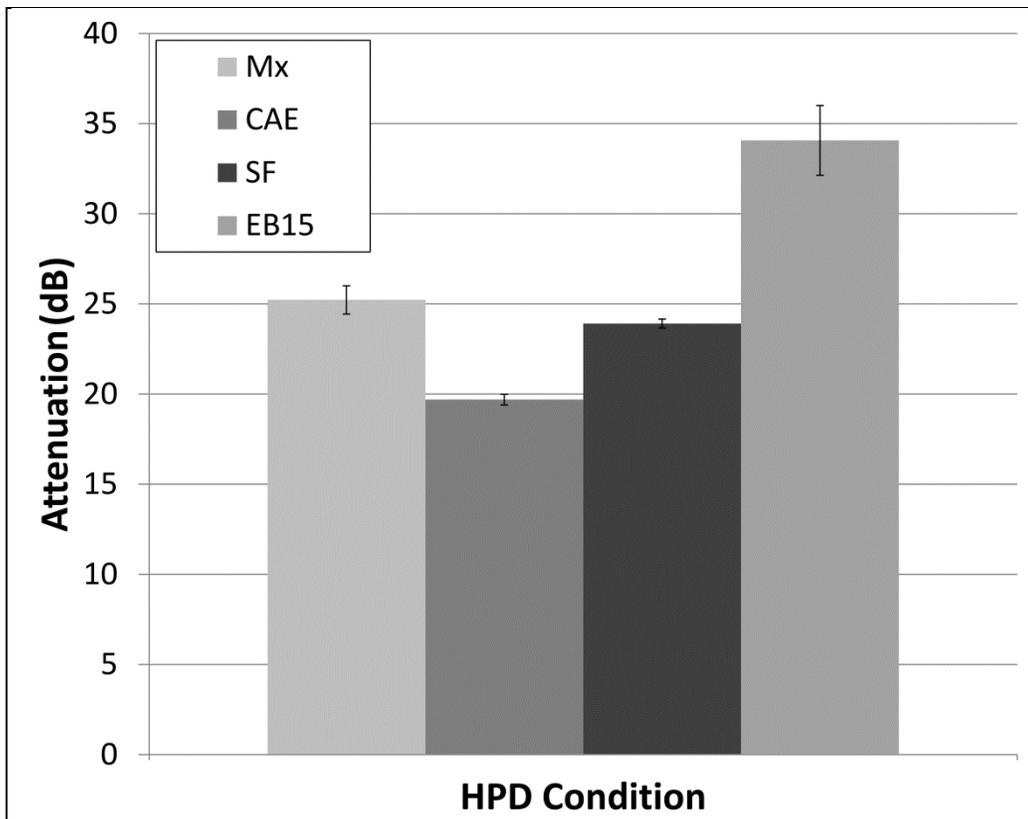


Figure 4. Average overall steady-state attenuation values measured for each HPD under test. The error bars represent ± 1 standard deviation.

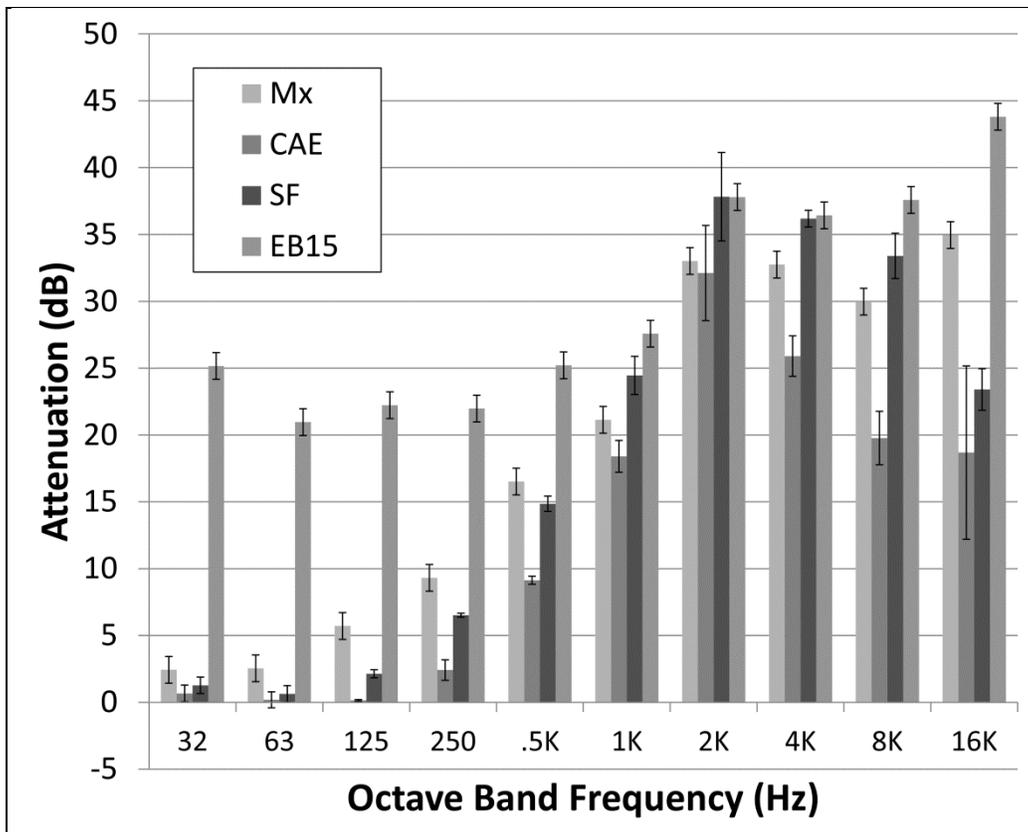


Figure 5. Average octave-band steady-state attenuation values measured for each HPD under test. The error bars represent ± 1 standard deviation.

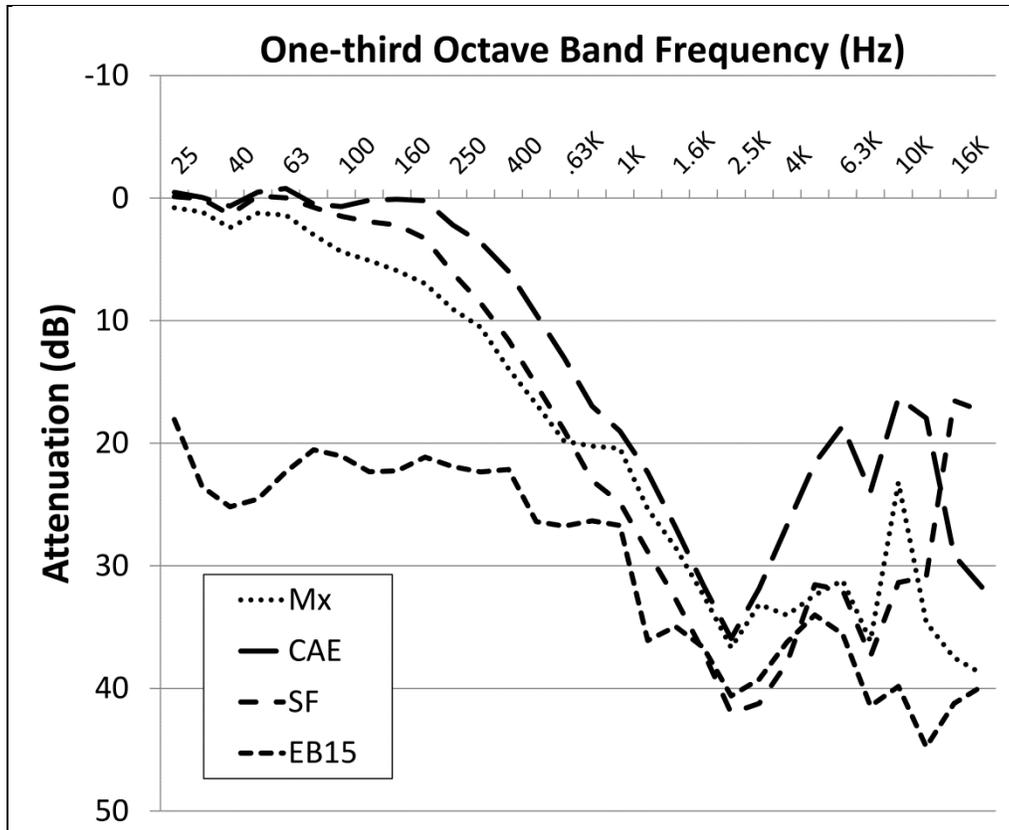


Figure 6. Average one-third octave-band steady-state attenuation values measured for each HPD under test. (Error bars not shown for visual clarity.)

The 34 dB of attenuation shown for the EB15 hearing protectors was clearly higher than for the other HPDs, but this earplug was the only HPD with electronic features, and it was tested in the “off” position. Therefore, it did not have any of the level-dependent features provided by the other earplugs. Of the three HPDs with mechanical filters, the most attenuation, approximately 25 dB, was observed for the Mx. The least attenuation overall was observed for the CAE, approximately 20 dB.

The ear canal typically amplifies frequencies in the 1- to 4-kHz range (Moore, 2012). Therefore, obstruction of the ear canal should result in not only passive attenuation of noise but also eliminate the amplifying function of the ear canal at those frequencies. Consistent with this prediction, all HPDs showed the most attenuation in this frequency range. The frequency envelope of attenuation for the EB15 differs in that the average attenuation of frequencies below 500 Hz is 22 dB versus 6 dB (Mx), 3 dB (SF), and 1 dB (CAE) for the other HPDs. At high frequencies there seemed to be some differences in the passive attenuation provided by the earplugs, and this effect was quite apparent at the one-third octave band level of analysis. The CAE consistently attenuated less across nearly all frequencies. At the octave band level, some of these finer differences disappeared, but the general pattern remains that the CAE attenuated the least, followed by the SF and the Mx HPDs; the EB15 attenuates the most.

Each of the recording events resulted in two recordings (left and right ears) and a set of attenuation values for each octave and one-third octave band. A two-factor analysis of variance with recording event as a covariate (ANCOVA) was computed for attenuation as the dependent variable with the independent variables being HPD and one-third octave band frequency. Table 1 shows the statistics for the significant variables. The data indicate significant main effects of HPD and of one-third octave band frequency, $F(3, 359) = 790.4, p < .01$; and $F(29, 359) = 311.7, p < .01$. The data indicates a significant interaction between HPD and frequency, $F(87, 359) = 12.5, p < .01$. Note that because the attenuation observed for the EB15 was clearly different from the other HPDs, it could potentially account for all of the significant effects. However, planned contrasts confirm that the three mechanical earplugs are significantly different from each other and from the EB15 ($p < .01$).

Table 1. Significant ANOVA results for attenuation ($\alpha < .05$).

Source of Variance	<i>dF</i>	<i>F</i>	<i>p</i>
HPD	3	790.4	0.000
Frequency	29	311.7	0.000
HPD*Frequency	87	12.5	0.000
Error	359	7.28	—

If attenuation is driving user acceptance, the CAE is the winner for the mechanical earplugs. There is less attenuation overall, in the speech range (300–3000 Hz) and in the higher frequencies (greater than 4 kHz) where monaural localization cues are derived. However, if comfort is the driver, acceptance may be more idiosyncratic, depending on the users’ perceptions of fit and preferences. Although no measures of comfort were used during testing, it was noted by the experimenters that the SF and EB15 earplugs are constructed with a softer, more pliable material and are available in multiple sizes. (Other versions of the CAE are manufactured in multiple sizes, but the version issued to the Marines and supplied for testing is available in only one size.) Since the EB15 was not tested with its talk-through microphones turned on, the frequency envelope of the pass-through levels is not known from this testing. Therefore, although the measured attenuation would seem undesirable for allowing the user to remain sensitive to the auditory environment, the conditions in which it was measured do not reflect normal intended usage.

3. Impulse Noise Attenuation Testing

We tested all four HPDs for their attenuation of impulse noise. For the three HPDs designed with mechanical filters, this was a test of whether the level-dependent filters function as intended to protect against impulse noise. The EB15 was tested in the passive “off” condition.

3.1 Facilities and Instrumentation

3.1.1 ATF, Reference Microphone, and Recording System

All impulse noise measurements were made in the EAR Distance Hall. Recordings were made using the French-German Research Institute of Saint-Louis (ISL) ATF designed to accommodate pressure levels of up to 190 dB peak (Buck and Parmentier, 1999). Recordings were made using the same reference microphone and PreSonus Firestudio system described in section 2.1.1. The reference microphone and ATF were 1 m apart at the same distance from the shock tube.

3.1.2 Impulsive Noise Signal

A pneumatic impulse noise source (PINS) was used to present impulsive noises for measurement. Figure 7 shows the reference microphone, ATF, and PINS used to present impulses for measurement. The average impulse level presented from the shock tube as measured with the reference microphone was 157 dB peak and the standard deviation of impulses was 1.9 dB.



Figure 7. Left to right, G.R.A.S 40BH reference microphone, Institute Saint Louis (ISL) auditory test fixture, and shock tube used for impulse testing.

3.2 Calibration

A reference level was established for all of the measurements by recording a 114-dB, 250-Hz calibration signal with each ATF microphone and the reference microphone. Subsequently, recordings were made of two instances of impulsive noise with the microphones of the ATF (unoccluded ears) and the reference microphone. These recordings were used to estimate the transfer function of the ear canal. From these recordings, it was determined that the left and right ears of the ATF contribute amplifications of 4.87 and 4.68 dB, respectively, due to resonance in the ear canal (Shaw, 1974). To determine attenuation, we computed the difference between the peak level measured by the ATF (the left and right ear each contributed separate data points) and the peak level measured by the reference microphone, minus the transfer function for that ear.

3.3 Testing Procedure

We positioned the HPD on the ATF and obtained a recording of the shock-tube-generated impulsive noise from the microphones of the ATF and the reference microphone. This process was repeated three times for each HPD with refitting between each measurement. During testing it was noted that different levels of attenuation were being obtained with the EB15 HPDs, and that these differences depended on the person inserting the earplugs. Depending on the depth and manner of insertion, attenuation values varied from about 40–60 dB. Noting this, a fourth set of recordings was conducted for the EB15 HPDs (with the insertion performed by the experimenter getting the better results) and the specifics will be discussed in the results section of this report.

3.4 Data Analysis and Results

At least three impulses were presented for each HPD, resulting in six attenuation values for each HPD. The average impulse attenuation values are shown in figure 8. The error bars represent ± 1 standard deviation.

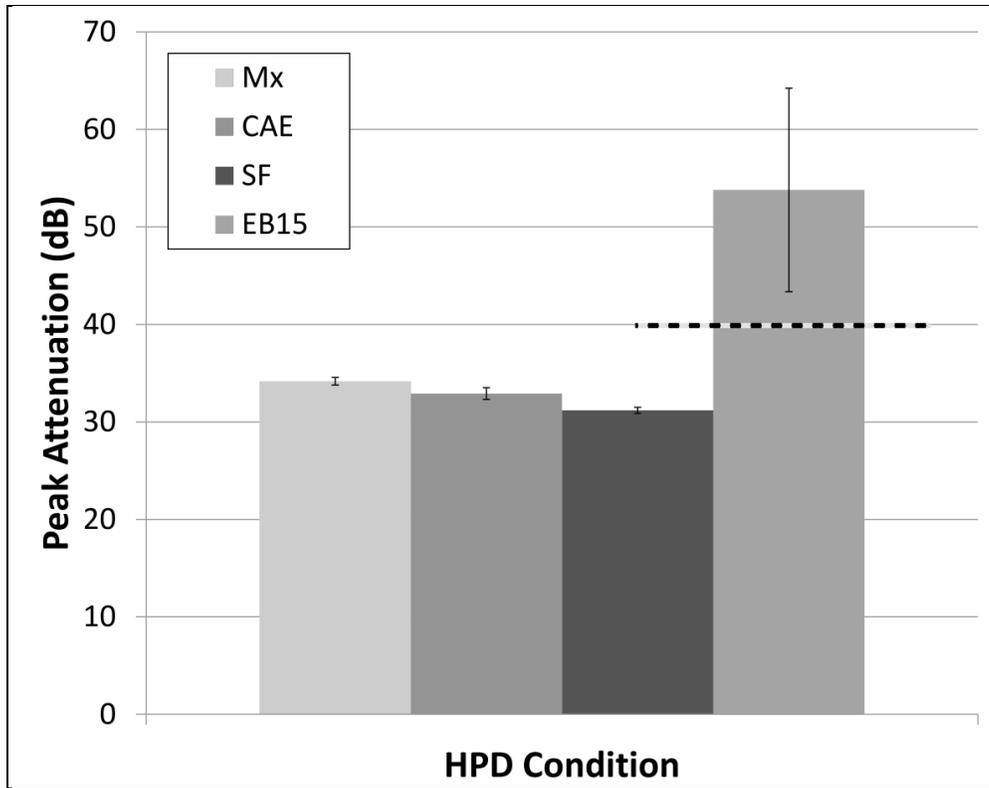


Figure 8. Average impulse attenuation measured for each HPD under test.

We were obtaining variable results with the EB15 foam ear-tips. Figure 8 shows the average of all values obtained for the EB15. Table 2 shows all eight values obtained by experimenters A and B. When experimenter A inserted the ear-tips, we obtained attenuation values that were approximately 10–20 dB higher. This is consistent with other documented findings that link attenuation to skill when rolling and inserting the foam earplugs. However, these values are probably higher than what would be expected for a human listener due to attenuation limits caused by bone-conducted sound transmission. The ATF does not account for bone-conducted transmission of sound, and as such, inflates estimates of impulsive noise attenuation. The dotted line in figure 8 represents the expected cap on actual protection due to the attenuation limits on bone-conducted sound transmission.

Table 2. Attenuation values (dB) obtained for the EB15 HPD.

Ear	EB15_1	EB15_2	EB15_3	EB15_4
Left	41	55	63	60
Right	41	43	64	62

Note: Lighter shading indicates insertions performed by experimenter B; darker shading indicates insertions performed by experimenter A.

All HPDs provided 30 dB of attenuation, showing that the filters functioned as intended to protect against impulsive noise. Of the HPDs with a level-dependent feature, the Mx provided the most attenuation (34 dB) and the SF provided the least (31 dB). A one-way analysis of variance (ANOVA) was computed for attenuation with HPD as the independent variable. The main effect of HPD condition was significant [$F(3, 22) = 24.0, p < .01$]. Simple contrasts confirmed that all of the HPDs were significantly different from each other ($p < .01$); however, it is unclear that there is practical significance in the differences in auditory sensitivity caused by the three different earplugs with mechanical filters.

4. Localization Testing Methods

The differences in the effect of the HPDs on the spectral envelope of attenuation may affect a user's auditory spatial perception and consequently, his or her acceptance of the HPD. Therefore, the ability to localize sounds was evaluated for each of the HPDs as well as for the bare head.

4.1 Participants

Thirteen listeners, aged 18–40 years, participated in this study. Due to equipment issues, data were not recorded for the first two participants; therefore, we report the data for 11 participants (8 male, 3 female). One of the investigators inspected the listeners' ears with an otoscope prior to testing to ensure that their ear canals were unobstructed and that there would be no interference with the use of earplugs. We then screened their hearing by measuring their pure tone thresholds for octave frequencies 250–4000 Hz using calibrated audiometric equipment in a sound-treated room. All 13 participants met the U.S. Army's H1 hearing classification, defined in the Army Hearing Conservation Program (DA PAM 40-501, 1998) as an average threshold level at 500, 1000, and 2000 Hz that does not exceed 25-dB hearing level (HL) with no individual threshold greater than 30-dB HL, and the threshold at 4000 Hz with no individual threshold greater than 45-dB HL. The investigators adhered to the policies for protection of human participants as prescribed in AR 70-25 (1990).

4.2 Facilities and Instrumentation

4.2.1 Loudspeaker Array

Target stimuli were presented from a spherical loudspeaker array consisting of 57 Meyer Sound MM-4XP miniature loudspeakers housed in the EAR Sphere Room (Henry et al., 2009). We used only the 16 loudspeakers on the horizontal ring (radius 2.5 m) at 0° elevation to present target sounds, with the loudspeakers located at equal intervals of 22.5° separation (figure 9).



Figure 9. Testing setup used for the localization test. (No helmet used in this experiment.)

4.2.2 Rotating Chair

Each participant sat in a rotating chair at the center of the loudspeaker array on a raised platform that placed their ears at the same elevation as the 0° loudspeaker ring. The chair was free to rotate 360° and was equipped with an optical shaft encoder and a laser tracker on the center of a horizontal bar attached to the chair in front of the participant. Although the bar is free to rotate plus or minus 90° in pitch, it was fixed in place to allow for responses only from the horizontal plane during this study. Participants began each trial facing 0° azimuth and then responded by rotating the chair to point the laser in the direction from which they believed a stimulus came, pushing a button to register their response. A computer recorded the direction of the response based on the outputs of the laser tracker and the optical shaft encoder, providing redundant positional information. During this study, the laser tracker data were used in the analyses.

4.3 Variables

There were two independent variables investigated in the study: head condition, and sound source azimuth. Five head conditions were evaluated: bare head, Mx, CAE, SF, and EB15. The 16 azimuth locations were 0° , $\pm 22.5^\circ$, $\pm 45^\circ$, $\pm 67.5^\circ$, $\pm 90^\circ$, $\pm 112.5^\circ$, $\pm 135^\circ$, $\pm 157.5^\circ$, and 180° . A 250-ms burst (with 5-ms ramps) of white noise at 70 dB was presented nine times from each of the loudspeakers for a total of 144 instances per block of trials. The order of presentation location was varied randomly within the block. A single block of trials was presented for each of the head conditions.

The dependent variable of interest was azimuth error, defined, as the difference in degrees between the perceived stimulus source location azimuth (as identified by the listener) and that of the actual stimulus source azimuth.

4.4 Procedures

After the initial audiometric screening, all participants were familiarized with the listening task prior to initiation of their first block. Each participant was then fitted properly with the appropriate HPD. Participants listened to blocks of stimuli that consisted of all trials for a particular head configuration condition (bare, Mx, CAE, SF, and EB15). Presentation of each block lasted approximately 25 min. Participants were given breaks between blocks to reduce the effects of fatigue. Additionally, each trial was initiated by the participant, so additional breaks could be taken if needed.

4.5 Data Analysis, Results, and Discussion

Our objective was to measure the effects of HPDs on auditory localization ability relative to that with the bare head as a measure of spatial auditory perception. Localization errors made in this study were calculated as both signed (constant) and unsigned azimuth errors. Signed error contains information about both the magnitude and direction of an error. Average signed error can reveal underlying distortions of the auditory space stemming from the acoustics of the equipment or the test space itself. However, when averaged, signed data underestimates overall error magnitude because errors in opposite directions cancel each other out. The precision of judgments must be obtained from the average unsigned error of localization responses and is a measure of random error (Hartmann, 1983). Therefore, both types of errors will be discussed.

Two-factor ANOVAs were conducted for the signed (table 3) and unsigned (table 4) azimuth error with the independent variables being HPD condition and sound source azimuth. Subject ID was included as a covariate in order to account for individual differences. Polar plots show the signed errors as a function of HPD and sound source azimuth (figure 10).

Table 3. Significant ANOVA results for signed azimuth error ($\alpha < .05$).

Source of Variance	<i>dF</i>	<i>F</i>	<i>p</i>
Azimuth	15	300.9	0.000
Head condition \times azimuth	60	12515.2	0.000
<i>Error</i>	<i>7580</i>	<i>2004.22</i>	—

Table 4. Significant ANOVA results for unsigned azimuth error ($\alpha < .05$).

Source of Variance	<i>dF</i>	<i>F</i>	<i>p</i>
Head condition	4	60.0	0.000
Azimuth	15	61.1	0.000
Head condition \times azimuth	60	3.7	0.000
<i>Error</i>	<i>7580</i>	<i>1710.25</i>	—

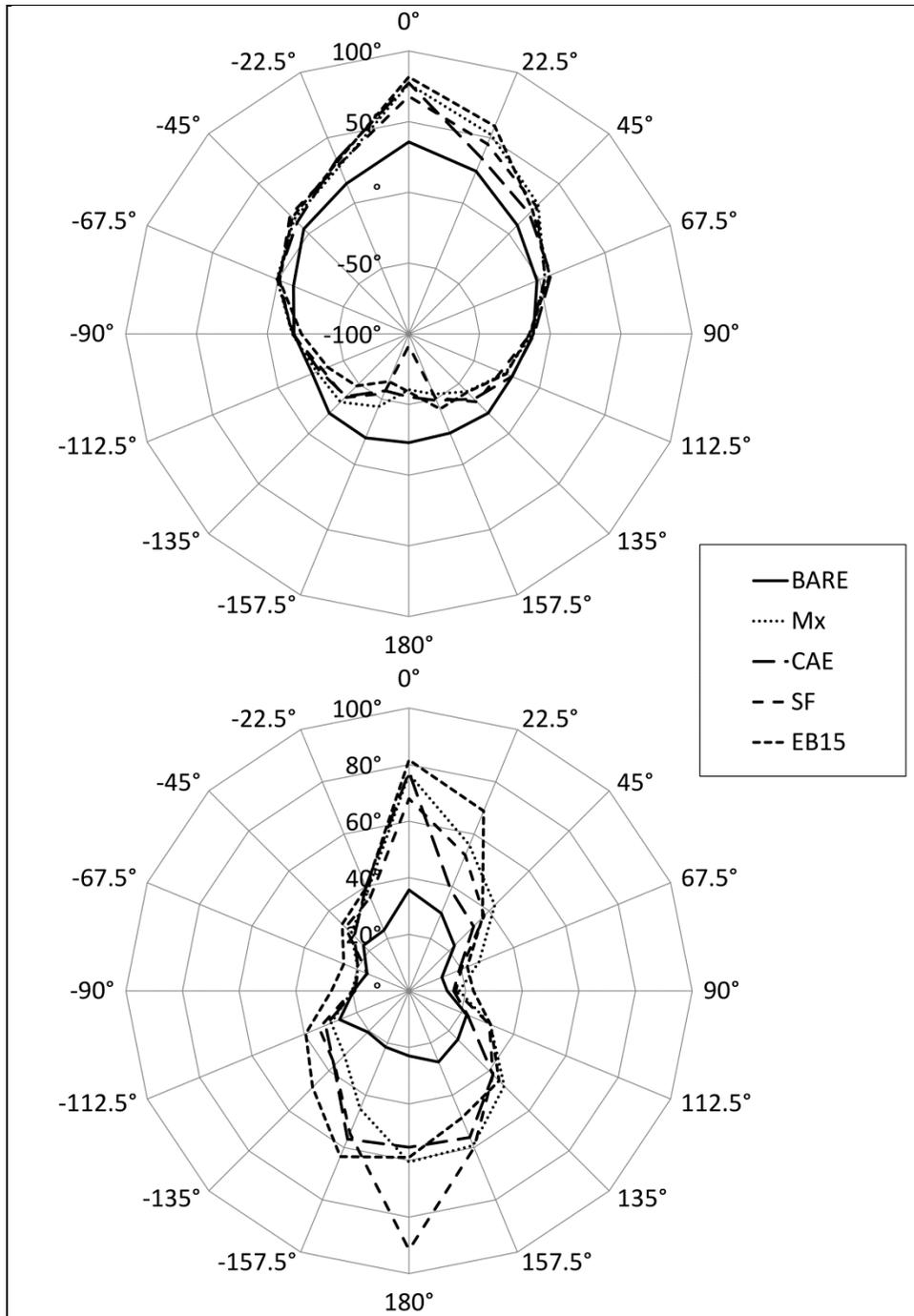


Figure 10. Signed and unsigned azimuth error as a function of head condition and azimuth.

In the signed error data, negative errors indicate the participant estimated the sound source to be closer to the front (0°) than the actual target location. Positive errors mean that the estimate was farther to the rear than the actual target location. If localization errors are driven by lack of precision, estimates will fall on either side of the target location and on average cancel out. Using average signed data will obscure any real differences in the magnitude of errors occurring for the

various HPDs. This is not to suggest that all errors are likely to be cancelled out. Differences due to an increase in front-back confusions will result in an increase in positive errors near 0° and an increase in negative errors near 180° . Even without HPDs, it is normal to observe some differences in error as a function of azimuth, due to front-back confusions.

The data did not indicate a significant difference in signed azimuth error as a function of hearing protection use. There was a main effect for azimuth— $F(15, 7580) = 300.9, p < .01$ —consistent with the expected changes in error size due to front-back confusions. The different effects of the HPDs are revealed in the interaction between head condition and azimuth— $F(60, 7580) = 12,515.2, p < .01$ —and are observed in the polar plot shown in the upper half of figure 10. Wearing hearing protection increased positive errors in the front near 0° , and increased negative errors in the rear near 180° , consistent with what would occur as a function of increased front-back confusions.

The signed error data allow us to detect any biases that signal problems with the measurement method or acoustics of the facility. The data shown here are symmetric relative to the midline. Although the data indicated a small difference between the left and right hemispheres, the differences are idiosyncratic and not of practical importance.

The bottom half of figure 10 gives the unsigned error data as a function of head condition and azimuth. There were significant main effects of head condition and azimuth [$F(4, 7580) = 60, p < .01$; $F(15, 7580) = 61.1, p < .01$]. Figure 11 shows the average unsigned error and standard deviation for each of the head conditions. A planned comparison of the average unsigned azimuth error observed for the HPDs and the bare head indicated that the difference (averaging 17°) is significant ($p < .01$). Table 5 lists the p values for all pair-wise comparisons; when significant, this is indicated with an asterisk. Of the HPDs, the unsigned azimuth error was least for the CAE (37°) and greatest for the EB15 (43°). Although there were some statistically significant comparisons, given that the overall range is 6° , it is not clear that they would be of practical significance to a user.

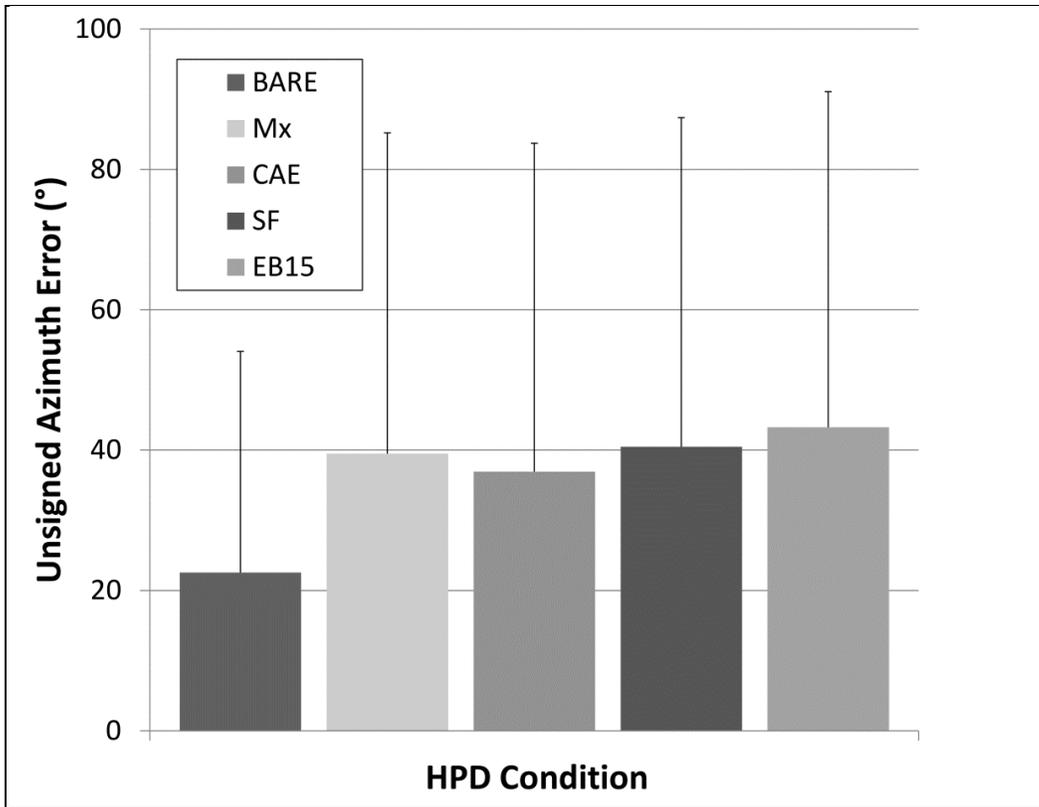


Figure 11. Average unsigned azimuth error as a function of head condition. The error bars represent ± 1 standard deviation.

Table 5. Results of special contrasts comparing the unsigned azimuth attenuation of the HPDs. Values shown are p values. Asterisks indicate significant contrasts.

	Mx		
CAE	0.086	CAE	
SF	0.509	0.018*	SF
EB15	0.013*	0.000*	0.064

The interaction between head condition and azimuth was significant [$F(60, 7580) = 3.7, p < .01$]. The plot on the bottom half of figure 10 suggests that this difference is due to an increase in the magnitude of errors near 0° and 180° when wearing hearing protection. This azimuth-dependent pattern of error magnitude is associated with errors that are the result of front-back confusions, otherwise known as reversals.

An analysis to determine whether the results can be explained by errors due to reversals was done by computing whether the reverse of an estimate was closer to the sound source location

than the estimate. If it was, the trial was coded as a reversal. Figures 12 and 13 show the percentages of trials coded as a reversal for each head condition and as a function of azimuth. The similarity of these graphs to figures 10 and 11 suggest that errors due to reversals drive most of the differences in localization performance. Performance was best for the bare head. Among the earplugs, performance was best with the CAEs and worst with the EB15. There was a significant increase in the tendency to make front-back reversal errors at 180° ($p < .05$) with the SF. However, for the most part, the differences between the earplugs were of no practical significance, suggesting that one might do best to choose based on an individual's preferred fit.

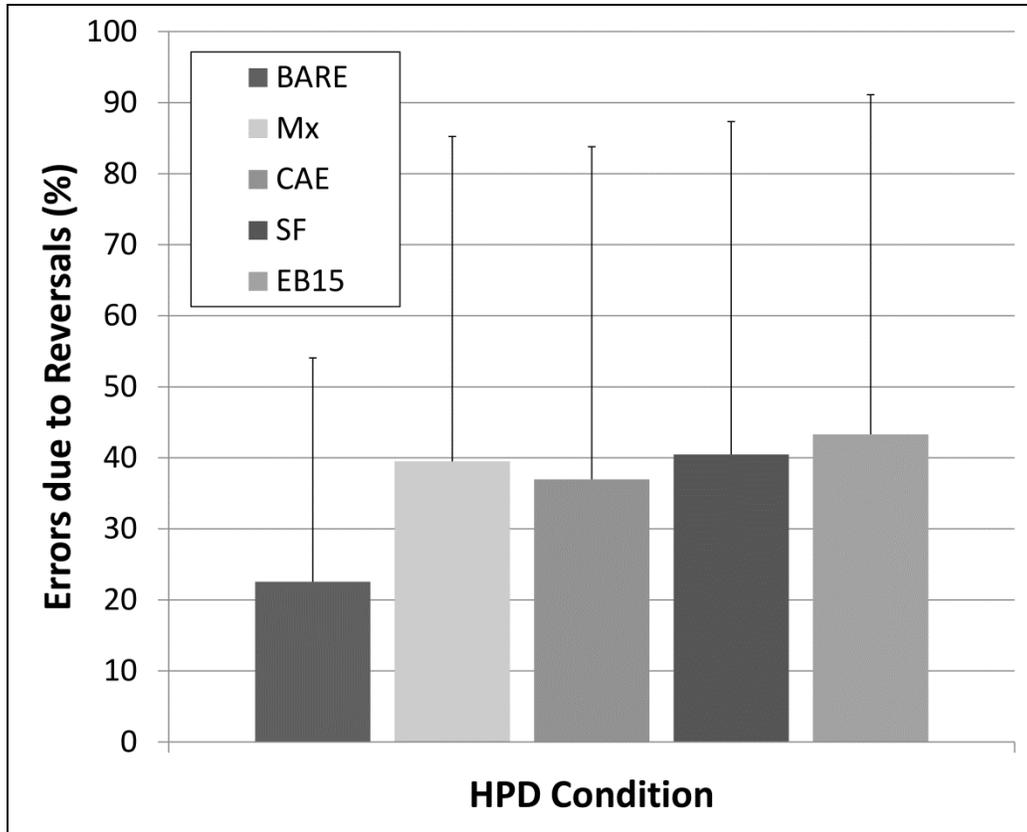


Figure 12. Percent of trials classified as reversals shown as a function of head condition.

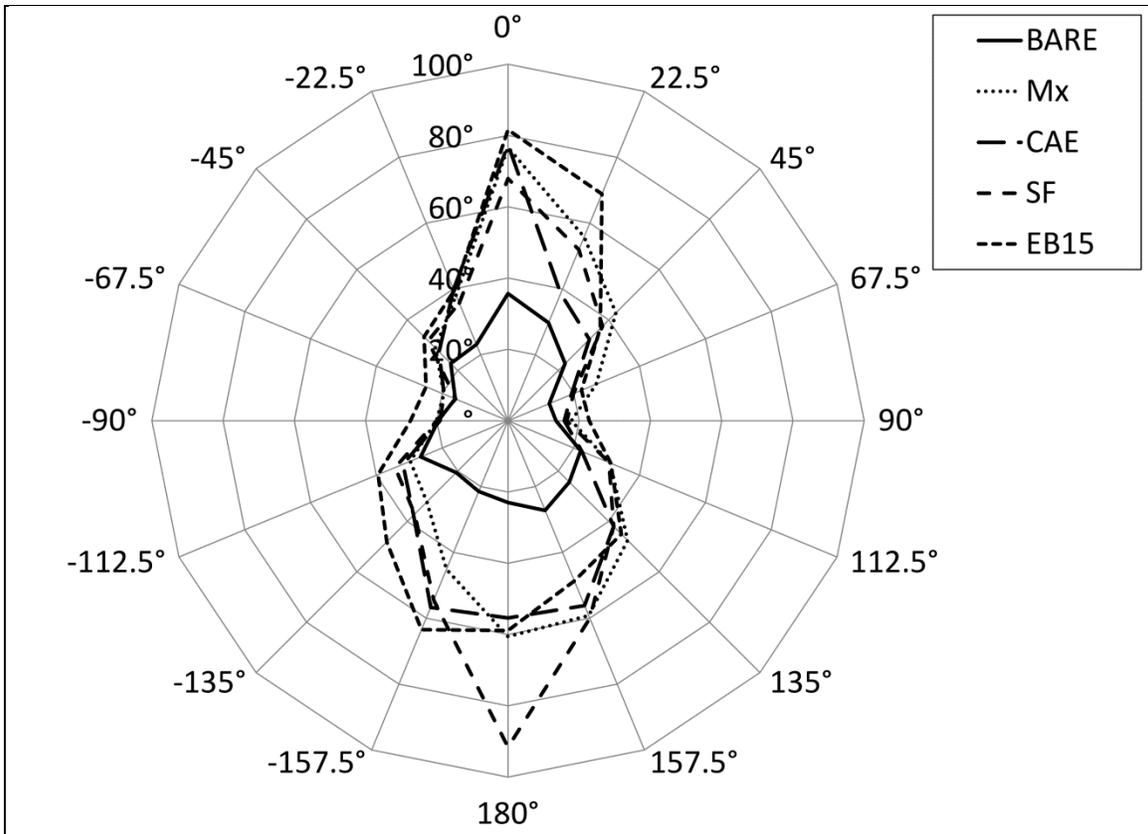


Figure 13. Percent of trials classified as reversals shown as a function of head condition and azimuth.

5. Summary and Conclusions

Four HPDs (Mx, CAE, SF, and EB15) were evaluated objectively for their attenuation of steady-state and impulsive noise. Their effects on auditory spatial perception were also assessed by measuring listener's ability to localize sounds while wearing the HPDs and comparing it to their performance without a HPD.

Measures of attenuation showed significant differences in the amount of attenuation provided by each of the HPDs. Three of the HPDs, the Mx, CAE, and SF, had a level-dependent filter designed to engage and protect against impulsive noise, but provide minimal attenuation of lower level steady-state noise. The CAE caused the least attenuation (greater than 20 dB) and the Mx had the most (25 dB). The fourth HPD, the EB15, was tested without the level-dependent electronics engaged and had 34 dB of attenuation. Analysis of the spectral envelope of this attenuation at one octave and one-third octave band resolutions suggests that the primary difference between the attenuation of the EB15 and that of the level-dependent HPDs is found in

the lower frequencies (less than 500 Hz). Among the level-dependent HPDs, the differences are in the higher frequencies, where the effects are most likely to be changes in spatial perception and mild effects on speech perception.

All HPDs provided at least 30 dB of attenuation of impulsive noise. There were significant differences between all of the HPDs; the EB15 had the most attenuation at 53 dB. However, it is unlikely that there is practical significance in the differences of the three level-dependent HPDs, as the range was 30 dB (SF) to 34 dB (Mx).

Measures of auditory localization with the HPDs revealed minor differences between them as compared with the bare head, consistent with their measured effects on attenuation. Specifically, of the HPDs localization was best with the CAE and worst for the EB15. Both the Mx and the SF had more attenuation of frequencies in the range above about 2 kHz than did the CAE and on average unsigned azimuth error was 2° – 3° greater than that observed for the CAE. Since the EB15 was tested without its level-dependent features active, it is not surprising that its performance was the poorest. It is more surprising that this difference was quite minimal. Since the target signal was presented at 70 dB, it is likely that it was sufficiently audible to gain localization information. Because the spectral transfer function of the active device is not known, it is not possible to predict the device's active performance.

By coding localization errors to determine which can be explained by front-back reversals, it is possible to argue that reversals were the primary cause of the degradation of localization performance observed for the HPDs as compared with the bare head. It does seem that localization performance decreases as a function of increased attenuation; however, the differences in localization performance among the HPDs were small compared to that with the bare head. It is suggested that users may wish to choose hearing protection based on personal preference and comfort, with the understanding that there may be some tradeoffs in that they may have slightly higher auditory detection thresholds and may find it more difficult to localize sounds.

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