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Etymotic EB-15 (Lo Position) BlastPLG™ Evaluation: Backup Alarm Localization Appended Experiment

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OBJECTIVE

A within-subjects experiment, published as Alali & Casali (in press) and provided prior to Etymotic Research, Inc., had been previously conducted in the Auditory Systems Laboratory at Virginia Tech to determine the effects of 7 different hearing protection devices (HPDs) on the abilities of normal-hearing listeners to localize, in azimuth, a vehicle backup (reversing) alarm. Additional variables included pink noise masking level (60 and 90 dBA) and standard versus modified (adding 400 and 4000 Hz) backup alarms. Following the original experiment, a new electronic hearing protector developed by Etymotic Research, Inc., the EB15 BlastPLG™ in its low gain (hereafter, "Lo" position) was subjected to the same experimental conditions in the appended experiment reported herein, albeit with a different group of normal-hearing subjects. The objective was to determine whether the Etymotic EB-15 device, due to its unique gain profile characteristics, offered any advantages in backup alarm azimuthal localization over the other HPDs in the original experiment. Thus, each subject performed the backup alarm localization experiment while wearing this device, and also while listening in an unoccluded (open ear) state. Because the original experiment and the appended EB-15 experiment were conducted on different groups of subjects and in different experimental sessions entailing independent orderings of conditions, statistical analyses to compare the conditions *across* the two experiments were not applicable. However, the means and 95% confidence limits for all HPD conditions across the two experiments are graphed herein to enable comparisons.

ACKNOWLEDGMENTS

The appended experimental trials on the Etymotic EB-15 Lo BlastPLG™ device were funded by a research contract to Virginia Tech from Etymotic Research, Inc. Dr. Mead Killion of Etymotic served as contract technical monitor. The conclusions reported herein are those of the authors and do not necessarily represent the positions of Virginia Tech or Etymotic Research, Inc.

BACKGROUND AND LITERATURE JUSTIFICATION

Relating to probably the most common auditory warning signal on industrial and construction sites, the backup (i.e., reverse) alarm signal, the Occupational Safety and Health Administration (OSHA) regulations state, "No employer shall use any motor vehicle equipment having an obstructed view to the rear unless: (b)(4)(i) The vehicle has a reverse signal alarm audible above the surrounding noise level or: (b)(4)(ii) The vehicle is backed up only when an observer signals that it is safe to do so" (Part 1926.601[b][4]) (OSHA, 2000). Even though OSHA mandates installing audible backup alarms on construction motor vehicles, accidents that stem from vehicular backing maneuvers occur frequently. Purswell & Purswell (2001) investigated OSHA accident reports from approximately 1972 through 2001 and found that of the roughly 150 backing accidents investigated, approximately 43% occurred while the backup alarm was operable. Clearly, the effectiveness of backup alarms in occupational settings is questionable, and one major issue is whether the alarms can be effectively localized, especially under hearing protection.

Auditory warning signals or alarms must capture workers' attention about critical information (Robinson & Casali, 2003). To do so, the auditory alarm must be recognizable (identifiable) as well as detectable. To initiate the reaction intended by the designers of the auditory signal, the signal should be informative, which connotes not only identification of the hazard, but also location of it in many scenarios. The aforementioned OSHA regulation emphasizes the signal *detection* aspect of the backup alarm signal design while largely ignoring the *information-conveying* aspect. As part of being informative, auditory warning signals need to be localizable in most applications, including the common need for forewarning of an approaching vehicle.

To foster localization, backup alarm signals should include in their frequency spectrum components that foster signal localization. In human hearing, frequencies below 1500 Hz and above 3000 Hz are important for localizing sounds in the horizontal plane outside the median plane (Hartman, 1999; Middlebrooks & Green, 1991). Also, to help localize horizontal sound sources in the median plane (i.e., front or back sound sources), the signal should have a broadband spectrum. Below 1500 Hz, the Interaural Time Difference (ITD), which is the difference in sound wave arrival time between the two ears, is primarily used to localize sound sources in the horizontal plane outside the median plane. Above 3000 Hz, the Interaural Level Difference (ILD), which is the difference in sound wave level between the two ears, is also used to localize sound sources in the horizontal plane outside the median plane. Most current commercial backup alarms emit near-pure tone signals with a dominant frequency in the 1000 – 1400 Hz frequency range (Laroche & Lefebvre (1998), and thus lack the frequencies that foster sound localization. Furthermore, the Society of Automotive Engineers (SAE) standard SAE J994b mandates a predominant frequency in the frequency range of 700-2800 Hz for backup alarms (SAE, 1978), which has limited coverage of localizable frequencies per ITD and ILD. It is evident that commercially-available backup alarms that consist of narrow-band spectra which do not include the frequencies that enable interaural phase and intensity cuing are not optimized; that is, they may not alert workers to the potential for hazardous situations resulting from vehicle reversing in part because their design, while being detectable, does not foster auditory localization. Furthermore, in the case of multiple vehicles in a construction environment, the rather obvious importance of knowing which vehicle(s) is currently closest to and approaching the worker has been empirically verified in a field study conducted by Withington (2004), in which 90% of the participants stated that it is important to know which of the surrounding vehicles is approaching them. To accomplish this task, localization of the backup alarm is of obvious importance.

In the scientific literature, there is a paucity of investigations of backup alarm effectiveness, and those that have appeared were focused on the influence of hearing protection devices (HPDs), background noise levels, workers' hearing abilities, and the acoustic features of the backup alarm signal on its detection (Laroche & Lefebve, 1998; Casali et al., 2004.) A single prior study by Withington (2004) actually examined, but only on a subjective basis, the effect of the backup alarm's acoustic features on how workers perform in localizing the source of the signal. In this study, self-report measures were used to assess workers' performance in localizing conventional backup alarms as well as broadband ones. The broadband alarm, consisting of a white noise-type signal, was reported by Withington to improve workers' localization performance over that reported for a conventional backup alarm. Although these results appear promising in terms of improving on-foot workers' safety, factors other than the acoustic features of backup alarms that may render workers' localization ability (e.g. background noise level and HPD-type) were not considered in the Withington study.

It is well-accepted that conventional passive HPDs are necessary as a countermeasure against noise-induced hearing loss in workers, but their use has been shown in a limited number of studies to be detrimental to sound localization in a horizontal plane, albeit not with backup alarms as the test signal though (e.g., see Atherley & Noble, 1970; Atherley & Else, 1971; Abel & Hay, 1996; Noble & Russell, 1972; Simpson et al., 2005; Boliz et al., 2001). As well as investigating the effect of the acoustic features of backup alarm signals on localizing them, it is also important to study the effect of different HPDs, including those that incorporate either passive or electronic augmentations (as does the EB-15), to localize backup alarm signals (see Casali, 2005; Casali, in press-a; Casali, in press-b, for reviews of the current state-of-the-art in HPD augmentation technologies). Such an experimental study should help industrial safety professionals select HPDs for their workers when localization is an important task, and foster future development of improved HPDs. Thus, a comparison of a wide variety of passive and electronic HPDs was a major focus of the research experiments discussed herein. In addition, the research had the objective of determining the localization effects of broad spectrum (i.e., pink) noise at the OSHA criterion level of 90 dBA and at a lower level of 60 dBA, as well as the localization effects of a frequency-widened backup alarm as compared to a standard backup alarm.

EXPERIMENTAL METHODOLOGY
(Original and Appended Experiments)

Participants: Original and Appended Experiments

A total of 12 participants, 8 males and 4 females, all older than 18 years, participated as subjects in the original localization experiment. In the appended experiment, there were 12 subjects (9 males, 3 females), all of which were different than the group in the original experiment. All qualifying participants were tested with a Beltone Model 114 pure-tone audiometer using a modified Hughson-Westlake procedure, and found to have normal hearing (i.e., defined as less than or equal to 25 dBHL at 250, 500, 1000, 1500, 2000, 3000, 4000, and 6000 Hz in both ears) and a symmetry difference of less than or equal to 15 dBHL between the two ears. The symmetry requirement was implemented to avoid any possible hearing-related bias in localizing the backup alarm stimuli.

Experimental Design: Original and Appended Experiments

To assess localization performance with objective measurements, an 8×2×2 completely within-subjects experimental design with three independent variables was applied in the *original* experiment, and a 2x2x2 within-subjects design was applied in the *appended* experiment with the same independent variables, but using different subjects than in the original study due to the fact that the original subjects were no longer available (see Figure 1). The independent variables were the HPD/listening condition (8 or 2 levels), background noise dB level (2 levels), and type of backup alarm signal (2 levels), detailed as follows.

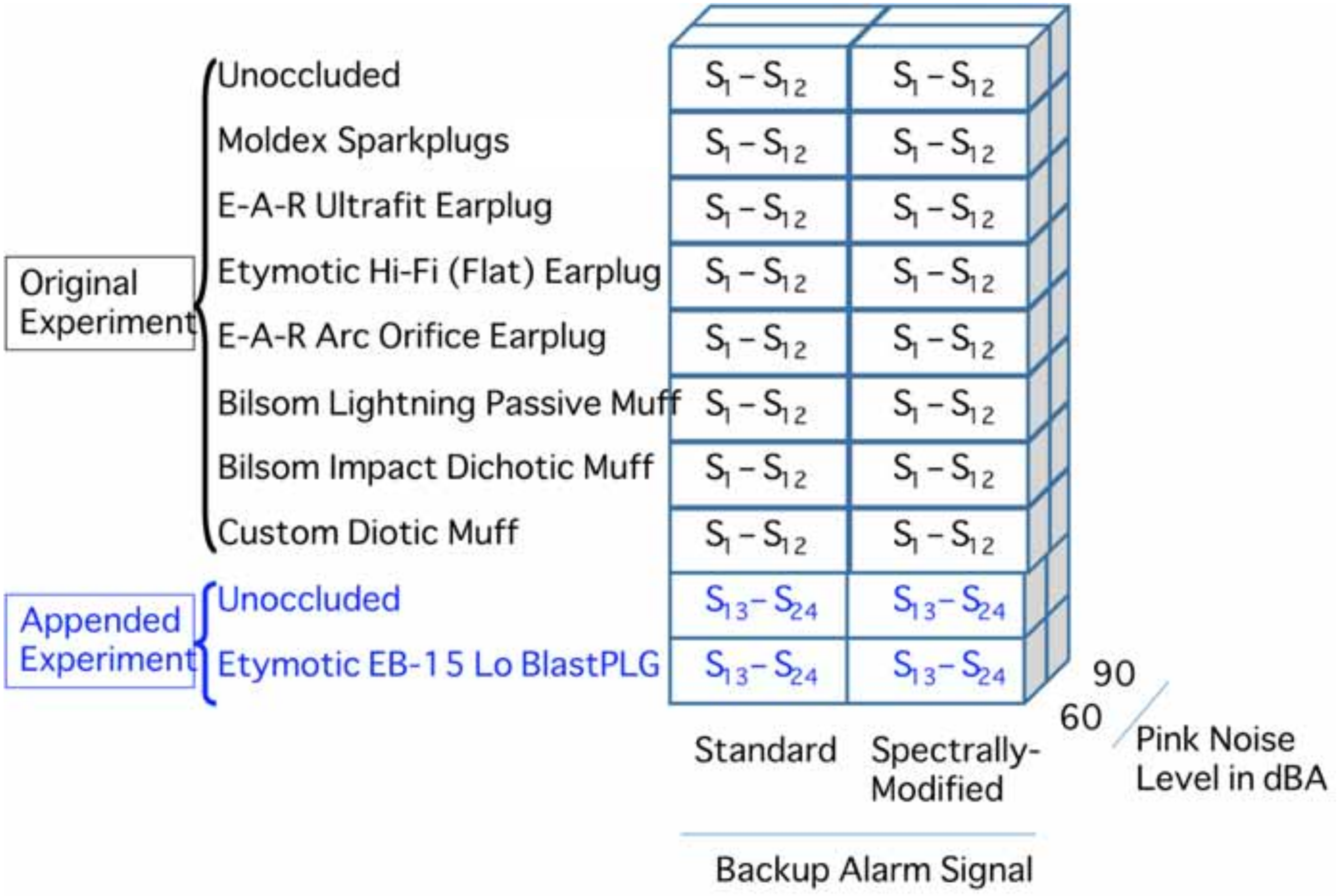
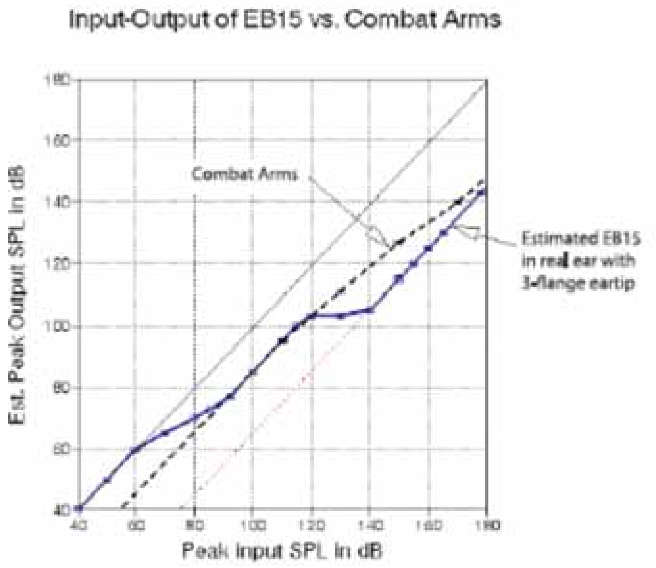


Figure 1. Experimental design with assignment of participants to independent variables in original and appended experiments. NOTE: Different sets of subjects were used for the two experiments, because they occurred at two different dates.

Hearing protection device (HPD) variable. In the original experiment, the HPD/listening conditions consisted of: 1) unoccluded (i.e., no HPD) condition, 2) Moldex Model-6604 foam earplug (SparkPlug^{TM} earplug), 3) E-A-R Ultrafit^{TM} premolded earplug, 4) Etymotic/E-A-R HiFi^{TM} earplug (a uniform or “flat” attenuation HPD), 5) E-A-R Arc^{TM} earplug (a level-dependent HPD), 6) Bilsom Leightning^{TM} L3HV passive earmuff, 7) Bilsom Impact^{TM} *dichotic* sound transmission earmuff (having two unique microphones, each feeding the sound transmission circuit for one earcup to maintain true stereo hearing), and 8) a custom-made *diotic* sound transmission earmuff (having one microphone that feeds the sound transmission circuit for both earcups, thereby negating any stereo cues).

In the *appended experiment,* the HPD/listening conditions were: 1) unoccluded (i.e., no HPD) condition, and 2) Etymotic EB-15 BlastPLG^{TM} in its “Lo” gain position which provides approximately 15 dB attenuation for sounds in the 90-110 dB range and transparent operation for sounds below 60 dB (this is the switch position towards the battery drawer on the EB-15). The input-output gain/attenuation characteristics for the EB-15 BlastPLG^{TM} are shown in Figure 2.

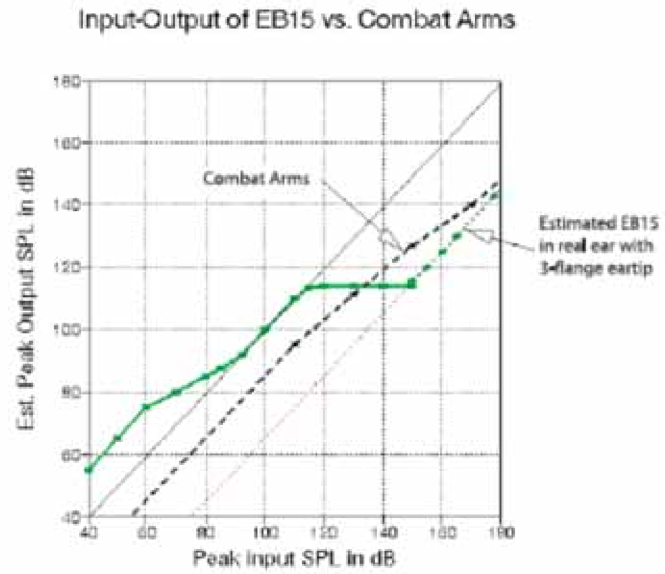
The rationale for selecting each HPD in the *original experiment* was as follows. The foam earplug was selected due to its popularity and prevalence in industry. In addition, the Moldex SparkPlug^{TM} foam earplug has the highest Noise Reduction Rating (NRR=33) compared to the other HPDs in the experiment. This was considered important, since backup alarms are common in road construction environments where the exposure levels can be quite high, necessitating an HPD of high NRR value. The E-A-R Ultrafit^{TM} premolded earplug (NRR=25) and the Etymotic/E-A-R HiFi^{TM} earplug (NRR=12) were selected based on several factors, including their ease of cleaning (i.e., hygienic benefit), and the fact that flanged polymer earplugs are popular in industry. Furthermore, unlike the attenuation profile of conventional passive earplugs which provide higher attenuation as frequency increases, the HiFi^{TM} earplug (which has identical flange design to the Ultrafit^{TM}) has near flat attenuation in the 100-8000 Hz frequency range. This is believed to be beneficial to pitch perception, and thus it was hypothesized that it potentially could provide an advantage in horizontal sound localization, as well as the fact that its annular sound port enables signals to enter the plug only after being “imprinted” by the outer ear, since that port is near the ear canal rim (e.g., Casali, in press-b). The two-ended E-A-R Arc^{TM} orifice-based, level-dependent earplug, an industrial version of the military Combat Arms^{TM} earplug, was included because its level-dependent end provides minimal attenuation at frequencies below 1000 Hz under low-level noise conditions, and its attenuation automatically increases in impulsive noises above about 110-120 dB, such as those from a piledriver (Casali, in press-b). Thus, it was thought that the Arc^{TM} earplug could have application in certain industrial environments where intermittent noise having primarily impulsive components is prevalent (e.g. as in the construction industry). However, in this first localization investigation, impulsive noise was not investigated, but instead, the interest was in whether this earplug might show localization benefit during the “quiet” periods (that is, 60 dBA noise level) that occur in intermittent noises, due to its minimal attenuation at those levels. In addition, the lower attenuation at frequencies below 1000 Hz could provide listeners with the ITD sound localization cue which may improve their localization performance. (For this experiment, only the level-dependent end of the Arc^{TM} earplug was tested in view that the conventional end of the Arc^{TM} is essentially the same as the Ultrafit^{TM} earplug).



Blue Curve: Lo switch position
EB15 acts as a 15 dB earplug for loud sounds between 85 and 115 dB SPL, where it acts somewhat like the Combat Arms earplug "open orifice" (dashed black curve).

EB15 is acoustically transparent, however, for quiet sounds below 60 dB SPL and provides superior blast protection in the 120-180 dB SPL range.

Dashed red curve: Turned off
EB1 provides approximately 35 dB of attenuation, similar to the Combat Arms earplug "closed orifice."



Green Curve: Hi switch position
EB15 is transparent for loud sounds between 85 and 115 dB SPL. EB15 provides 15 dB gain for quiet sounds between 0 – 60 dB SPL, and provides blast protection in the 120-180 dB SPL range.

Dashed red curve: Turned off
EB1 provides approximately 35 dB of attenuation, similar to the Combat Arms earplug "closed orifice."

Figure 2. Input-output gain/attenuation characteristics for the Etymotic EB-15 BlastPLG^{TM} (Lo setting, blue curve, used in appended experiment herein). (Provided courtesy of M. Killion, May, 2010.)

The earmuffs, as a class of HPDs, were included in the original experiment for several reasons, including their prevalent use in certain construction environments as well as the fact that unlike earplugs, because they cover the pinnae, earmuffs remove any localization cueing that may be established by pinnae configuration and imprinting. The inclusion of the Bilsom Leightning^{TM} Hi-Visibility L3HV passive earmuff was based on its high attenuation (NRR=30) relative to most other commercial earmuffs. Two active (electronic sound transmission) earmuffs, also known as sound restoration or sound pass-through devices, were also tested (see Casali, in press-a, for a discussion of this class of electronic HPD). The custom-made diotic earmuff (NRR=23 based on its passive mode of operation), consisted of a Bilsom Impact^{TM} dichotic product, with the dichotic feature converted to a diotic design by the research team. This product was not a commercially-available product at the time of this writing; however, other diotic designs have been available from various manufacturers. The Bilsom Impact^{TM} dichotic earmuff (NRR=23) was selected because this type of design is often considered by safety professionals for industrial environments that are characterized by intermittent noise. In relatively quiet environments, the Bilsom Impact^{TM} dichotic muff amplifies the surrounding warning signals (and other sounds in its passband) after picking the signal through a microphone attached to the outside of each earcup. As noise increases above a certain level (i.e., 82 dBA as in manufacturer's descriptions), sound transmission muffs of this type *typically* shut off (or reduce) their pass-through gain and the earmuff reverts to a passive mode to protect listeners' hearing. Using a custom-made acoustical test fixture (per ISO/DIS 6290) with a 1-inch microphone connected to a Larson-Davis 3200D spectrum analyzer, an objective test was performed by the authors to determine the actual under-earcup output of two samples of the Bilsom Impact dichotic muff in noise levels widely spanning 82 dBA. In a noise field of surrounding, incident pink noise, presented at constant individual levels ranging from 75 dBA to 90 dBA, the Impact^{TM} dichotic earmuff yielded under-earcup levels of approximately 90 to 91 dBA with the gain set to *maximum* (as it was set in the experiment described herein).

The difference between the diotic and dichotic earmuffs in the original experiment was limited to the design of how the microphones feed each earcup. In the diotic earmuffs, only one microphone attached to one of the earcups transmits the signal to both of the earcups simultaneously. In the dichotic earmuffs, two microphones, one attached to each earcup, feeds each earcup separately. This difference in design was hypothesized to influence participants' localization performance since the diotic technology is expected to destroy the ITD and ILD while the dichotic one is expected to maintain them. Further discussion of these types of HPD technologies is provided elsewhere (e.g., Casali, in press-a,b).

The rationale for selecting the HPD/listening conditions for the *appended experiment* were as follows. The Etymotic EB-15 BlastPLG^{TM} is a newly-developed prototype device that was based on hearing aid technology. In addition to other available replaceable eartips, it employs 2 sizes of the basic three-flanged polymer eartips of the E-A-R Ultrafit^{TM} style and these were used in the appended experiment herein. In its Lo gain position, the provision of approximately 15 dB attenuation (see Figure 2) for sounds in the 90-110 dB range by the EB-15 would provide adequate protection in *many* construction noises. However, it was also hypothesized that its *transparent behavior* (i.e., provision of tuned amplification to overcome the insertion loss provided by the flanged eartip) for sounds below 60 dB would potentially foster localization benefits when compared to passive earplugs or muffs. Thus, this was the major interest in including this device in the appended experiment. In this regard, the decision to set the EB-15 on its “Lo” setting was made by Mead Killion of Etymotic in discussion with the authors-experimenters, and this setting was used in all trials.

Background noise level variable. The levels of the background noise included in this study were 60 dBA and 90 dBA (i.e., “low” and “high”, respectively) of pink noise (i.e., flat-by-octave within +/- 3 dB). The higher level, 90 dBA, was selected because it comprises the noise Permissible Exposure Limit (PEL) (i.e., criterion level) of OSHA, and because it is representative of many noise levels produced from various construction equipment as measured on construction sites. 90 dBA is at or above the levels at which the pass-through circuits of the electronic sound-transmission earmuffs (and the gain circuit of the EB-15 BlastPLGs^{TM}) were reported by the manufacturer to shut-off (though the objective test described above yielded an under-earcup level of about 90-91 dBA with the Bilsom electronic muff), while 60 dBA is well below the shut-off level, therefore invoking the amplification of the sound transmission devices. Also, it should be obvious that in construction sites, intermittent quiet periods do occur and workers are advised to keep their hearing protectors on, in view that unexpected noise can manifest at any time. Thus, this is the reason for including a 60 dBA level in the study, in that workers will still have to localize backup alarms during quiet periods, often with hearing protectors on.

Backup alarm signal variable. The third independent variable considered in this study was the type of the backup alarm signal. The participants’ localization performance was assessed under both a standard backup alarm and a spectrally modified backup alarm. The “standard” backup alarm used includes dominant frequencies of 1000 Hz, 1250 Hz and 3150 Hz while the spectrally modified backup alarm signal was augmented by the research team to include primary frequency components of 400 Hz and 4000 Hz, in addition to the same dominant frequencies of the standard alarm (Figure 3). It was hypothesized that the modified backup alarm signal would provide more accurate sound localization judgments in the horizontal plane than would the standard backup alarm signal. This was because the additional frequencies (i.e., 400 Hz and 4000 Hz) should enable use of the ILD and the ITD in localizing the source of the alarm when it emanates longitudinally from outside the median plane. Additionally, the spectral cues in the modified signal (the broad bandwidth of the backup alarm signal) were expected to increase the performance of listeners with respect to front-rear localization.

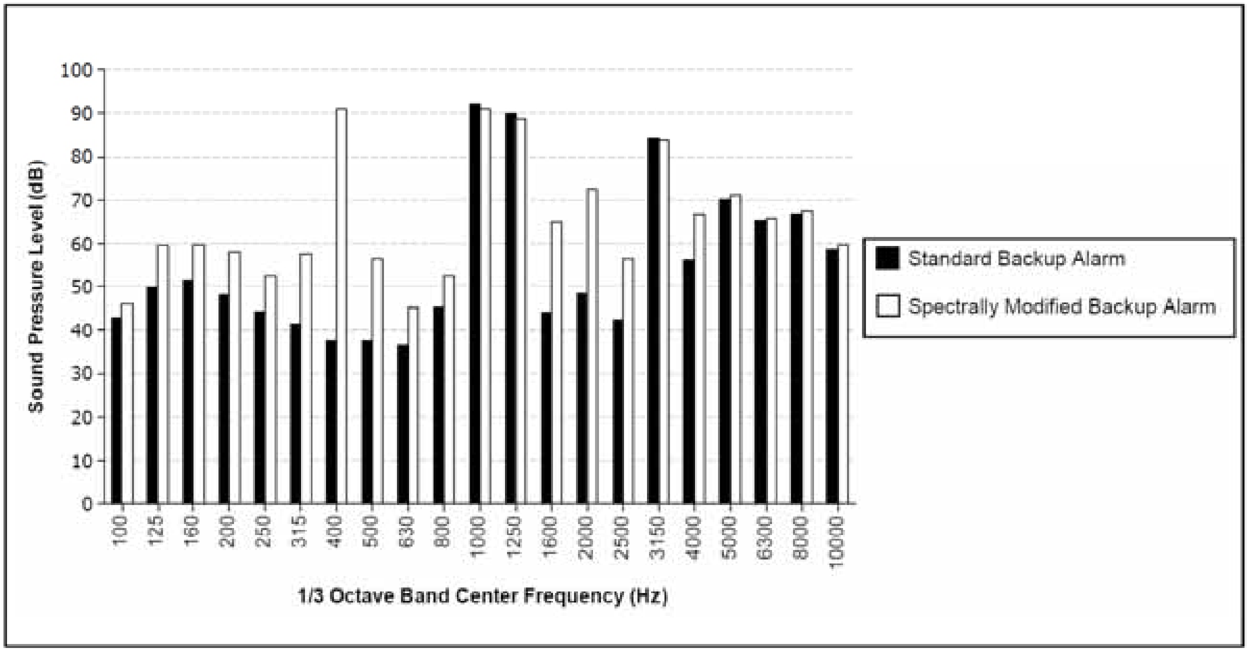


Figure 3. Standard and spectrally-modified backup alarm spectra as used in both experiments.

Experimental Facility and Apparatus

Background noise field. A hemi-anechoic room, with dimensions 19 ft long by 18 ft wide by 8.5 ft high, in the Virginia Tech Auditory Systems Laboratory was used as the test environment, and it was identically set up and calibrated for both experiments. This established an approximate free-field over a reflecting plane to simulate an outdoor environment free of large obstructions and including a reflective ground surface, such as asphalt, concrete, or packed earth of a typical construction site. The 60 and 90 dBA background noise was generated by an Atlas Soundolier noise generator, Model GPN-1200A, routed through 2 Sony STR DE-135 amplifiers and 2 Phoenix Gold VSS2 speaker selectors, to 4 Infinity SM-155 loudspeakers (Figure 4). To provide a flat-by-octave spectrum (i.e. pink noise) at the participant's head, 2 AudioControl C-131 one-third octave equalizers were used in the circuit. The spectrum of the background noise was verified before each experimental session, at the participant's head position, by using a Larson-Davis 2800 Real-time Spectrum Analyzer and a Larson-Davis model 2559 ½-inch microphone, which was calibrated to 94 dBA at 1 kHz using a Quest QC-20 calibrator.

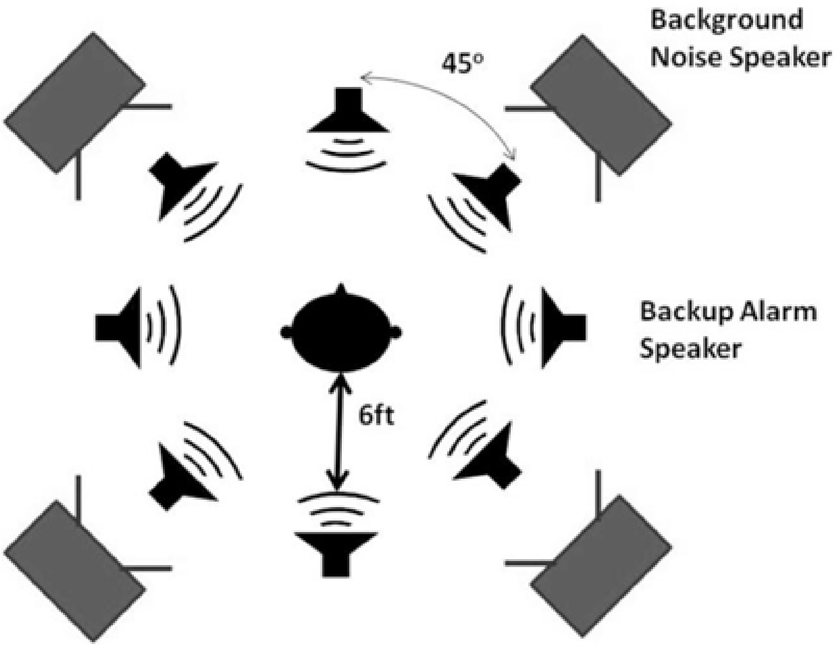


Figure 4. Experimental test environment with loudspeaker placement for pink noise and for backup alarms in 360-degrees azimuth. (An acoustically-transparent black curtain which was between the subject and the backup alarm loudspeakers, visually obscuring the loudspeaker locations, is not shown).

Backup alarm sound field. The modified backup alarm signal was synthesized at a sampling rate of 192 KHz with 16-bit resolution using Adobe Audition^{TM} Software. The two additional frequencies, 400 Hz and 4000 Hz, were added by using the software to add to the standard backup alarm signal. Using the same software, on each trial, the backup alarm signal under test was simulated to be approaching the participant's position by increasing its intensity over time. A DELL laptop computer was used to store the two backup alarm signals, and input them to a Parasound P/LD-1100 Line Drive preamplifier and a Sony STR DE-135 amplifier. The backup alarm signal was routed through 2 Phoenix Gold VSS4 speaker selectors, enabling the alarm to be selectively and on demand by the experimenter, output through one of 8 Klipsch Comm Sat loudspeakers that were placed in a circle at six ft away from the participant's head center position and at his/her ear height (Figure 4). All loudspeakers were obscured from the participant's view by a black, acoustically transparent curtain.

Participant's localization response controls. To respond to each presented backup alarm signal, the participant used a stylus connected to a Fujitsu tablet PC to point, on a 360-degree digital compass with a 1-degree interval, to the location of the approaching backup alarm signal as he/she perceived it. A LabVIEW custom-made program installed on the tablet PC was used to present the 360-degree digital compass and an ENTER DIRECTION digital button. The participant was asked to press this button to store his/her response. To monitor the participant's use of the LabVIEW program, a 17" Dell monitor, connected to the video-out port of the tablet PC, was viewed by the experimenter. The participant did not know the number of backup alarm source loudspeakers, and he/she was allowed to turn his/her head during each localization trial.

Procedure

Screening and familiarization session. During a screening and familiarization session, the participant read and signed an informed consent document and then underwent the audiometric test for normal hearing and bilateral symmetry. Also during this session, the participant was instructed in the procedures of the experiment and practiced in a familiarization task that required him/her to localize 16 approaching beeps (8 beeps presented from each Klipsch loudspeaker twice each) of the spectrally modified backup alarm signal in the lower background noise condition (60 dBA of pink noise) while being unoccluded. To meet the familiarization criterion, the participant must have been able to achieve at least 50% correct of his/her localization responses on this task.

Experimental sessions. There were 4 experimental sessions attended by each subject in the original experiment, and one experimental session in the appended experiment. Each session included factorial combinations of the independent variables (per Figure 1) consisting of: two hearing protection conditions, both background noise levels, and both backup alarm conditions which were each presented twice. Presentation of both backup alarms was accomplished in a random fashion within a session, as were the background noise levels, to avoid order effects. Also, in the original experiment, the order effect of assigning two hearing protection conditions to each of the four sessions for each participant was minimized via counterbalancing of order by a Latin Square; in the appended experiment, the ordering of the EB-15 and the unoccluded condition were randomized within the single session across subjects. In each experimental session, participants performed the localization task in 64 experimental trials once per hearing protection condition. The 64 experimental trials consisted of presentation of two redundant trials for each of the two different backup alarm signals, from each of the eight Klipsch speakers in the two background noise conditions. Before starting the experimental session, the participant was seated in a chair placed in the middle of the test room, refreshed on the experimental procedures, instructed to move his/her head if needed to localize the backup alarm signal, and fit properly with the assigned HPD by the experimenter. Next, the participant performed the 64 experimental trials of the localization task. In each experimental trial, the participant, wearing the assigned HPD (or open ear condition) was presented with one of the background noise levels and one of the backup alarm types.

The backup alarm's sound level was increased during each trial to simulate a vehicle approaching from 240 ft away to 19 ft away from the listener. The rate of increase in intensity was calibrated to simulate an approach speed of 10 mph; this speed was selected because it represented one of the faster reversing speeds among construction vehicles. The change in sound level of the backup alarm at the participant's ear, corresponding to the simulated distance from the participant, is depicted in Figure 5. On each trial, once the backup alarm began to sound, the participant had 15 seconds to perceive the location of the backup alarm signal and 15 seconds to provide his/her estimate of the alarm's location using the tablet PC's 360-degree compass. If the participant did not respond within 15 seconds, he/she was then instructed to make his/her immediate best guess for the perceived angular location of the backup alarm signal.

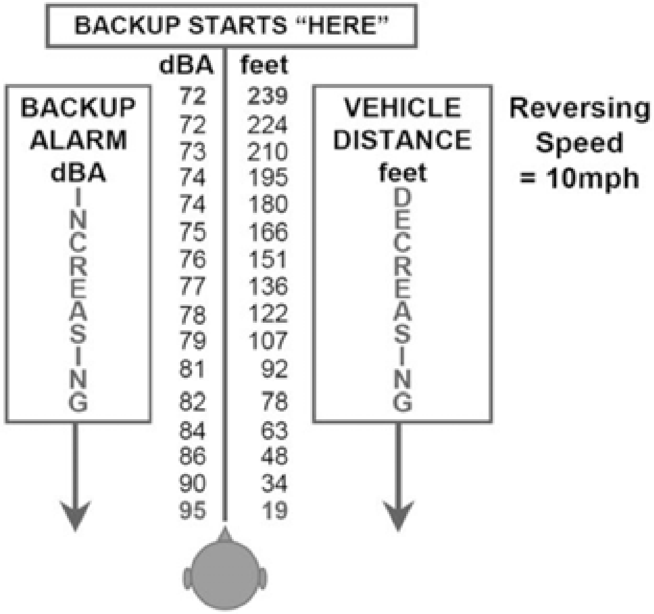


Figure 5. Backup alarm simulated approach toward participant, with dBA increment by distance.

Dependent Measures of Localization Performance

Four objective, quantitative dependent measures were obtained from the data set to assess participants' localization performance: 1) *percentage correct localization*, i.e., any response within 22.5^0 to the right or left of the alarm's actual azimuthal location was considered correct; 2) *percentage of right-left localization errors,* i.e., an error occurred when an alarm that emanated from within an angle of +/- 45^0 from directly to the right of the subject was judged as coming from the left, and vice-versa, 3) *percentage of front-rear localization errors,* i.e., an error occurred when an alarm that emanated from within an angle of +/- 45^0 from directly in front of the subject was judged as coming from the rear, and vice-versa, and 4) *localization absolute deviation in degrees* from the alarm's azimuthal location, i.e., the error in judgment from the alarm's actual direction, which ranged from 0^0 to 180^0.

Localization Data Reduction (both experiments) and Statistical Analysis (original experiment)

The raw data values that were collected via computer using LabVIEW™ software from the 360-degree azimuth tablet PC compass pointer were reduced after exporting these data to a Microsoft Excel™ spreadsheet. In each session for each participant and for each noise level condition, the two redundant trials obtained for each of the two different backup alarm signals from each of the 8 loudspeaker positions were averaged together. To investigate for statistically-significant differences in the original experiment, a within-subject Analysis of Variance (ANOVA) was applied to each of the four dependent measures. An alpha level of 0.05 was used for all decisions regarding statistical significance; that is, any differences reported herein on the original experiment's graphs were statistically significant at $p \leq 0.05$. Main effects and interactions that were revealed by the ANOVAs as significant were further analyzed by Tukey's Honestly Significant Difference (HSD) test to determine the exact loci of significance, also at an alpha level of 0.05, for the original experiment; in this regard, *mean values coded with different letters, as reported on the graphs below, are statistically-different at* $p \leq 0.05$*. (The appended experiment's data set could not be mixed with this analysis in similar fashion due to the fact that in comparison to the original experiment, a different set of subjects was used and also because the randomization scheme for condition ordering could not be merged with that of the original experiment, since they were conducted at different points in time.)* In the case of both experiments, graphical presentations of the data below include both the mean and 95% confidence intervals about the mean. In this manner, lacking subject and ordering commonality across the two experimental designs (as noted above) it was not possible to statistically compare the original and appended experiments via mixed ANOVAs; therefore, the reader may simply use the confidence limits on the ensuing graphs to visually gauge statistical differences between conditions across the two experiments.

RESULTS IN GRAPHICAL FORM

Refer to text above for descriptions of experimental conditions, variables, and dependent measures shown on vertical axes in the ensuing graphs.

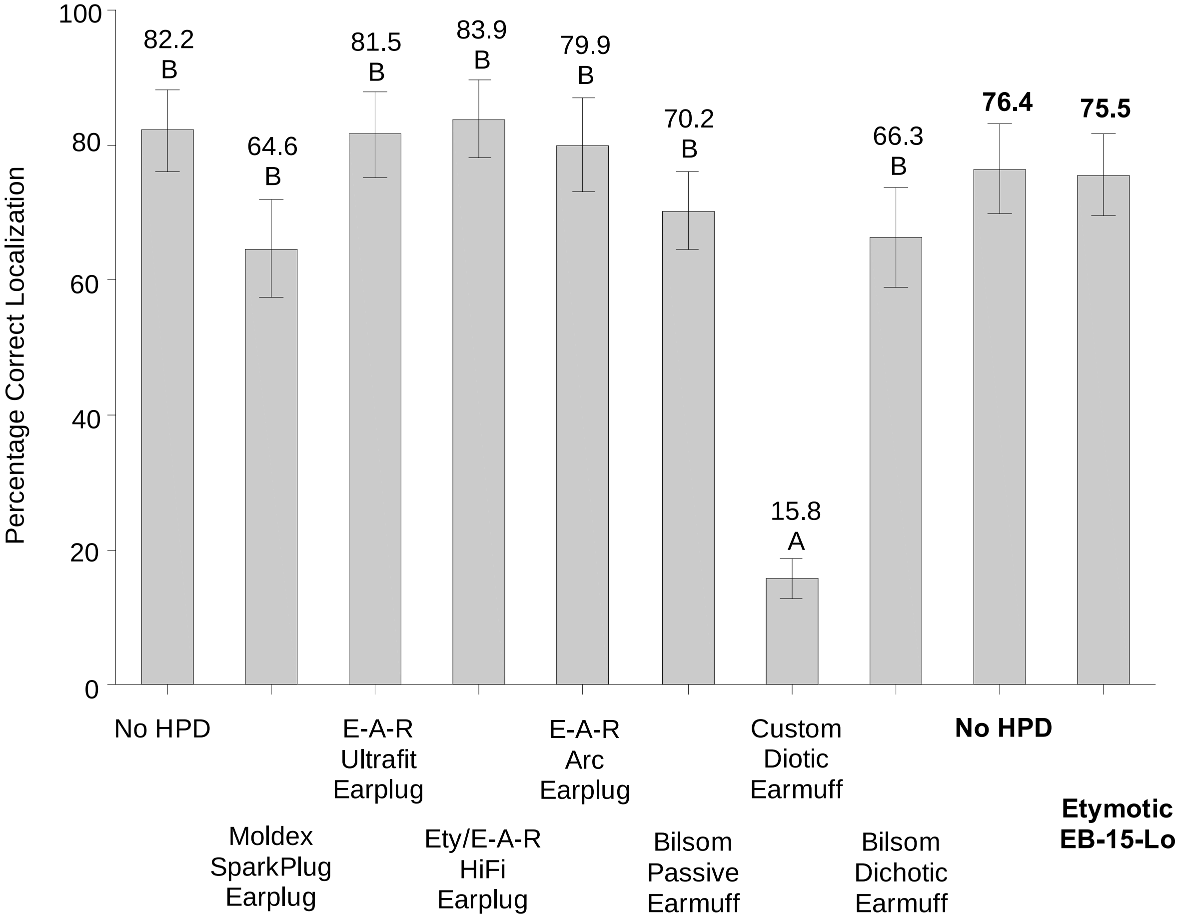


Figure 6. Main effect of HPD/listening condition (averaged across noise levels and backup alarms) on percentage correct localization; mean values shown on bars with 95% confidence intervals. Means with the same letter are not significantly different at $p \leq 0.05$ (original experiment conditions only). Data for appended experiment are from a different group of subjects than original experiment, and are shown in **boldface font.**

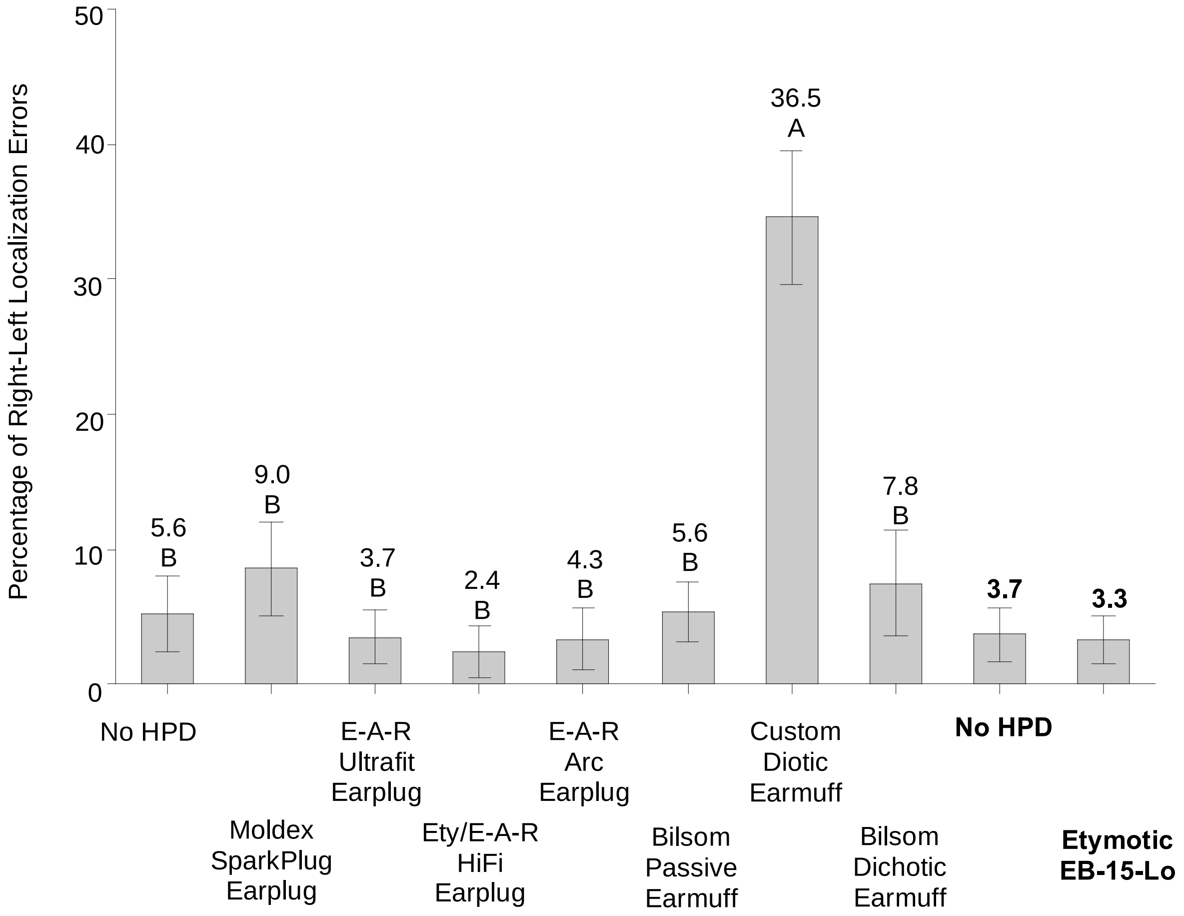


Figure 7. Main effect of HPD/listening condition (averaged across noise levels and backup alarms) on percentage of right-left localization errors; mean values shown on bars with 95% confidence intervals. Means with the same letter are not significantly different at $p \leq 0.05$ (original experiment conditions only). Data for appended experiment are from a different group of subjects than original experiment, and are shown in **boldface** font.

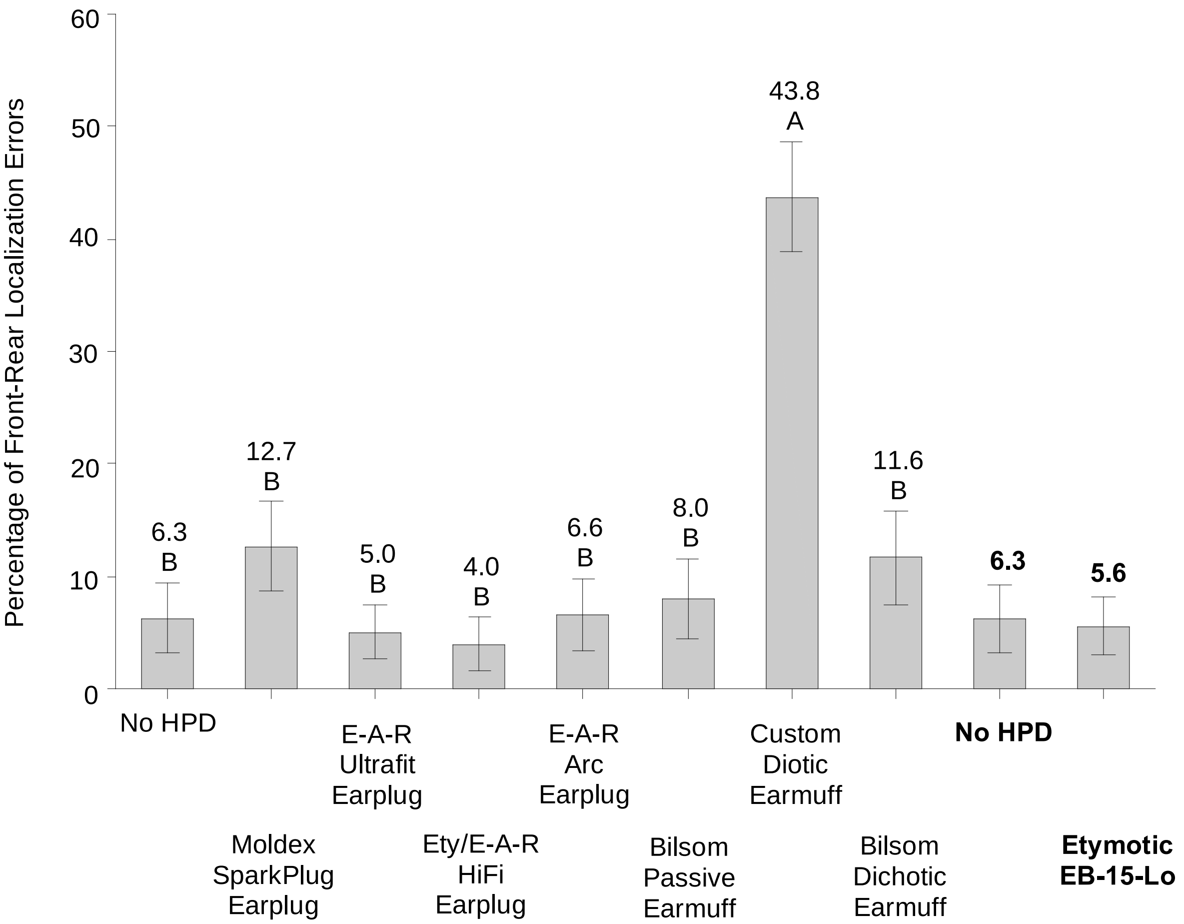


Figure 8. Main effect of HPD/listening condition (averaged across noise levels and backup alarms) on percentage of front-rear localization errors; mean values shown on bars with 95% confidence intervals. Means with the same letter are not significantly different at $p \leq 0.05$ (original experiment conditions only). Data for appended experiment are from a different group of subjects than original experiment, and are shown in **boldface font.**

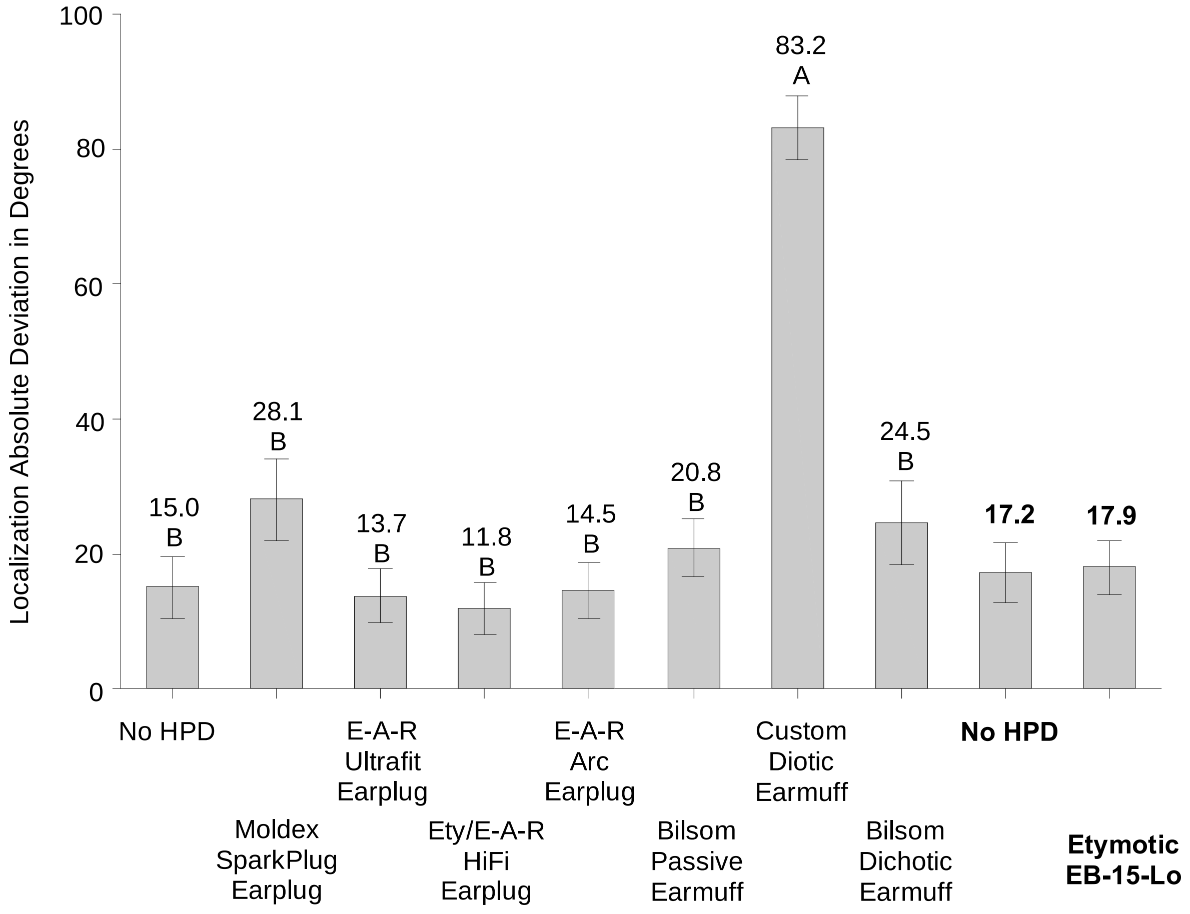


Figure 9. Main effect of HPD/listening condition (averaged across noise levels and backup alarms) on absolute localization deviation in degrees; mean values shown on bars with 95% confidence intervals. Means with the same letter are not significantly different at $p \leq 0.05$ (original experiment conditions only). Data for appended experiment are from a different group of subjects than original experiment, and are shown in **boldface** font.

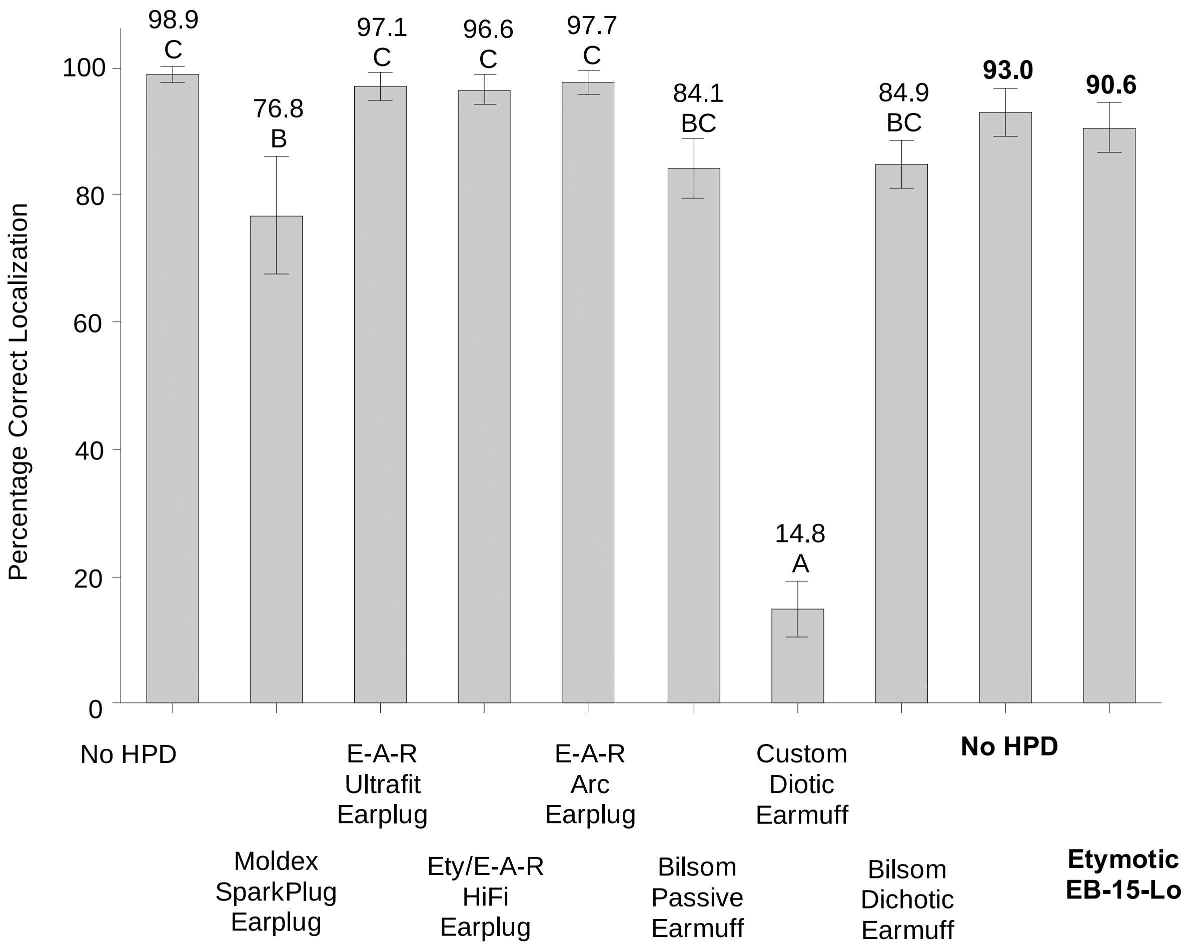


Figure 10. Effect of HPD at 60 dBA background noise level (from interaction) on percentage correct localization; mean values shown on bars with 95% confidence intervals. Means with the same letter are not significantly different at $p \leq 0.05$ (original experiment conditions only). Data for appended experiment are from a different group of subjects than original experiment, and are shown in **boldface** font.

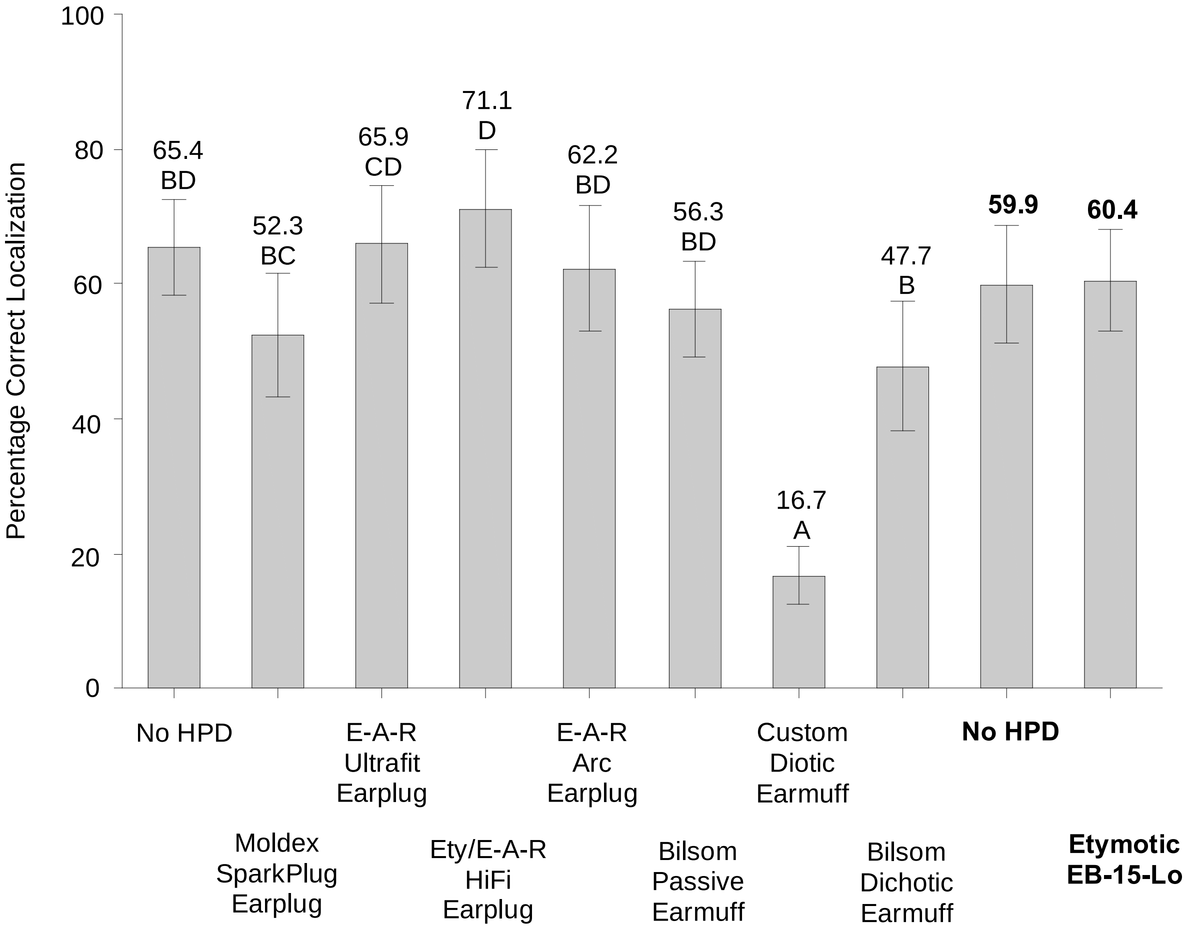


Figure 11. Effect of HPD/listening condition at 90 dBA background noise level (from interaction) on percentage correct localization; mean values shown on bars with 95% confidence intervals. Means with the same letter are not significantly different at $p \leq 0.05$ (original experiment conditions only). Data for appended experiment are from a different group of subjects than original experiment, and are shown in **boldface** font.

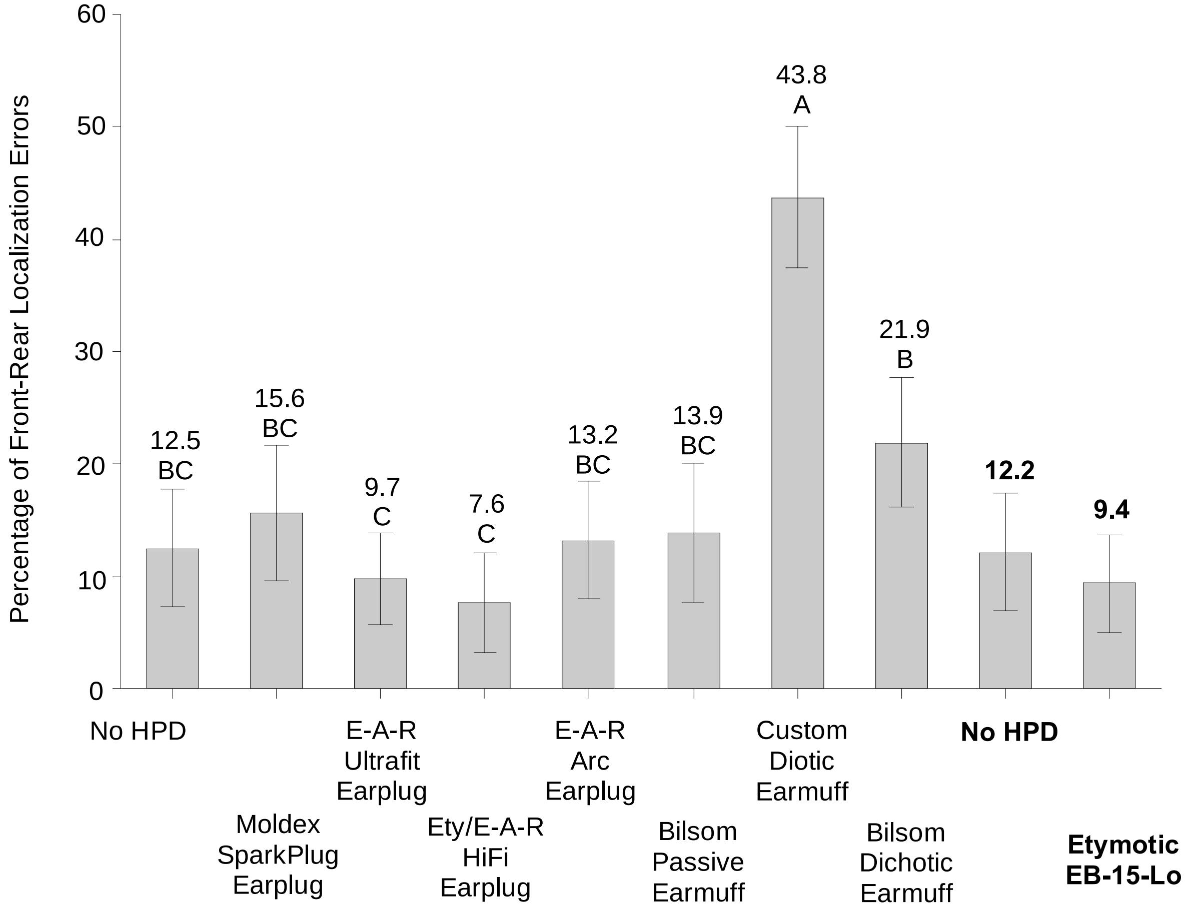


Figure 12. Effect of HPD/listening condition at 90 dBA background noise level (from interaction) on percentage of front-rear localization errors; mean values shown on bars with 95% confidence intervals. (In the 60 dBA condition, there were no significant differences, therefore the data are not plotted for 60 dBA.) Means with the same letter are not significantly different at $p \leq 0.05$ (original experiment conditions only). Data for appended experiment are from a different group of subjects than original experiment, and are shown in **boldface** font.

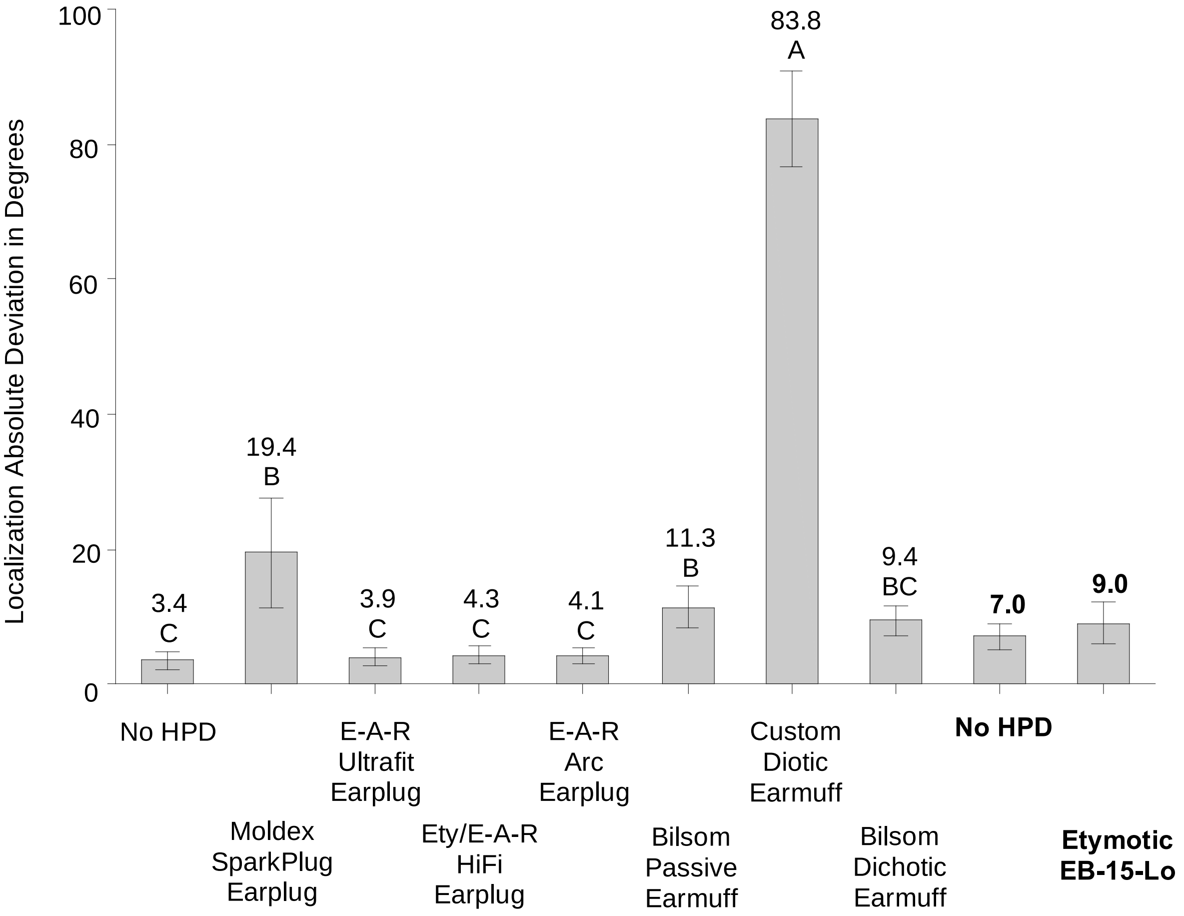


Figure 13. Effect of HPD/listening condition at 60 dBA background noise level (from interaction) on localization absolute deviation in degrees; mean values shown on bars with 95% confidence intervals. Means with the same letter are not significantly different at $p \leq 0.05$ (original experiment conditions only). Data for appended experiment are from a different group of subjects than original experiment, and are shown in **boldface** font.

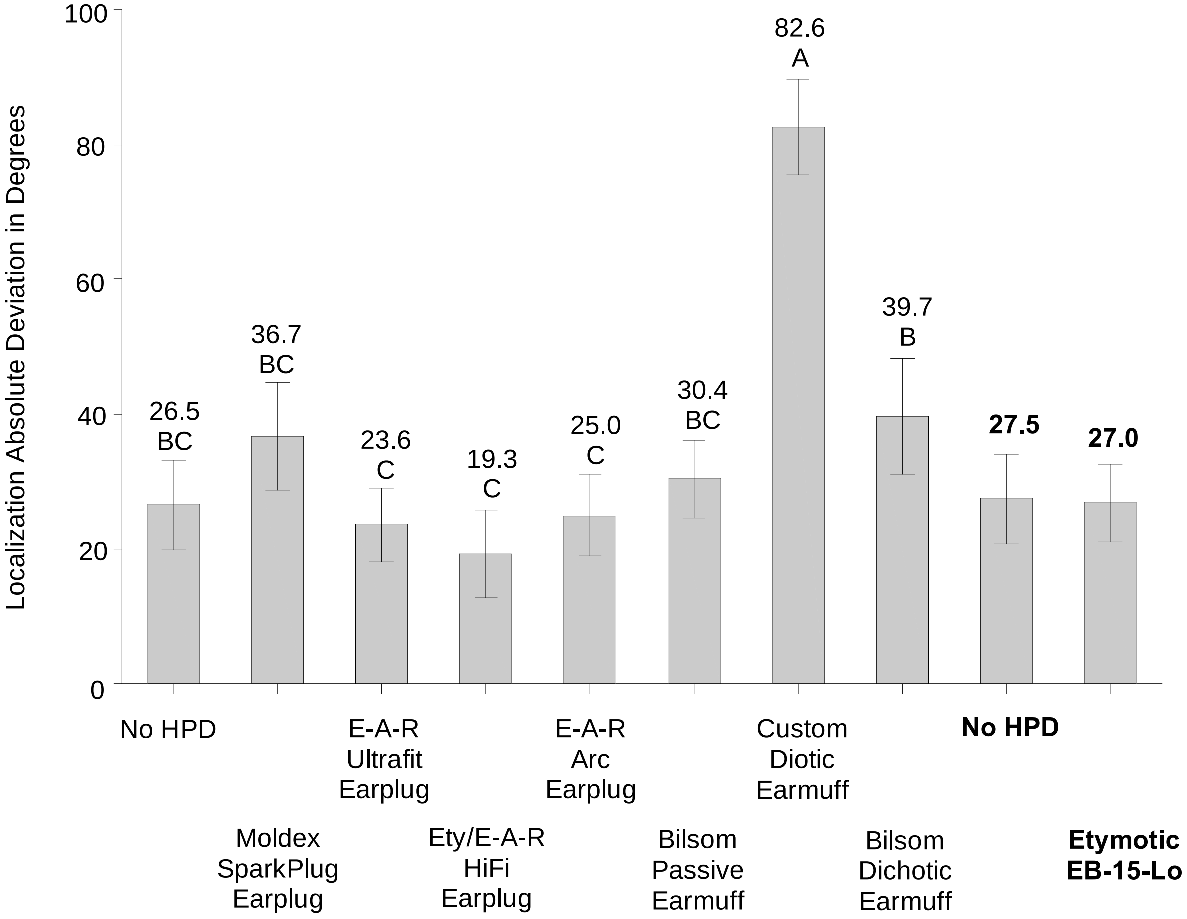


Figure 14. Effect of HPD/listening condition at 90 dBA background noise level (from interaction) on localization absolute deviation in degrees; mean values shown on bars with 95% confidence intervals. Means with the same letter are not significantly different at $p \leq 0.05$ (original experiment conditions only). Data for appended experiment are from a different group of subjects than original experiment, and are shown in **boldface** font.

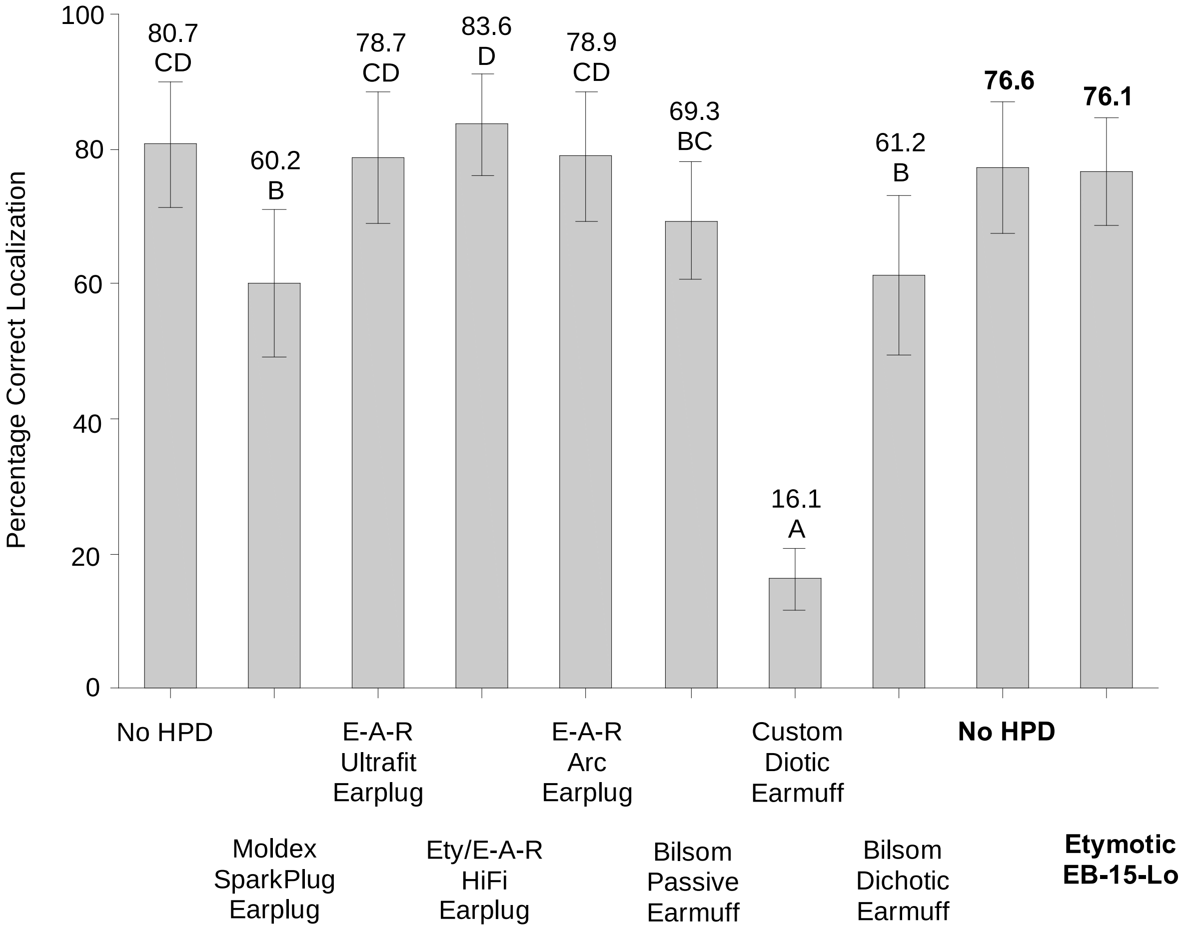


Figure 15. Effect of HPD/listening condition with the standard backup alarm (from interaction) on percentage correct localization; mean values shown on bars with 95% confidence intervals. Means with the same letter are not significantly different at $p \leq 0.05$ (original experiment conditions only). Data for appended experiment are from a different group of subjects than original experiment, and are shown in **boldface** font.

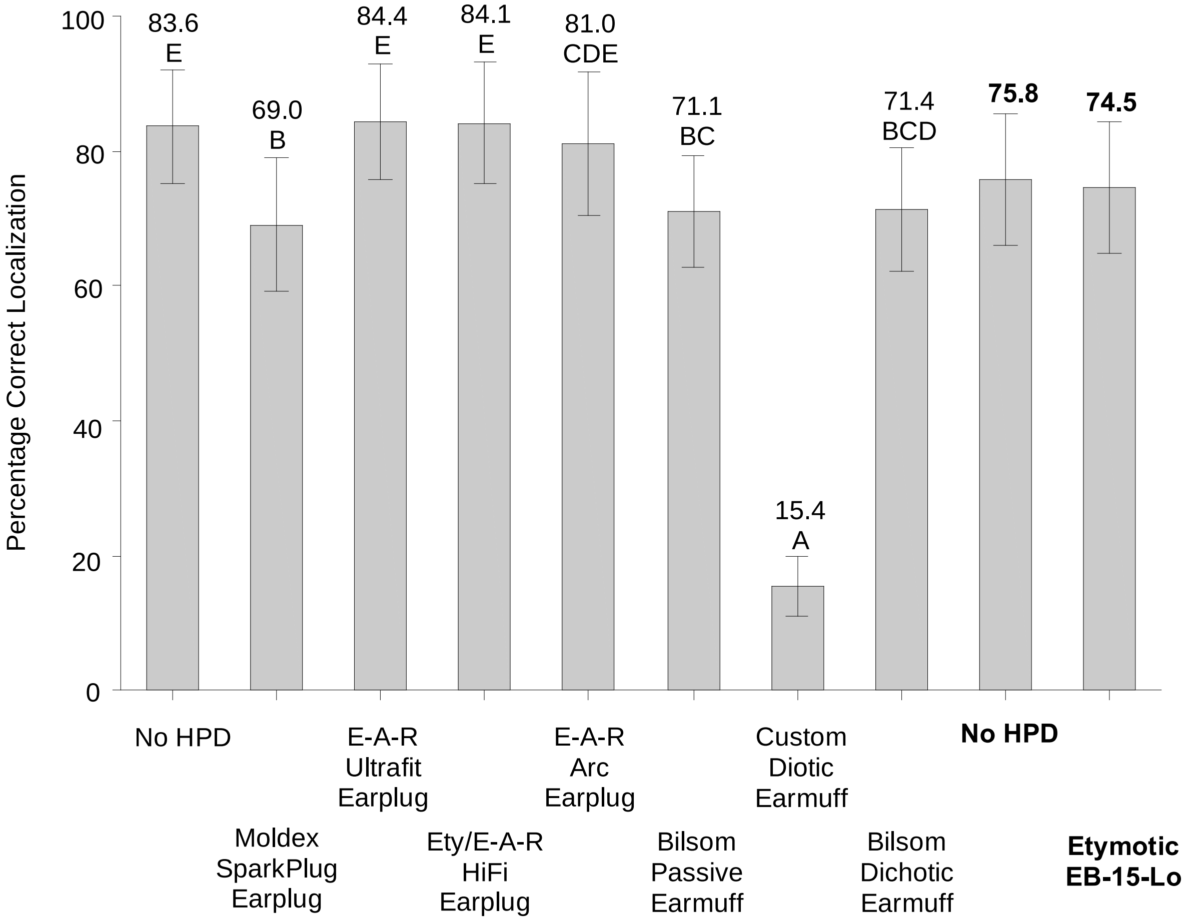


Figure 16. Effect of HPD/listening condition with the spectrally modified backup alarm (from interaction) on percentage correct localization; mean values shown on bars with 95% confidence intervals. Means with the same letter are not significantly different at $p \leq 0.05$ (original experiment conditions only). Data for appended experiment are from a different group of subjects than original experiment, and are shown in **boldface** font.

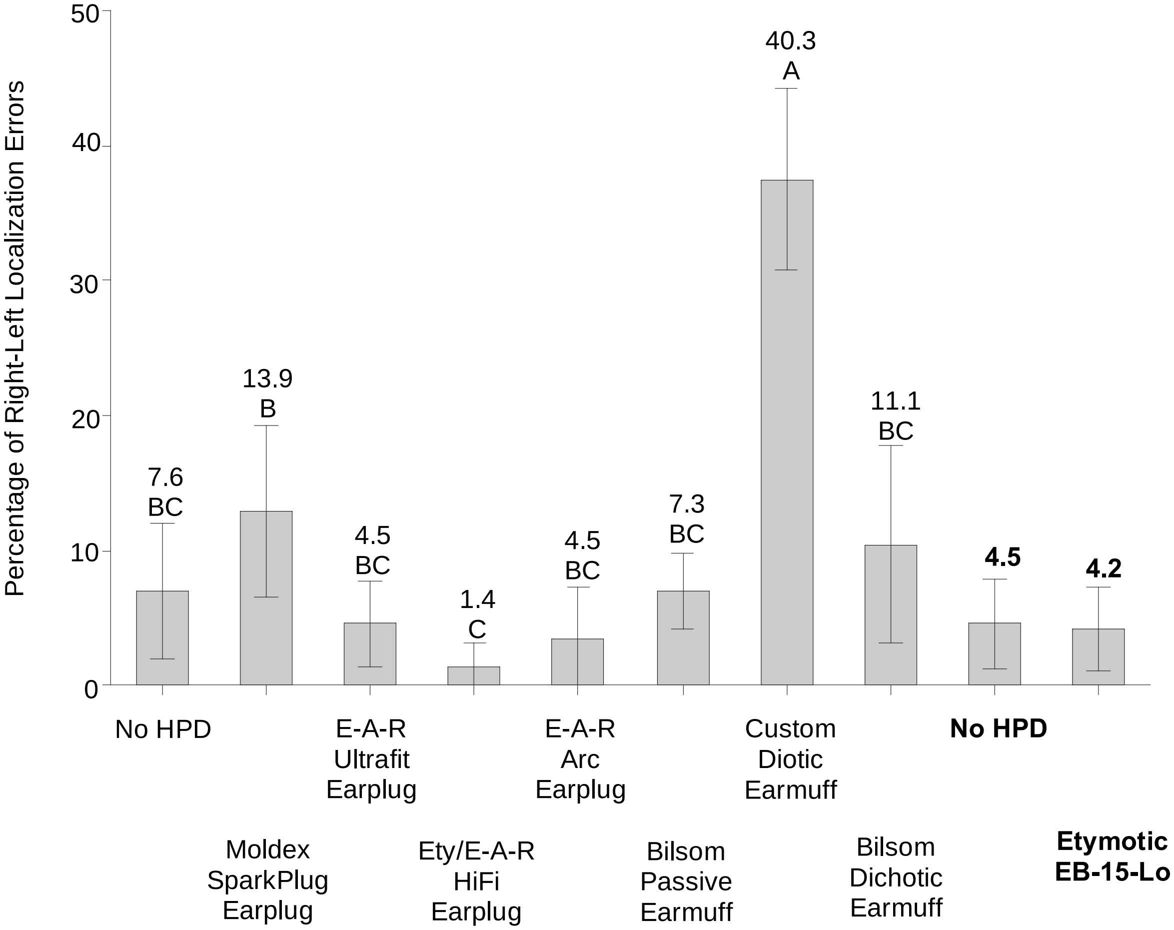


Figure 17. Effect of HPD/listening condition with the standard backup alarm (from interaction) on percentage of right-left localization errors; mean values shown on bars with 95% confidence intervals. Means with the same letter are not significantly different at $p \leq 0.05$ (original experiment conditions only). Data for appended experiment are from a different group of subjects than original experiment, and are shown in **boldface** font.

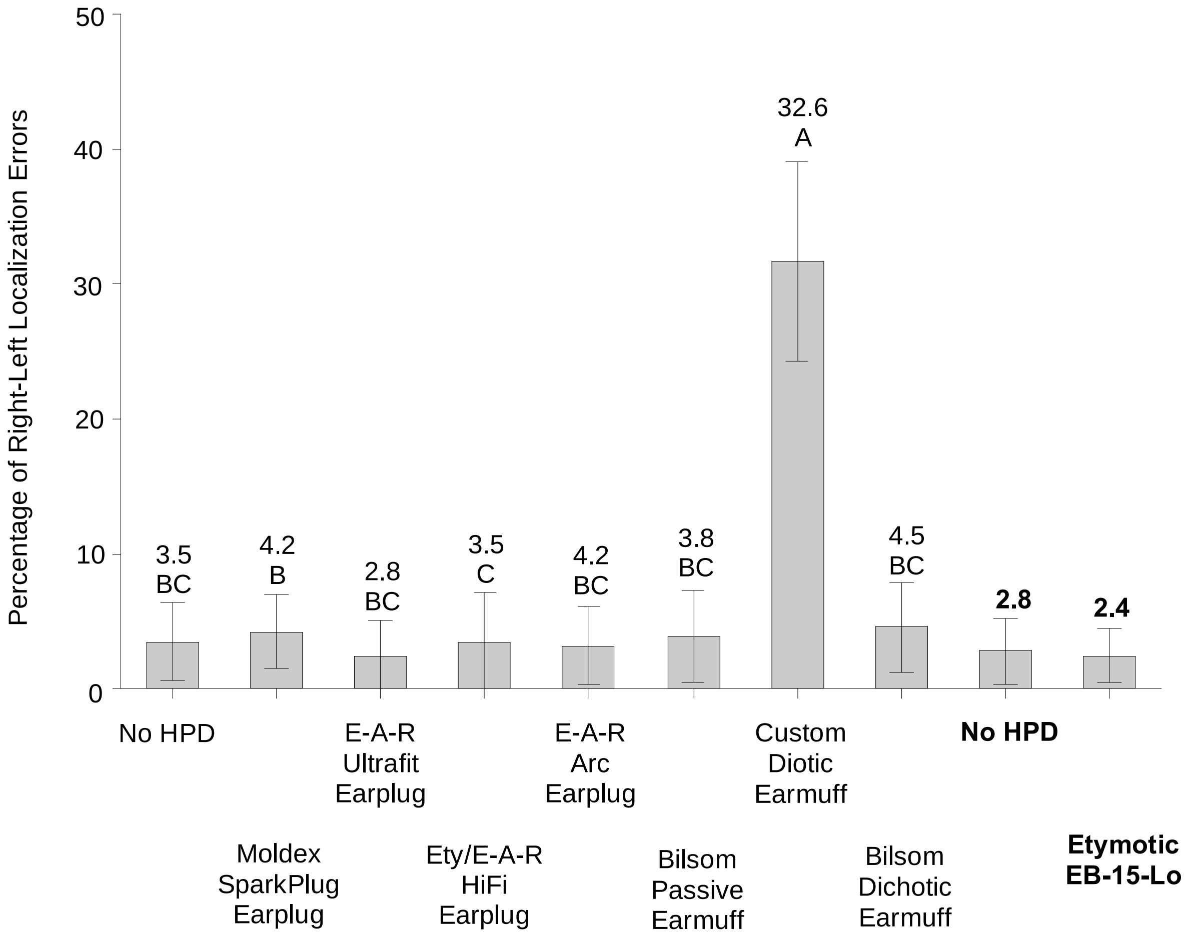


Figure 18. Effect of HPD/listening condition with the spectrally modified backup alarm (from interaction) on percentage of right-left localization errors; mean values shown on bars with 95% confidence intervals. Means with the same letter are not significantly different at $p \leq 0.05$ (original experiment conditions only). Data for appended experiment are from a different group of subjects than original experiment, and are shown in **boldface** font.

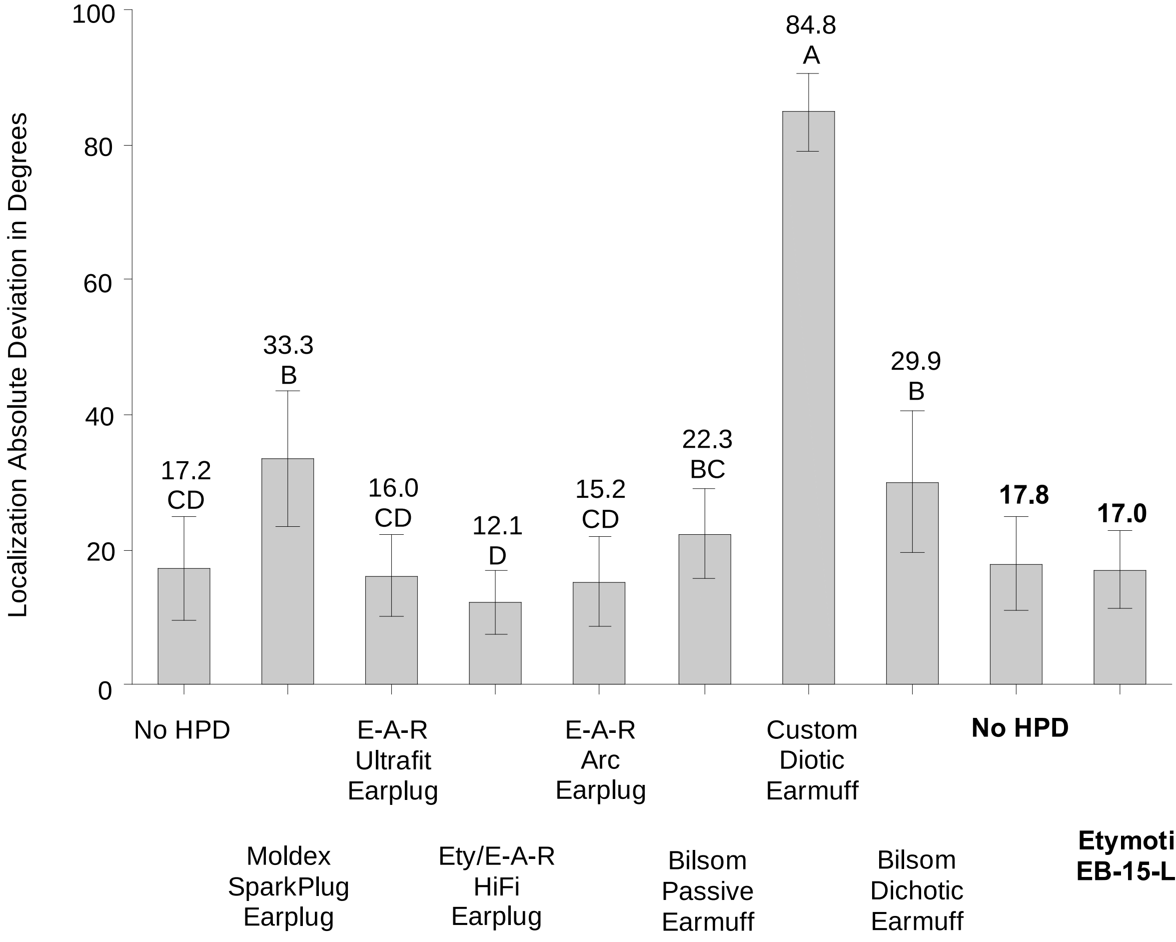


Figure 19. Effect of HPD/listening condition with the standard backup alarm (from interaction) on localization absolute deviation in degrees; mean values shown on bars with 95% confidence intervals. Means with the same letter are not significantly different at $p \leq 0.05$. Means with the same letter are not significantly different at $p \leq 0.05$ (original experiment conditions only). Data for appended experiment are from a different group of subjects than original experiment, and are shown in **boldface** font.

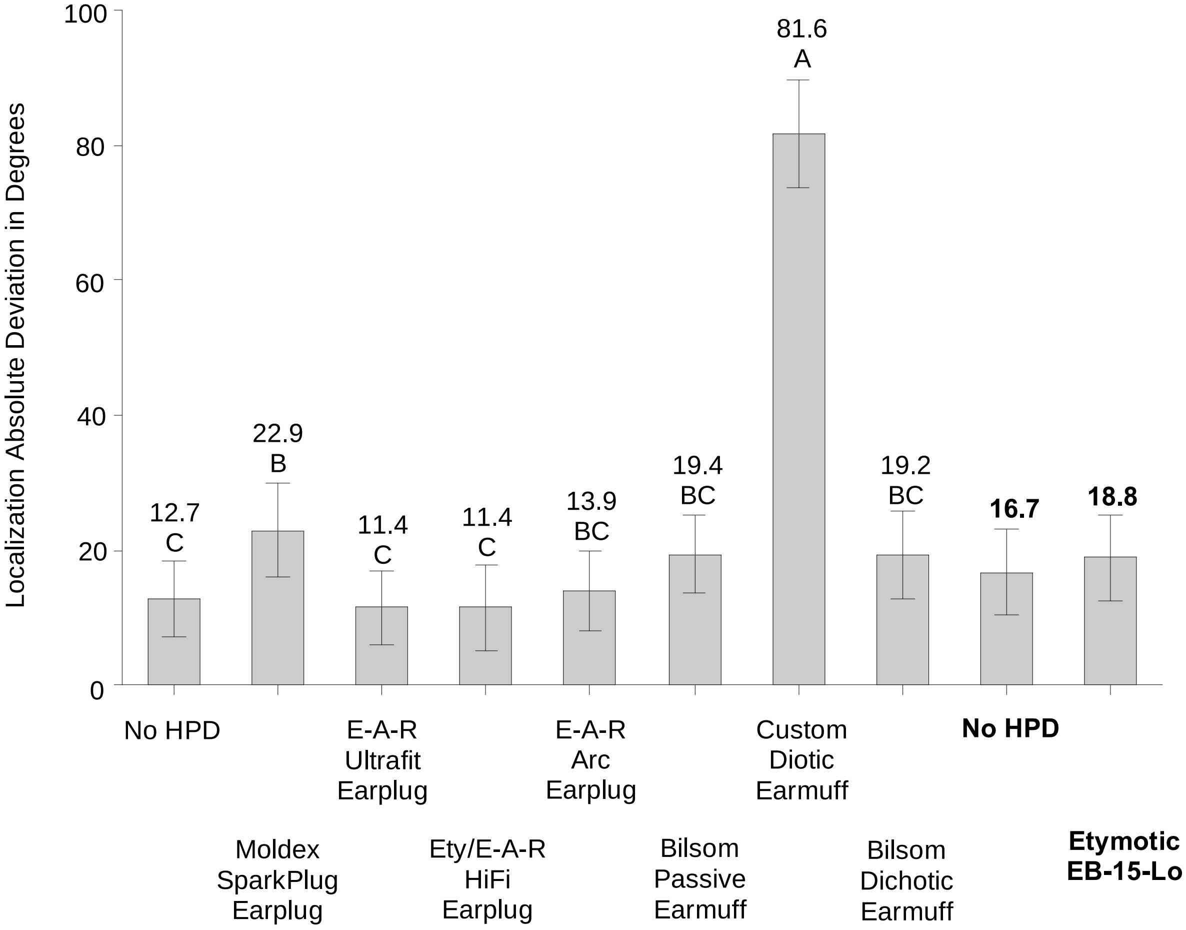


Figure 20. Effect of HPD/listening condition with the spectrally modified backup alarm (from interaction) on localization absolute deviation in degrees; mean values shown on bars with 95% confidence intervals. Means with the same letter are not significantly different at $p \leq 0.05$ (original experiment conditions only). Data for appended experiment are from a different group of subjects than original experiment, and are shown in **boldface** font.

CONCLUSIONS FROM THE GRAPHS

Conclusions from the Original Experiment

The conclusions from the original experiment on the set of 7 HPDs and open ear conditions are discussed in detail in Alali & Casali (in press), and thus will not be repeated here. But in brief summary, the original experiment clearly demonstrated that there were significant differences between certain HPDs, as well as between certain HPDs and the open ear condition, in regard to localization performance in response to backup alarms. In general terms, the electronic *dichotic* earmuff was shown to have no advantage over its passive earmuff counterpart, and the electronic *diotic* earmuff was the poorest device for localization on all 4 dependent measures, and thus its application is contraindicated for backup alarm environs. Among earplugs, the Etymotic/E-A-R Hi-Fi™ earplug ranked as highest in achieving localization performance on most measures, and it was statistically better than the foam earplug in some conditions. Also in certain experimental conditions on the measure of localization absolute deviation, the Hi-Fi™ earplug was significantly better than either the passive muff or dichotic electronic muff. This result points to the importance of pinnae-derived cues which are lost with muff's circumaural enclosures, and perhaps also the importance of the entry of the signal's sound entry into the HPD as close to the ear canal as possible, as is inherent in the design of the Hi-Fi™ earplug as discussed earlier. In any case, more detail is available on all results from the original experiment in Alali & Casali (in press).

Conclusions from the Appended Experiment

The conclusions from the appended experiment are based only on the comparison of the open ear condition to the EB-15 Lo BlastPLG™ condition which were experienced by the second set of 12 subjects in within-subject design. The conclusions for that comparison are quite straightforward, due to the high consistency across all 4 dependent measures and across all combinations of noise level (60 and 90 dBA) and backup alarm type (standard and spectrally-modified). In brief, the EB-15 Lo BlastPLG™ did not show any sizable disadvantage as to localization performance when compared to open ear performance, on any of the dependent measures, based upon the fact that the graphed 95% confidence limits for the EB-15 and the open ear were substantially overlapping in all cases.

More specifically, in terms of the 3 "percentage" measures of localization performance, i.e., percentage correct localization, percentage front-back errors, and percentage right-left errors, the EB-15's advantage (+) to disadvantage (-) when compared to the open ear ranged from +2.8% to -2.4% across the 10 graphs. These magnitude differences are very small, and of little practical importance, lending credence to a conclusion that at least for normal hearers localizing backup alarms in azimuth, the EB-15 Lo BlastPLG™ provides localization performance on an equivalent level to the open ear. In similar fashion, when the dependent measure of localization absolute deviation (in degrees) is considered, the EB-15's advantage (+) to disadvantage (-) when compared to the open ear ranged from +0.8 degrees to -2.1 degrees across the 5 graphs. Again, the very small angular differences between the open ear performance and the EB-15 Lo BlastPLG™ performance supports a conclusion that the EB-15 Lo BlastPLG™ is suitable for providing protection against many noise hazards that surround the presence of backup alarm warning signals which must be localized, and the localization performance for those alarms will be no worse than that of the open ear, at least for normal hearers.

Finally, general comparisons between the 8 HPD/listening conditions of the original experiment and the 2 HPD/listening conditions of the appended experiment may be made by reviewing the graphs numbered 6-20 above. However, drawing any firm conclusions from such a comparison must be done with caution, since the subject groups and randomization orderings for the two experiments were completely different.

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