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The Impact of Hearing Protection on Sound Localization and Orienting Behavior

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Human Effectiveness Directorate
Warfighter Interface Division
Battlespace Acoustics Branch
Wright-Patterson AFB OH 45433-7901

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FOR THE DIRECTOR

//Signed//

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The effect of hearing protection devices (HPDs) on sound localization was examined in the context of an auditory-cued visual search task. Participants were required to locate and identify a visual target in a field of 5, 20, or 50 visual distractors randomly distributed on the interior surface of a sphere. Four HPD conditions were examined: earplugs, earmuffs, both earplugs and earmuffs simultaneously, and no hearing protection. There was also a control condition in which no auditory cue was provided. A repeated measures analysis of variance revealed significant main effects of HPD for both search time and head motion data, indicating that the degree to which localization is disrupted by HPDs varies with the type of device worn. When both earplugs and earmuffs are worn simultaneously, search times and head motion are more similar to those found when no auditory cue is provided than when either earplugs or earmuffs alone are worn, suggesting that sound localization cues are so severely disrupted by double hearing protection that the listener can recover little or no information regarding the direction of sound source origin. Potential applications of this research include high-noise military, aerospace, and industrial settings in which HPDs are necessary but wearing double protection may compromise safety and/or performance.

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The Impact of Hearing Protection on Sound Localization and Orienting Behavior

Brian D. Simpson, Robert S. Bolia, Richard L. McKinley, and **Douglas S. Brungart,** Air Force Research Laboratory, Wright-Patterson Air Force Base, Ohio

The effect of hearing protection devices (HPDs) on sound localization was examined in the context of an auditory-cued visual search task. Participants were required to locate and identify a visual target in a field of 5, 20, or 50 visual distractors randomly distributed on the interior surface of a sphere. Four HPD conditions were examined: earplugs, earmuffs, both earplugs and earmuffs simultaneously (double hearing protection), and no hearing protection. In addition, there was a control condition in which no auditory cue was provided. A repeated measures analysis of variance revealed significant main effects of HPD for both search time and head motion data ($p < .05$), indicating that the degree to which localization is disrupted by HPDs varies with the type of device worn. When both earplugs and earmuffs are worn simultaneously, search times and head motion are more similar to those found when no auditory cue is provided than when either earplugs or earmuffs alone are worn, suggesting that sound localization cues are so severely disrupted by double hearing protection the listener can recover little or no information regarding the direction of sound source origin. Potential applications of this research include high-noise military, aerospace, and industrial settings in which HPDs are necessary but wearing double protection may compromise safety and/or performance.

INTRODUCTION

Many occupational environments are characterized by high levels of noise that necessitate the use of hearing protection devices (HPDs) to enhance overall performance and safety and reduce the risk of noise-induced hearing loss. Although HPDs can effectively attenuate the overall level of ambient noise, they may also have the undesirable consequence of attenuating auditory stimuli that are relevant to an operator's task. For example, they may impair an operator's ability to detect and recognize warning signals (Casali & Wright, 1995; Robinson & Casali, 1995), understand speech (Gower & Casali, 1994; Robinson & Casali, 2000; Van Wijngaarden & Rots, 2001; Wagstaff & Woxen, 2001), identify operationally relevant environmental sounds, and localize sound (see, e.g., Noble, Murray, & Waugh, 1990). Indeed, the inability to identify or localize sounds has been implicated as a contributing factor to occupational accidents (Laroche, 1994; Laroche, Ross, Lefebvre, & Larocque, 1995).

In an effort to more fully understand the impact of HPDs on operator performance, a number of researchers have investigated the degree to which HPDs influence a listener's ability to localize sound (Abel & Armstrong, 1993; Bolia, D'Angelo, Mishler, & Morris, 2001; Bolia & McKinley, 2000; Noble, 1981; Noble et al., 1990; Noble & Russell, 1972; Vause & Grantham, 1999). Results from these studies indicate that sound localization accuracy in both azimuth and elevation is degraded with HPDs as compared with when the listener's ears are unoccluded.

Azimuthal errors were largely attributable to an increase in front/back confusions, suggesting that spectral features in the 3- to 6-kHz region, which are believed to contribute to front/back

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discrimination (Shaw, 1997), were disrupted by the HPDs. However, when continuous stimuli were used and unrestricted head movements were allowed, localization in azimuth was largely restored, suggesting that listeners were able to use the corresponding changes in interaural time and level differences, which mediate localization in the left/right dimension (Mills, 1972), to disambiguate the front/back location of a sound source. The use of exploratory head movements, however, also led to substantial increases in search times. Localization in the vertical dimension, which is mediated by features in the spectral fine structure above approximately 5 kHz (Blauert, 1969/1970; Butler & Belendiuk, 1977; Middlebrooks, 1992), remained relatively poor, however, even when these exploratory head movements were allowed (Noble, 1981; Noble et al., 1990).

Although these effects were found when either earplugs or earmuffs were worn, they were most pronounced with earmuffs, which effectively obscure the pinnae. These findings appear to indicate that high-frequency, pinna-based spectral cues, which mediate localization in the vertical and front/back dimensions, are substantially disrupted by the use of HPDs but that interaural difference cues remain relatively intact.

One issue that these earlier studies failed to consider was the impact of double hearing protection – earplugs and earmuffs worn simultaneously – on sound localization. Double hearing protection is a common practice, and often a requirement, in high-noise environments, including many military, aerospace, and industrial settings (National Institute of Occupational Safety and Health, 1998; U.S. Air Force, 1994). Although it is clear that sound is attenuated to a greater degree with double hearing protection than with either earplugs or earmuffs alone (e.g., see Berger, 1983), the impact of double hearing protection on sound localization per se is unknown. That is, the modifications imposed on the incident sound wave by the two HPDs worn simultaneously may lead to disruptions in localization cues that would not occur when either device alone is worn. Moreover, anecdotal reports from operators in high-noise environments suggest that sound localization is extremely difficult with double hearing protection. These effects need to be quantified.

The effects of HPDs on the orienting behavior of listeners in a sound localization task have not previously been examined in detail. As discussed previously, results in the literature have shown that listeners can improve localization accuracy by employing exploratory head movements to resolve some ambiguous localization cues. However, localization degrades differently in the left/right, front/back, and vertical dimensions when HPDs are worn, suggesting that the relevant cues for sound localization in each of these dimensions are affected differently. It is reasonable, therefore, to assume these differences would be manifested in specific orienting behaviors and that the types of head motion used when orienting to a sound could provide additional information about the ways that HPDs disrupt localization cues. For example, reliable azimuthal cues and relatively ambiguous elevation cues might lead to a target search consisting of a ballistic azimuthal change in head position followed by a serial search of the vertical plane.

The purpose of this investigation was to extend the findings of previous studies assessing the impact of HPDs on sound localization to the case in which listeners wear double hearing protection. A visual search task was employed in which an auditory stimulus was presented at the same location as the visual target in order to cue the target location. Because this task involves the integration of sensory information across the auditory and visual systems, it represents an ecologically valid scenario that is relevant to occupational settings. Target acquisition times and head motion data were collected in order to reveal specific ways in which cues for sound localization are affected by the use of HPDs.

METHODS

Participants

Three men and 4 women, 18 to 39 years of age (mean = 23 years), served as participants in this experiment. All had normal hearing (i.e., bilateral thresholds <15 dB above audiometric zero from 125 to 8000 Hz; American National Standards Institute [ANSI], 1997) and 20/20 (or better) uncorrected vision. All participants were given at least 2 hr of training in the visual search task (with and without auditory cuing and with no hearing protection) prior to formal data collection.

Experimental Design

A within-subjects design was employed in which five auditory conditions were presented. An auditory cue was presented in four conditions: no HPD (unoccluded), foam earplugs (earplugs), circumaural earmuffs (earmuffs), and foam earplugs worn under circumaural earmuffs (earplugs+earmuffs). No auditory cue was presented in the fifth (control) condition (no cue). These five conditions were combined factorially with three set-size conditions (5, 20, or 50 visual distractors) for a total of 15 experimental conditions. The order of conditions was randomized independently for each participant, and only one experimental condition was tested within a single block of trials.

Apparatus

The experiment was conducted in the Air Force Research Laboratory Auditory Localization Facility at Wright-Patterson Air Force Base, as depicted in Figure 1. This facility consists of an anechoic chamber, the walls, floor, and ceiling of which are covered with 1.1-m thick fiberglass wedges to reduce echoes. The low-frequency cutoff of the chamber is 63 Hz. A 4.3-m geodesic sphere with 277 loudspeakers mounted on its surface is housed in the facility. A participant is seated in the facility such that his or her head is positioned in the middle of the sphere. The loudspeakers employed in this experiment (266 in total) surround the participant 360° in azimuth and from approximately –70° to +90° in elevation and are directed inward toward the center of the sphere.

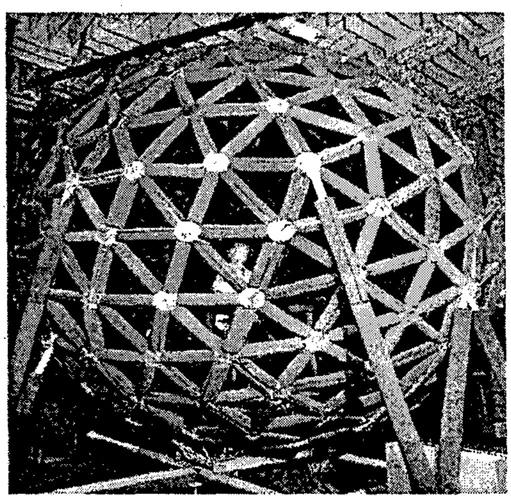

Figure 1. The Auditory Localization Facility in the Air Force Research Laboratory at Wright-Patterson Air Force Base.

The hearing protection devices used in this study were the E.A.R. Classic foam earplug and the Tasco #2900 Sound Shield circumaural earmuffs. The attenuation properties of these devices, worn singly and in tandem, are shown in Figure 2 as measured using the *American National Standards Methods for Measuring the Real-Ear Attenuation of Hearing Protectors* (ANSI, 2002).

Head position data were captured by a Polhemus Fastrak electromagnetic head tracker, the sensor of which was mounted on a cap worn by the participant. Head azimuth and elevation, measured with respect to the forward intersection of the horizontal and vertical planes, was captured during all trials at a rate of 20 Hz.

Stimuli

Mounted directly in front of each loudspeaker on the sphere in the Auditory Localization Facility is a square cluster of four LEDs, which served as visual stimuli in the search task. Each LED cluster subtends a visual angle of approximately 0.5°, and each is individually addressable such that one, two, three, or four LEDs within a cluster may be energized at a time. A visual target was defined by the presence of two or four energized LEDs from a single cluster; a visual distractor was defined by the presence of one or three energized LEDs from a single cluster. Each cluster of four LEDs is randomly oriented such that a participant's judgment regarding the identity of a visual stimulus must be based solely on the number of LEDs energized and not on the spatial pattern of energized LEDs.

The auditory stimulus used to cue the visual target location was a continuous broadband (70 Hz–16 kHz) pink noise generated by the source function on a Hewlett-Packard 35665A Dynamic Signal Analyzer and presented from the loudspeaker at the location of the visual target. In order to ensure that the auditory stimulus

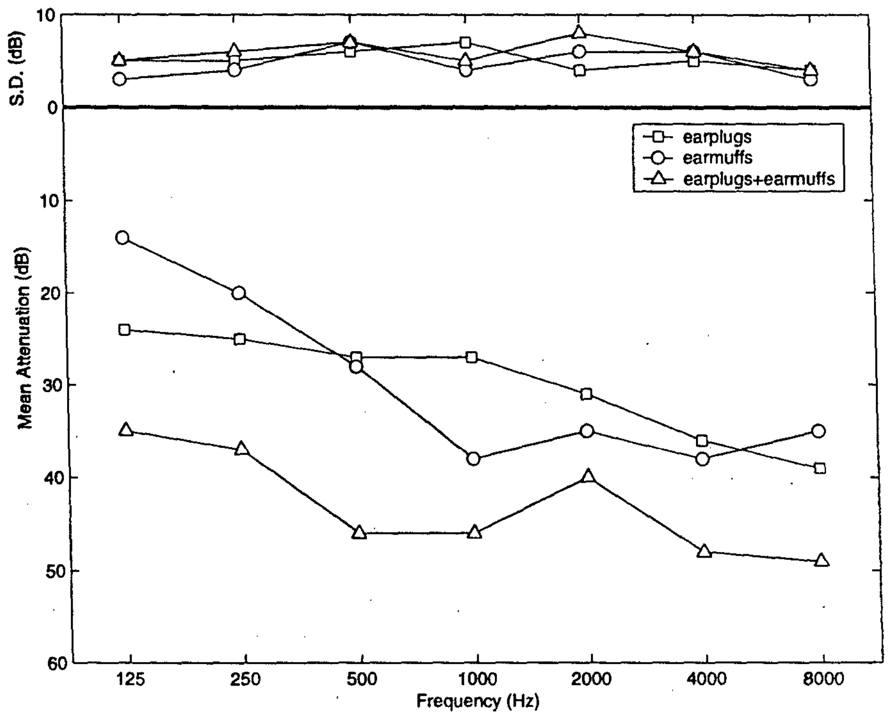

Figure 2. Mean attenuation values, obtained using the real ear attenuation method (ANSI, 2002), are plotted as a function of frequency for the hearing protection devices tested. Standard deviation values are shown in the top panel. Values for the earplugs and earmuffs conditions are averaged across 20 participants, as specified by ANSI, 2002; the value for the earplugs+earmuffs condition is averaged across 10 participants.

was well within each participant's audible range and the audibility of the stimulus did not vary with the HPD configuration in use, individual thresholds were measured for each participant and with each HPD configuration (unoccluded, earplugs, earmuffs, and earplugs+earmuffs) using broadband pink noise in a diffuse sound field. Then, during the visual search task, the auditory stimuli were presented 30 to 35 dB above these measured thresholds for each specific participant and each HPD configuration (i.e., 30–35 dB sensation level). Signal presentation levels are shown for each participant and each HPD configuration in Table 1.

Procedure

The procedure used in this study was derived from an earlier experiment on auditory-cued visual search (Bolia, D'Angelo, & McKinley, 1999). At the inception of each trial, an even number of LEDs (two or four) was energized from the cluster of LEDs located directly in front of the participant (0° azimuth, 0° elevation). The participant demonstrated a readiness to begin

TABLE 1: Presentation Levels (dB SPL)

	Participant							
	1	2	3	4	5	6	7	Mean
Unoccluded	44.3	46.3	50.5	45.8	50.3	47.2	55.0	48.49
Earplugs	74.5	79.5	81.0	74.0	82.5	76.2	80.8	78.36
Earmuffs	80.3	82.0	80.8	76.0	82.7	83.3	93.3	82.63
Earplugs+earmuffs	86.3	89.8	83.8	85.5	92.3	89.3	94.5	88.79

the search task by pressing one of two buttons on a response box indicating the number of LEDs observed at this location, which ensured that the participant was facing forward at the start of the trial. After the button was pressed, LED clusters representing one target and the appropriate number of distractors (randomly distributed throughout the sphere) were energized and, if the condition dictated, an auditory cue was presented simultaneously from the location of the target. On each trial, the participant searched the field of distractors in order to locate the target; once the target was located, the participant was to identify the number of LEDs energized in the target cluster and press the appropriate button on the response box. The search time interval for each trial began when the stimulus was presented and was terminated when the participant pressed the response button.

The experiment was divided into blocks, with each block containing approximately 65 trials. The number of blocks in each of 12 2-hr sessions varied slightly depending on the difficulty of the experimental conditions (and thus the associated search times). In all, two repetitions for each of the 266 target locations were collected in each of the 15 experimental conditions for a total of 7980 responses per participant.

RESULTS

Response Accuracy

Mean percentages of correct responses were analyzed using a 5 (auditory conditions) × 3 (set size) repeated measures analysis of variance (ANOVA). This and all subsequent ANOVAs employed the Huyhn-Feldt correction to guard against violations of sphericity. Neither of the main effects nor the interaction was found to be statistically significant ($p > .05$). Percentage correct ranged from 94% to 99% for each of the conditions tested. These results indicate that participants always performed the search task with a high level of accuracy and that there was no evident trade-off between search time and accuracy, regardless of the experimental manipulation.

Search Time

Mean search times were subjected to a similar 5 × 3 ANOVA, revealing significant main effects of auditory condition, $F(4, 24) = 239.11$, $p < .05$, and set size, $F(2, 12) = 328.75$, $p < .05$, and a significant Auditory Condition × Set Size interaction, $F(8, 48) = 93.84$, $p < .05$. This interaction is illustrated in Figure 3, which shows mean search times plotted as a function of set size in each of the auditory conditions. All the differences that will be described were compared using paired t tests with an alpha level of .05 after application of the Bonferroni correction for multiple tests. In addition, we performed simple linear regression analyses in order to determine the slopes of the functions relating search time to set size.

Search times in the earplugs condition and earmuffs condition were significantly different from those in the unoccluded condition at all levels of set size, but they were not significantly different from each other at any level of set size. In the unoccluded condition, search times remained relatively constant, independent of the set size (slope ≈ 3 ms/distractor). In the earplugs condition, search times increased moderately as the set size was increased (slope ≈ 18 ms/distractor), and in the earmuffs condition, search times increased to a slightly greater extent (slope ≈ 24 ms/distractor) with set size.

These set size effects in the earplugs and earmuffs conditions relative to the unoccluded condition presumably result from the fact that the HPDs distort the incoming waveform such that the cues used for sound localization are disrupted. As the complexity of the visual display increased (i.e., as the set size increased), the reliance on the auditory cue for efficient searches increased, but because the localization cues were less reliable with HPDs, the larger set sizes led to greater search times. The slightly greater slope for the earmuffs condition relative to the earplugs condition is probably attributable to the fact that circumaural earmuffs completely cover the pinnae, thus degrading the pinna-based spectral cues that mediate localization in the front/back and vertical dimensions to a greater degree than do the earplugs. Set size effects, however, were much smaller in all three of these conditions than in the no-cue condition (slope ≈ 267 ms/distractor), which served as a lower bound for performance in the visual search task. These data are consistent with the results of Bolia and McKinley (2000).

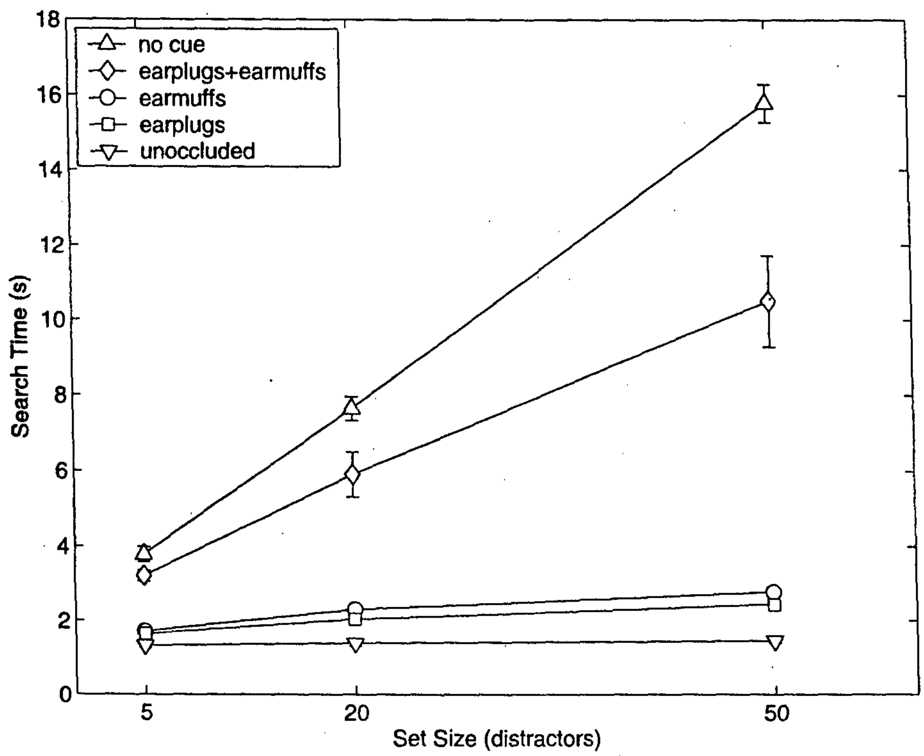

Figure 3. Mean search times in the visual search task plotted as a function of the number of visual distractors for each of the HPD configurations tested. Error bars indicate ±1 standard error. Note that these error bars are small relative to the size of the symbols in the unoccluded, earplugs, and earmuffs conditions.

Perhaps the most interesting finding is that the pattern of results in the earplugs+earmuffs condition was more similar to that found in the no-cue condition than to that found in any of the other conditions. Search times in the earplugs+earmuffs and no-cue conditions were significantly different from the search times in the other three conditions at all levels of set size, but they were not significantly different from each other except at the largest set size. Search times in the earplugs+earmuffs condition increased at a rate of 162 ms/distractor, an order of magnitude greater than search times found for the single-HPD conditions, suggesting that localization cues were severely disrupted when double hearing protection was worn. Anecdotal reports from the participants were consistent with these results: They indicated that when both earplugs and earmuffs were worn simultaneously, the auditory stimulus did not appear to provide any directional information.

Head Motion in Azimuth

The total angular extent of head motion in azimuth was computed on a trial-by-trial basis and averaged across participants in each experimental condition. These data, depicted in Figure 4, were subjected to a 5 (auditory conditions) × 3 (number of distractors) repeated measures ANOVA, revealing significant main effects of auditory condition, $F(4, 24) = 38.78, p < .05$, and number of distractors, $F(2, 12) = 20.86, p < .05$, and a significant Auditory Condition × Number of Distractors interaction, $F(8, 48) = 11.77, p < .05$. We examined this interaction in greater detail by performing tests of simple main effects of set size at each level of auditory condition and of auditory condition at each level of set size. Tests of set size were found to be significant for the earmuffs, earplugs+earmuffs, and no-cue auditory conditions, indicating that in each of these conditions the total angular extent of head

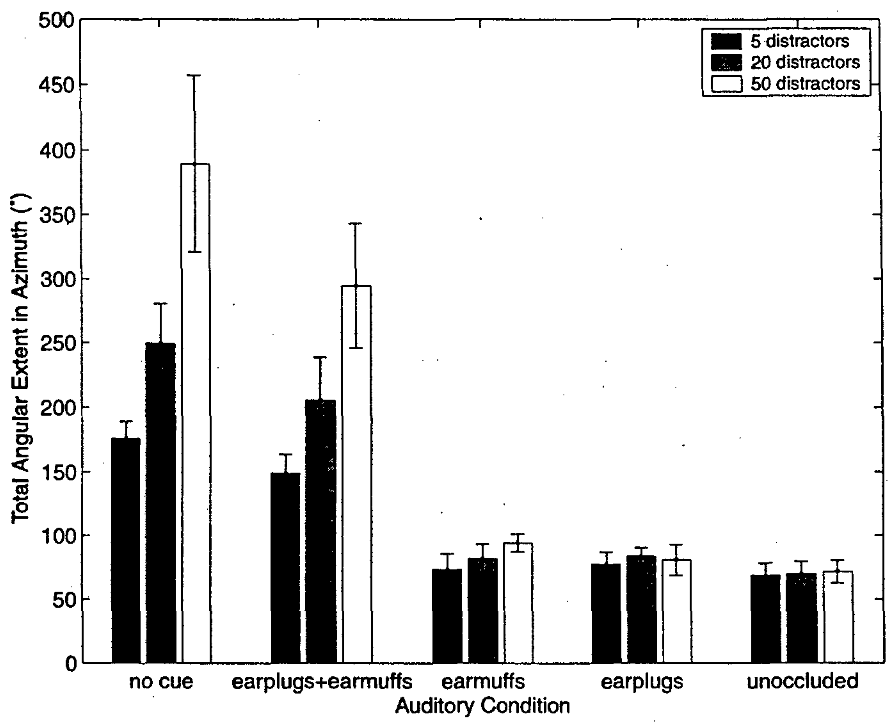

Figure 4. Total angular extent of head movements in azimuth for all experimental conditions examined. Error bars indicate ±1 standard error.

motion in azimuth varied with set size. However, tests of set size yielded no significant differences in the unoccluded and earplugs conditions, suggesting that head motion was independent of set size for these conditions.

Tests of simple main effects of auditory condition revealed significant differences at each level of set size. Post hoc paired *t* tests with Bonferroni corrections demonstrated that azimuthal angular extent was not significantly different between the earplugs+earmuffs and no-cue conditions at any level of set size but that each was significantly different from that in the unoccluded, earplugs, and earmuffs conditions at every level of set size. These results suggest that the search task with an auditory cue and double hearing protection was most similar to the case in which no auditory cue was provided, which again is consistent with the reports of the participants.

Head Motion in Elevation

As with azimuth, the total angular extent of head motion in elevation was computed on a trial-by-trial basis and averaged across participants in each experimental condition. These data, shown in Figure 5, were subjected to an ANOVA analogous to that described earlier, which revealed significant main effects of auditory condition, $F(4, 24) = 40.84$, $p < .05$, and set size, $F(2, 12) = 26.52$, $p < .05$, and a significant Auditory Condition × Set Size interaction, $F(8, 48) = 16.45$, $p < .05$. We further investigated this interaction by performing tests of simple main effects of set size at each level of auditory condition and of auditory condition at each level of set size. Tests of set size were found to be significant only for the earmuffs, earplugs+earmuffs, and no-cue auditory conditions, indicating once again a set size effect for these conditions but not for the unoccluded and earplugs conditions. Tests of simple main effects of auditory condition revealed significant differences at each level of set size. As was the case for azimuthal angular extent, post hoc paired *t* tests with Bonferroni corrections demonstrated that

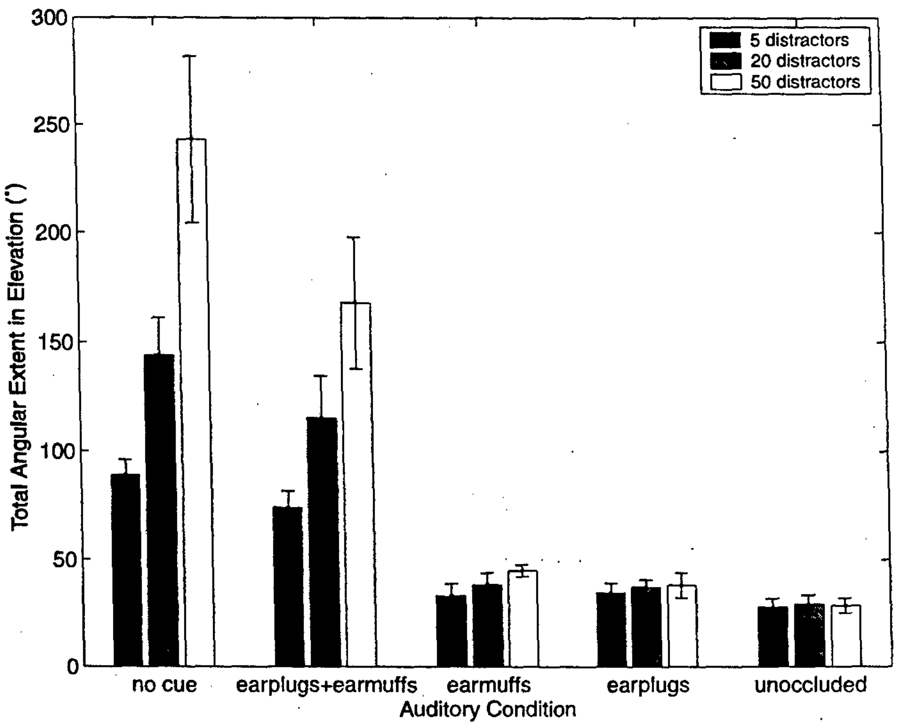

Figure 5. Total angular extent of head movements in elevation for all experimental conditions examined. Error bars indicate ±1 standard error.

angular extent in elevation for the earplugs+earmuffs and no-cue conditions was significantly different from that in the other three auditory conditions (unoccluded, earplugs, and earmuffs) at every level of set size and, as before, the earplugs+earmuffs condition was not significantly different from the no-cue condition at any level of set size.

These data indicate that head motion in both azimuth and elevation was affected by HPDs, suggesting that localization cues may be disrupted in all dimensions with hearing protection. Moreover, these head motion data are consistent with the search time data. Specifically, both measures suggest that two general classes of search patterns existed in this study. This can be more easily seen in Figure 6, in which head position is plotted as a function of time to provide a more detailed view of search patterns. Each column represents a single trial in which a target, located at 124° azimuth and 45° elevation, is presented in a field of 50 distractors for a single auditory condition. (Note that this was a particularly difficult condition because of the number of distractors and the location of the target.) The upper panels depict head position in azimuth; the lower panels depict head position in elevation. All data are from a single representative participant.

These data support the notion that the search patterns fell into two general classes. The earmuffs, earplugs, and unoccluded conditions (the three rightmost columns in Figure 6) appear to fall into one class of search patterns, in which the search was characterized by a fairly deliberate head movement to the location of the target, resulting in relatively short search times. This suggests that the localization cues in these conditions were not substantially disrupted by the HPDs.

Within this class of search patterns, however, differences across conditions can also be seen if one examines head position in the vertical plane. Specifically, for conditions in which spectral cues were expected to be distorted (i.e., the earplugs and earmuffs conditions), search patterns in the

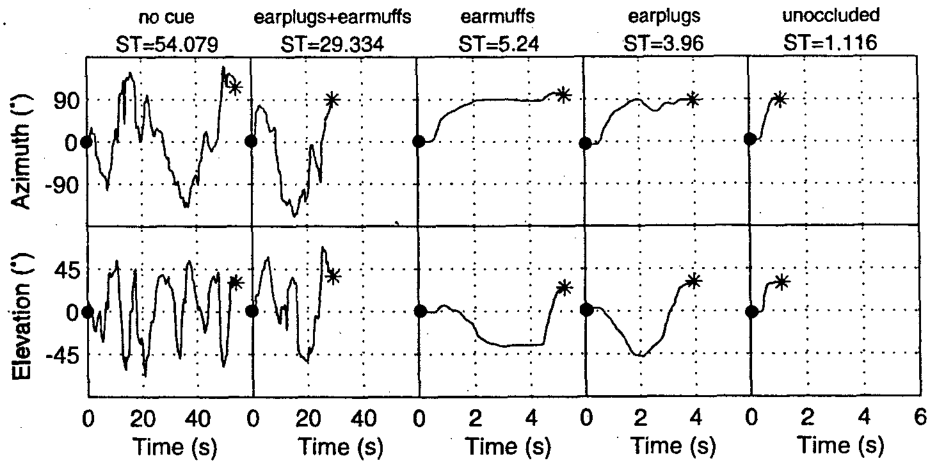

Figure 6. Head motion in azimuth (upper row) and elevation (lower row) plotted as a function of time for a single trial (visual target at 124° azimuth and 45° elevation, presented in a field of 50 distractors) in each of the five different HPD configurations. Filled circles indicate the participant's head position at the beginning of the trial (0° azimuth, 0° elevation); asterisks indicate the participant's head position at the time a response was made. All data are from the same participant. Note that the time scale for the earmuffs, earplugs, and unoccluded conditions differs from that of the no-cue and earplugs+earmuffs conditions.

vertical dimension are somewhat less deliberate than in azimuth: The initial vertical head movement is not in the direction of the target, suggesting that some disruption of the cues mediating localization in the vertical dimension took place. Horizontal head motion in these conditions, however, appears to fall along a relatively straight path directly to the target azimuth, suggesting that the cues mediating horizontal localization remained salient whether they resulted from reliable static or dynamic cues. In contrast, in the unoccluded condition, in which no distortion of localization cues was introduced, both horizontal and vertical head motion appear to follow a direct path to the target location, suggesting that the participant was able to reliably make use of the cues available for sound localization. These head motion data are consistent with the results of Bolia and Nelson (2001).

The no-cue and earplugs+earmuffs conditions (the two leftmost columns in Figure 6) appear to fall into a separate class of search patterns, in which head movements do not appear to be deliberate: Participants appear to have been systematically searching the visual field, but the search patterns appear to be unrelated to the location of the auditory stimulus, resulting in greater angular extent of head motion and longer search times. The similarity in search patterns across these two conditions suggests that localization cues in the earplugs+earmuffs condition are severely degraded and provide little information to the participant about the location of the target. That is, in the absence of auditory cues, participants appear to adopt a strategy in which they systematically search the visual field for the target. When an auditory cue is presented but participants are wearing both earplugs and earmuffs, a similar search pattern is seen, suggesting that they are getting very little in the way of reliable localization cues.

DISCUSSION

Based on the results from earlier studies on localization with single HPDs (e.g., Bolia et al., 2001; Noble, 1981), a degradation in sound localization performance, particularly in the vertical plane, was expected with double hearing protection. However, the results from the present study suggest that the use of double hearing protection degrades sound localization to a much greater degree than what had been expected. It is unlikely that a disruption in spectral cues alone could explain why search times in the earplugs+earmuffs condition approached those found in the no-cue condition. Moreover, head position data for the earplugs+earmuffs condition indicate that the angular extent of head motion in both azimuth *and* elevation approach that of the no-cue condition. These results suggest that the donning of double hearing protection may have disrupted interaural difference cues in addition to spectral cues.

One plausible explanation for the large search times seen in the earplugs+earmuffs condition is that the level of the stimulus transmitted via the ear canal (i.e., air-conducted sound) could have been reduced so dramatically by double hearing protection that the transmission of the stimulus through alternative pathways (e.g., bone and tissue conduction) may have contributed significantly to the overall perceived stimulus. The transfer functions through these alternative pathways to the cochleae are unknown, but the lack of acoustic isolation between the cochleae resulting from bone conduction would probably lead to a disruption in interaural difference cues and also lead to stimulus properties that are inconsistent with those of the airborne sound. The combination of air-conducted and bone-conducted sound could result in ambiguous directional information, and thus reduced localizability, thereby providing no benefit to the participant performing the search task. Similar degradations in binaural and spatial hearing have been found in listeners with conductive hearing losses and have been attributed to a disruption in localization cues resulting from increases in the ratio of bone-conducted sound to air-conducted sound (see, e.g., Noble, Byrne, & Lepage, 1994; Zurek, 1986). These issues must be examined in greater detail in future studies in order to more fully understand the factors contributing to this effect.

SUMMARY

The results of the experiment described herein demonstrate that the use of HPDs may substantially degrade sound localization performance in an auditory-cued visual search paradigm. Moreover, different HPD configurations affected search performance differentially, as revealed by search time and head motion data. Performance in the double hearing protection condition (earplugs+earmuffs) was almost as poor as performance in the control condition (no cue), suggesting that the localization cues normally present in air-conducted sound were severely disrupted when double hearing protection was used. Search times with double hearing protection were more similar to those in the no-cue condition than to those in any of the other conditions in which an auditory cue was presented. Similarly, measures of head motion in both azimuth and elevation revealed search patterns consistent with a severe disruption of spectral cues and interaural difference cues. These results were surprising and suggest that double hearing protection may have attenuated the auditory stimulus entering through the ear canal to such a degree that nonlocalizable sound arriving through alternative pathways (e.g., bone conduction) may have contributed significantly to the overall stimulus.

IMPLICATIONS FOR DESIGN

The high noise levels that exist in many operational environments necessitate the use of double hearing protection in order to prevent noise-induced hearing loss, but the impact of these high-attenuation HPDs on communication effectiveness and spatial hearing pose a difficult problem for the human factors practitioner. As we have noted, merely increasing the attenuation of the airborne sound (e.g., through the use of more robust HPDs) will do little to mitigate the impact of sound entering the system through bone and tissue conduction. Moreover, noise control engineering efforts focused on the source of noise, although necessary, may be insufficient. New technologies must be developed that are capable of adequately attenuating the bone-conducted sounds at the operator. Well-fitting, sound-attenuating helmets, facial masks, and body suits may help to insulate the body from acoustic energy, thereby reducing the energy transmitted to the auditory system. However, at the extremely high noise levels found in many operational environments, even these measures provide only a modicum of protection.

A better understanding of the characteristics of bone conduction may lead to the development of appropriate algorithms for active cancellation of bone-conducted sound analogous to those algorithms employed in active noise reduction systems for airborne sound. Because the current level of understanding does not support this approach, operators in high-noise environments should, at a minimum, be informed of the potential deleterious effects on spatial hearing of wearing double hearing protection in order to avoid reliance on impoverished information.

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