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The Effects of Hearing Protectors on Auditory Localization: Evidence from Audio-Visual Target Acquisition

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Response times (RT) in an audio-visual target acquisition task were collected from 3 participants while wearing either circumaural earmuffs, foam earplugs, or no hearing protection. Analyses revealed that participants took significantly longer to locate and identify an audio-visual target in both hearing protector conditions than they did in the unoccluded condition, suggesting a disturbance of the cues used by listeners to localize sounds in space. RTs were significantly faster in both hearing protector conditions than in a non-audio control condition, indicating that auditory localization was not completely disrupted. Results are discussed in terms of safety issues involved with wearing hearing protectors in an occupational environment.

auditory localization hearing protection visual search

1. INTRODUCTION

Over the last three decades, a great deal of research has been conducted on hearing conservation programs and the design and evaluation of hearing protection devices (HPDs). Contemporary hearing protectors effectively

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reduce the amount of ambient noise that reaches the auditory system, and as such are used effectively in occupational environments to prevent noise-induced hearing loss and to enhance task performance and personal safety. Surprisingly, very little attention has been paid to the potential safety hazard inherent in the disruption of auditory localization by hearing protectors, in spite of the fact that it is well-known that the physical properties of the individual HPDs result in modification of the monaural and binaural spectral cues important for localization (Wightman & Kistler, 1997). The issue of mislocalization of routine sounds and warning signals in the workplace is recognized in some occupational health arenas. Workplace accidents, and even fatalities, have been attributed to the inability to hear or localize critical audio cues in the immediate environment (Laroche, Ross, Lefebvre, & Larocque, 1995). Hearing protector designers appear to be moving slowly toward ameliorating this situation.

Only a few researchers have examined the effects of conventional hearing protectors on localization acuity. Atherley and Noble (1970) had listeners localize a 1000-Hz pure tone in the horizontal plane with and without a circumaural HPD, and found that while wearing the HPD: (a) more errors were made and (b) listeners more frequently perceived the source as coming from the hemifield contralateral to its actual position. The latter effect was unexpected—under normal listening conditions listeners almost never make such contralateral errors. Furthermore, the reason for the commission of such errors is not well understood. For a 1000-Hz tone, the dominant cue for localization is the difference in source arrival times between the two ears (Wightman & Kistler, 1992). Why this cue should be disrupted by the presence of a circumaural earmuff is not at all clear. Moreover, in a study by Abel and Hay (1996), a similar effect was found with a stimulus frequency of 4000-Hz but not with a 500-Hz stimulus, suggesting that interaural differences in intensity rather than time are disrupted. However, the effect at 1000-Hz is robust, and has been replicated, both in an anechoic environment (Noble & Russell, 1972) and in a reverberant room (Atherley & Else, 1971).

In a later study, Noble and Russell (1972) examined the combined effects of different stimuli and different types of hearing protection on localization acuity. Participants localized a broadband noise or a 1000-Hz pure tone while wearing either circumaural earmuffs or earplugs. Listeners made more errors when the stimulus was broadband, suggesting disruptions of the spectral cue. They performed better with earplugs than with earmuffs,

but not as well as in the unoccluded condition, a difference that the authors attribute to an increase in the number of front-back confusions in the earmuff condition. Finally, listeners in this study made no more contralateral errors with earplugs than they did without hearing protection. Whereas this would tend to suggest that, in situations in which the accurate localization of auditory events is crucial, earplugs should be employed in lieu of earmuffs, later research (Noble, 1981) demonstrated that, when free head movements are permitted, listeners localize as accurately in azimuth with either earplugs or earmuffs as they do without occlusion. However, response times (RT) are slower when hearing protection is worn, and the addition of the dynamic head motion cue does not restore proficient localization in the vertical plane.

In a more recent investigation, Vause and Grantham (1999) had participants localize a brief broadband sound (the cocking of an M-16 assault rifle), presented over loudspeakers arrayed in the horizontal plane, while wearing different types of hearing protection commonly worn by U.S. Army combat personnel. Specifically, listeners wore either a combat helmet, a foam earplug, a custom-molded musician's earplug, or one of the two possible helmet-earplug combinations. These researchers reported an increase in average localization error for all hearing protector conditions over the unoccluded control condition, as well as increases in the number of front-back confusions, the latter implicating a disruption of the spectral cues.

Bolia and his colleagues (Bolia, D'Angelo, Mishler, & Morris, in press) have extended these findings by examining the effects of hearing protectors on the localization of sound sources whose locations were not restricted to the horizontal plane. In this investigation, listeners localized brief broadband sounds presented over 272 loudspeakers distributed over the entire range of azimuths ($\pm 180°$), with elevations ranging from -75 to $+90°$, while wearing either a foam earplug or a circumaural earmuff. Results indicated gross disturbances in both the horizontal and vertical dimensions, with azimuth and elevation error increasing by 5 and 15°, respectively, and the percentage of front-back confusions increasing by 25%.

One problem with drawing conclusions about real-world phenomena from such experiments is that they reflect neither the complexity of real-world tasks nor the abundance of non-auditory sensory cues available in any occupational context. The objective of the present study was to evaluate the effects of hearing protection on a more ecologically valid task: aurally-aided visual search (Bolia, D'Angelo, & McKinley, in press). In this case, it is not

localization acuity per se that is being investigated, but rather how degradations in localization acuity contribute to the time required for a listener to locate and identify an audio-visual target among a background of visual distractors.

2. METHOD

2.1. Participants

Three males between the ages of 21 and 35 participated in the experiment. One of the participants was recruited from the volunteer participant pool maintained at the Air Force Research Laboratory, one was a first lieutenant in the United States Air Force, and one was one of the principal investigators. All participants had pure tone thresholds of less than 15 dB above audiometric zero and uncorrected 20/20 vision.

2.2. Apparatus

All testing was conducted in the Air Force Research Laboratory's Auditory Localization Facility (ALF) at Wright-Patterson Air Force Base, OH, consisting of a geodesic sphere of radius 2.3 m, centered within a cubic anechoic chamber of side 6.7 m. The aluminum struts of the sphere were covered with 2.5-cm acoustic foam in order to minimize reflections. Located at each of the sphere's 277 vertices, spaced approximately 15° apart, was a Bose 4.5" Helical Voice Coil full-range loudspeaker (Model 118038), facing the center of the sphere. Mounted 5 cm above the anterior surface of each loudspeaker was a square array of light-emitting diodes (LEDs), each of which emitted a 620-nm wavelength light at a luminance of about 200 mL (Perrott, Cisneros, McKinley, & D'Angelo, 1996).

The two HPDs employed in this investigation were the E.A.R. Classic foam earplug and the Tasco Sound Shield circumaural earmuff. The frequency-dependent attenuation of these devices was determined using the real-ear method (Standard No. ANSI S12.6-1984; American National Standards Institute, 1984), and is depicted graphically in Figure 1.

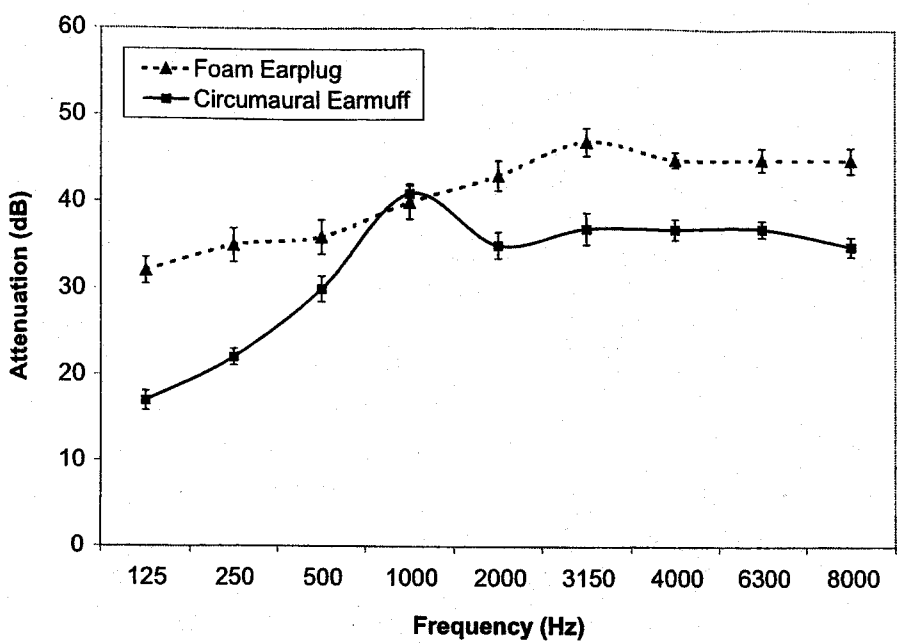

Figure 1. Sound attenuation as a function of frequency for each of the hearing protection devices employed in the experiment. Error bars indicate one standard error of the mean in each direction.

2.3. Procedures

At the beginning of each session, the observer was seated at the center of the ALF, with the room darkened and all of the LEDs turned off. Before the commencement of testing in the occluded conditions, the participant donned earmuffs or inserted earplugs under the supervision of the experimenter. At the inception of each trial, an even number of LEDs was energized at the fixation point (0° azimuth, 0° elevation). Before the participant was permitted to continue, he was required to correctly indicate, via a two-button response switch, the number of LEDs energized (i.e., 2 or 4). This guaranteed that the participant was always facing forward at the beginning of each trial. Once this was accomplished, the target and distractor LED clusters were energized simultaneously, and the observer began his search. The clusters at the distractor locations contained either 1 or 3 energized LEDs. The target cluster always contained either 2 or 4 energized LEDs, and the search task involved finding the target and indicating the number of LEDs that were

energized using a two-button switch (see Figure 2 for a schematic illustration of the visual identification task). All targets fell within ±180° in azimuth, and between −70 and +90° in elevation. In the auditory conditions, an acoustic stimulus (pink noise, 40 dB SL) emanated from the same location as the target, and remained on until the completion of the trial. RT and correctness of response were stored for each trial.

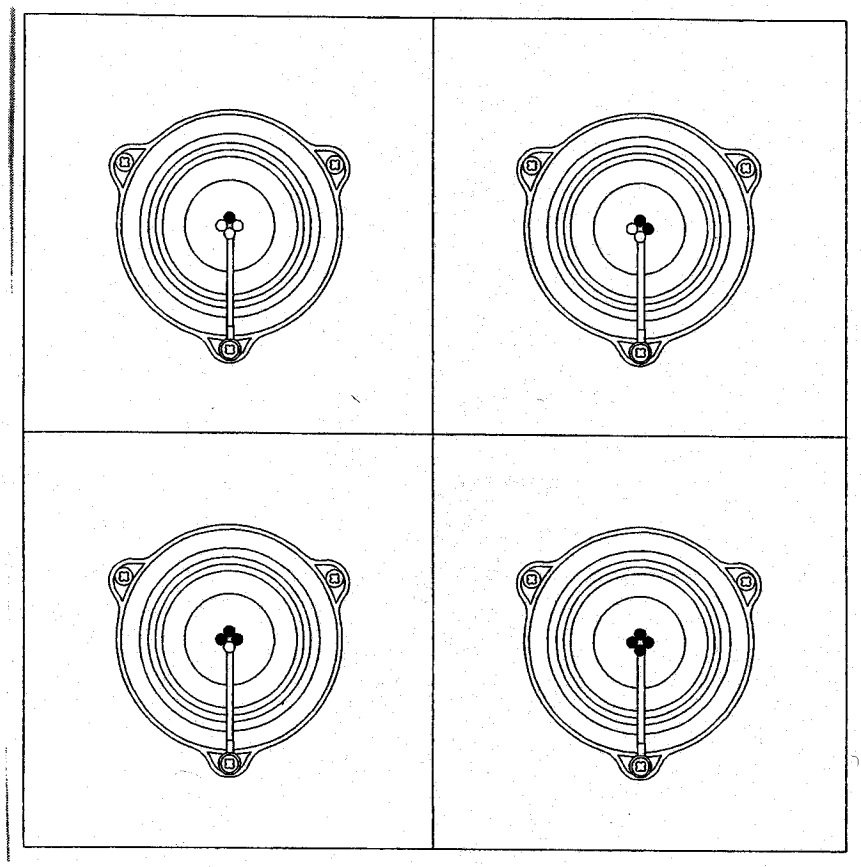

Figure 2. Schematic diagram of the loudspeaker and light-emitting diode (LED) array configuration for all possible targets and distractors. Filled circles indicate energized LEDs. Target configurations are depicted on the right side of the figure, distractor configurations on the left.

2.4. Experimental Design

Four sensory conditions of non-audio, unoccluded, earplugs, or earmuffs were combined factorially with three distractor set sizes of 5, 10, or 25

distractors. In the non-audio condition, the purpose of which was to set an upper bound for RTs in the types of target searches under investigation, participants completed a simple visual search task. In the unoccluded audio condition, participants performed the same task, augmented by an audio cue co-located with the visual target. The two occluded conditions were identical to the unoccluded with the exception that participants wore either earplugs or earmuffs. In all of the conditions, each of the 266 loudspeakers in the ALF was used once as a target location. The distribution of distractor locations was random.

Participants were given 60 practice trials on each of the conditions prior to testing. Subsequent to practice, each of the participants completed 5 blocks of 266 trials (one trial per target location) for each of the 4 (sensory conditions) × 3 (set sizes) = 12 possible treatments. The order in which the conditions were run was randomized.

3. RESULTS

3.1. Percent Correct

Mean percentages of correct responses were analyzed using a 4 (sensory condition) × 3 (set size) repeated measures analysis of variance. Neither of the main effects nor the interaction were found to be statistically significant ($p > .05$). Percent correct varied 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 tradeoff between search time and accuracy, regardless of the experimental manipulation.

3.2. Response time

Mean RTs for all of the experimental conditions were analyzed using a 4 × 3 repeated measures analysis of variance similar to that used in the analysis of the percent correct data, revealing significant main effects of sensory condition, $F(3, 6) = 1763.56$, $p < .05$, and set size, $F(2, 4) = 1473.40$, $p < .05$, and a significant sensory condition × set size interaction, $F(6, 12) = 826.44$, $p < .05$. The interaction is illustrated in Figure 3, in which RT is plotted as a function of set size for each of the four sensory conditions.

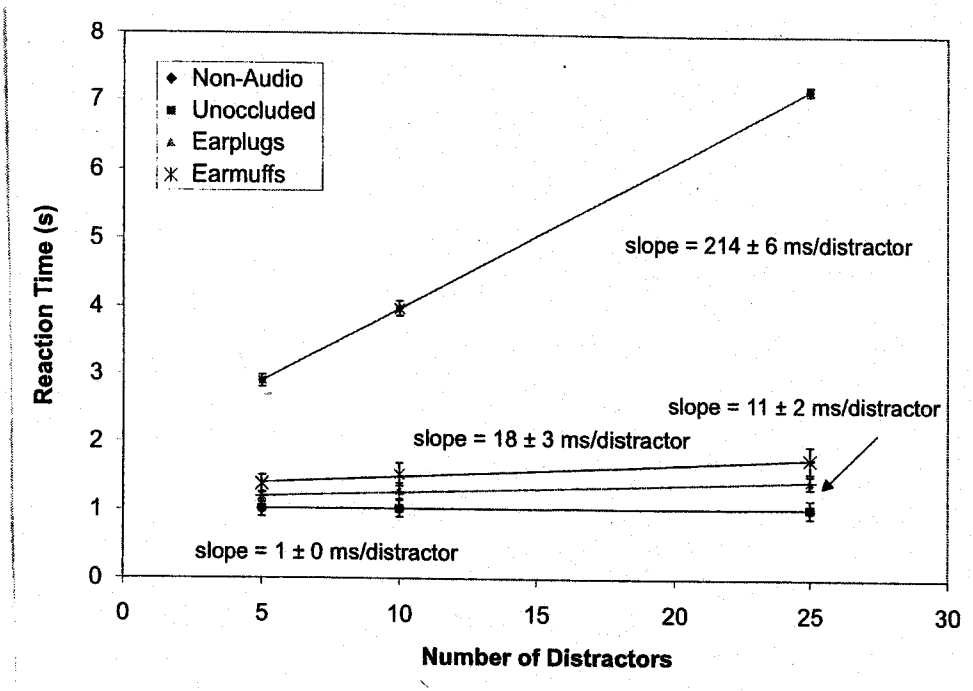

Figure 3. Response time (RT) as a function of distractor set size for each of the four sensory conditions. The markers represent actual data, ± standard errors. The lines are the best-fit lines determined by simple linear regression on the mean RT data. The slopes of the regression lines (± standard errors) are also given, and represent the increase in RT for each additional distractor added to the set.

The interaction was further investigated by tests of simple main effects of the sensory conditions as a function of set size, and of the set sizes as a function of sensory condition. All simple main effects were statistically significant ($p < .01$), excepting the unoccluded and hearing protector conditions analyzed as functions of set size. Post hoc t tests corrected for family-wise α-error were performed to compare pairwise the mean RTs for all of the set sizes within each sensory condition for which simple main effects were significant, and for all sensory conditions within each set size. Furthermore, simple linear regression analyses were performed on the mean response times as a function of set size for each sensory condition. For the non-audio and the two hearing protector conditions, the RT versus set size functions did not differ significantly from linearity ($p < .05$). For the unoccluded condition, this difference was marginal ($p = .08$).

Within the non-audio condition, all effects of set size were significant ($p < .01$). As Figure 3 illustrates, RTs in this condition increased linearly

with set size. The regression analysis revealed a rate of increase of 214 ms per distractor ($t = 357.6$, $p < .05$).

Under the unoccluded and hearing protector conditions, none of the effects of set size reached statistical significance at the .01 level, implying that, regardless of the complexity of the target and distractor array, RT was approximately constant. This interpretation is supported by the regression analyses, which yielded RT versus set size functions with slopes of 0 ms per distractor for the unoccluded condition ($t = 3.27$, $p = .08$), 11 ms per distractor for the earplug condition ($t = 5.9$, $p < .05$), and 18 ms per distractor for the earmuff condition ($t = 6.7$, $p < .05$).

Within each set size, RTs in the non-audio condition were significantly slower than in all of the other conditions ($p < .01$). Within no set size did RTs in the earplug condition differ from those in the earmuff condition ($p > .01$). Performance in the unoccluded condition differed significantly from that in the earplug condition only in the 10 and 25 distractor cases. Differences between the unoccluded and earmuff conditions were significant for each set size ($p < .01$).

4. DISCUSSION

Most of the studies on the effects of hearing protection on auditory localization have reported gross disturbances in the ability of listeners to determine the location of a sound source. These studies have typically been performed under conditions of less than optimal audio cues (e.g., pure tones), restricted or no head movements, and lack of visual feedback. In an occupational environment, many sounds are broadband or are associated with objects that are either immediately visible or that can be brought easily into an operator's field of view by a brief head movement. The results of the present investigation indicate that, whereas RTs in a task requiring accurate localization are significantly slower when the operator is wearing hearing protection, this difference is probably negligible when compared to the performance advantage obtained in any of the audio conditions over the non-audio control. However, it should be noted that the definition of "negligible" depends on the particular application domain, and it may be the case that differences on the order found here (200–300 ms) are critical in some occupational environments.

This research suggests that hearing protection should not occasion mislocalization of sounds in most occupational environments, provided that

they are of sufficiently long duration and are spectrally complex. Whereas these criteria are met by many occupational sounds, they are certainly not definitive. More work needs to be undertaken to determine how listeners perform when the sounds they are required to localize are of shorter duration, potentially eliminating the dynamic cue afforded by head motion, or of more limited bandwidth, degrading the spectral cues necessary to localize sounds outside of the horizontal plane. Furthermore, research is needed in the area of localization in noisy environments, and on the effects of ambient noise on localization by listeners wearing hearing protectors. Finally, all of the studies conducted up to this point have involved normal hearing listeners. It is not known whether these results generalize to hearing-impaired populations.

An additional question is whether listeners learn to localize proficiently and rapidly when they wear hearing protectors for hours at a time over the course of several months, as is often the case in occupational environments. If the degradation in performance is due exclusively to disruption of the spectral cues, recent research by Hofman, Van Riswick, and Van Opstal (1998) suggest that they might. Hofman and his colleagues modified the structure of the pinnae of 4 participants by having them wear custom-made molds, fitting snugly into the concha, for up to 6 weeks. These molds provided a significant disruption of the spectral cues used for localization in elevation, and, initially, the ability to localize in elevation was completely obliterated. However, after 19–39 days, localization proficiency was almost completely restored. Additionally, once the adaptation had occurred, listeners were able to localize equally well with or without the molds, implying that humans are able to maintain multiple spectral filter sets simultaneously. Whether or not this occurs in occupational environments in which hearing protectors are worn remains an open question.

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