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The Effect of Microphone Placement on Localization Accuracy with Electronic Pass-through Earplugs

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Many audio applications make use of electronic pass-through listening devices that intercept the signals entering a listener's ears and electronically process them in real time. An important issue in designing such devices is ensuring that they maintain the listener's natural ability to localize sound sources. Previous research suggests that optimal localization requires a completely-in-the-canal (CIC) design with a system bandwidth of at least 13 kHz. However, most practical designs have to make engineering compromises in terms of bandwidth and/or microphone placement that cause some degradation in localization performance. This paper compares open-ear localization to localization with seven different pass-through devices: five custom-molded earplugs with different microphone configurations; a CIC hearing aid; and an electronic earmuff. The results show that earplugs interfere substantially less with localization than earmuffs, but that the frequency response has a larger impact on performance than does physical configuration in earplug systems that are bandlimited to frequencies below 6 kHz.

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THE EFFECT OF MICROPHONE PLACEMENT ON LOCALIZATION ACCURACY WITH ELECTRONIC PASS-THROUGH EARPLUGS

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ABSTRACT

Many audio applications make use of electronic pass-through listening devices that intercept the signals entering a listener's ears and electronically process them in real time. An important issue in designing such devices is ensuring that they maintain the listener's natural ability to localize sound sources. Previous research suggests that optimal localization requires a completely-in-the-canal (CIC) design with a system bandwidth of at least 13 kHz. However, most practical designs have to make engineering compromises in terms of bandwidth and/or microphone placement that cause some degradation in localization performance. This paper compares open-ear localization to localization with seven different pass-through devices: five custom-molded earplugs with different microphone configurations; a CIC hearing aid; and an electronic earmuff. The results show that earplugs interfere substantially less with localization than earmuffs, but that the frequency response has a larger impact on performance than does physical configuration in earplug systems that are bandlimited to frequencies below 6 kHz.

1. INTRODUCTION

Many areas of applied acoustics are based on systems that intercept audio signals that listeners would normally hear, process them, and output them again to the listener's ears in real time. The classic example is the hearing aid, which shifts the dynamic range of an arbitrary audio signal into a region that is both comfortable and clearly audible for a hearing impaired listener. Electronic pass-through systems also have important applications in hearing protection devices, where they can be used in conjunction with passive attenuation materials to produce earplugs or earmuffs that allow listeners to hear low-level sounds at normal listening levels but protect them from sounds that are loud enough to cause hearing damage.

An important factor to consider in the design of pass-through listening devices is how well they preserve the directional audio cues that listeners normally use to determine the locations of sound sources. These cues are vitally important because they allow listeners to maintain their situational awareness in complex acoustic environments and to respond quickly and correctly to sounds such as sirens and alarms that alert them to the locations of dangerous objects and events.

Unfortunately, it is often impossible to preserve unadulterated localization cues within the constraints inherent in the design of practical pass-through listening devices. Previous research suggests that two requirements must be met to maintain completely accurate sound localization cues in these systems. The first involves the placement of the input microphones. Head-related transfer function (HRTF) measurements made with blocked meatus have shown that microphones must be placed several millimeters inside the ear canals before they fully capture the directional cues that listeners use to localize sounds [1]. This implies that optimal localization performance can only be achieved with so-called "CIC" earplug systems that fit completely inside the listener's ear canals. The second requirement for maintaining accurate localization cues in pass-through systems is related to transducer bandwidth. King and Oldfield [2] have shown that optimal localization performance can be achieved only with broadband stimuli that have at least 13 kHz of bandwidth. This implies that localization accuracy will be somewhat degraded by the use of a pass-through listening device unless the microphone, amplifier, and driver in that device are all capable of producing 13 kHz of bandwidth.

Because most of the available transducers that meet the size and power constraints required for CIC designs are not capable of producing 13 kHz of bandwidth, many current CIC hearing aid designs are not generally able to fully preserve sound localization performance in normal-hearing listeners [3]. CIC hearing protectors may also have difficulty providing enough acoustic isolation to adequately protect listeners from damaging levels of ambient noise. Consequently, most current pass-through listening devices incorporate compromises in microphone placement and/or transducer bandwidth that lead to a degradation in localization accuracy.

Without some information on how microphone placement and bandwidth actually influence localization performance, it is difficult for audio designers to know how engineering tradeoffs that are made in these areas might eventually impact sound localization. In this paper, we examine the effects that five different external microphone configurations had on localization accuracy with a custom-molded earplug design that fully filled the concha of the listeners. We also compare these results to localization performance with commercially available CIC hearing aids, with commercially available electronic earmuffs, and with unoccluded ears. The results provide insights on the relative impact that microphone placement and transducer bandwidth have on localization performance with pass-through listening devices.

2. METHODS

Participants: Two different groups of listeners participated in the experiment. The first group (Group A) consisted of four principle investigators from our laboratory (3 male, 1 female), including three of the co-authors of this study. The second group (Group B) consisted of five paid volunteers (4 male, 1 female). Both groups had normal hearing (< 15 dB HL from 500 Hz to 8 kHz), and all of the listeners had previous experience in localization tasks.

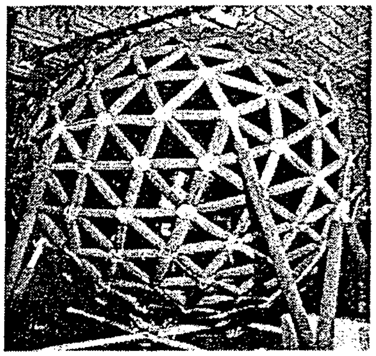

Figure 1: *Listener in the Auditory Localization Facility (ALF) at Wright-Patterson AFB. See text for details.*

Apparatus: The experiments were conducted in the Air Force Research Laboratory's Auditory Localization Facility (ALF), shown in Figure 1. The ALF is an aluminum-frame geodesic sphere, 4.6 m in diameter, with 4.5-in loudspeakers (Bose 118038) located at each of the 272 vertices on its inside surface. This arrangement provides a roughly even distribution of loudspeaker locations with approximately 15° of great-circle arc between each pair of adjacent speakers. Acoustic reflections have been minimized by housing the ALF inside a 6.7 m x 6.7 m x 6.7 m anechoic chamber and by covering its aluminum frame structure with 2.5 cm acoustic foam. Each loudspeaker in the ALF is equipped with a cluster of four independently selectable red LEDs that can be used to provide visual information to a listener standing on an adjustable platform with his or her head at the center of the sphere.

Stimuli: The stimuli in the experiment were derived from a broadband noise signal that was digitally sampled with a 24-bit real-time digital signal processor (Tucker-Davis RP2) and switched on and off within each trial with one of two different gating patterns: in the "short" conditions, the stimuli were generated by gating the noise signal into a short burst with a total length of 250 ms including 25 ms $\cos^2$ on and off ramps; in the "long" or "continuous" conditions, the stimuli were generated by gating the noise on with a 25 ms $\cos^2$ ramp, maintaining the noise at a constant level until the listener responded, and then gating the noise off with a 25 ms $\cos^2$ ramp.

Pass-through Devices: The two different listener groups were tested with two different sets of conditions. Group A (the principle investigators) participated in a total of seven conditions. The first five conditions involved custom-molded earplugs that were manufactured by Westone Laboratories specifically for the purposes of this study. The plugs were similar in shape to the standard Westone Style No. 40 solid full-thickness sound attenuating earplugs (left panel of Figure 2), but they also incorporated both an external microphone for picking up the ambient sound field (Knowles FG-3329) and an internal driver (Knowles BK 8507) for electronically transmitting the sounds picked up at the external microphone back into the listener's ear canals. A total of twenty sets of plugs were used in the study, one set for each listener with each of the following five external microphone configurations (which are illustrated in the right panel of Figure 2): **P-16**, where the microphone was encased in a cylindrical sponson that held it at a 16° angle relative to the flat outer surface of the plug, with the front of the microphone flush with the upper front corner of the plug (just outside and below the crus of helix); **P-45A**, where the microphone was encased in a sponson that held it at a 45° angle relative to the flat outer surface of the plug and extended it roughly 1 cm away from the concha (as seen in the front view in Figure 2); **P-45B** where the microphone was in a semi-recessed sponson that held it at a 45° angle just off the surface near the back and top of the plug (over the center of the cymba concha); **P-90A**, where the microphone was embedded flush with and perpendicular to the flat outer surface near the front and bottom of the plug (roughly midway between the tragus and the antitragus); and **P-90B**, where the microphone was embedded flush with and perpendicular to the flat outer surface near the back and top of the plug (over the cymba concha). In each case, the signals from the external microphones were passed through to the drivers mounted inside the plugs at approximately the same listening level that would have occurred if no plugs were worn. This pass-through circuit was tested with a hearing aid analyzer (AudioScan RM500) and was found to have a steep rolloff at frequencies above 6 kHz due to the limited response range of the drivers used in the plugs. In addition to the five plug configurations, the listeners in Group A participated in two additional control conditions: **Open**, where they wore no earplugs and listened to broadband noise stimuli, and **6 kHz**, where they wore no earplugs but listened to stimuli that were bandlimited to 6 kHz (with a 191-point FIR lowpass filter implemented in the RP2 DSP processor) and masked by a 6 kHz highpass-filtered noise (which was played continuously through a powered loudspeaker near the bottom of the ALF) in order to simulate open-ear hearing with the limited bandwith of the electronic pass-through earplugs[1].

Group B (the paid volunteers) participated in the following three conditions: **CIC**, where the listeners wore disposable CIC hearing aids (Songbird Digital) set in the low-gain "Enhancer" fitting range (note that the manufacturer reports a bandwidth from 200 Hz to 7400 Hz on these devices); **Earmuff**, where the listeners wore electronic earmuffs (Sordin Supreme) with the gain set such that the sound levels inside the earcups were approximately the same as the sound level outside the earcups; and **Open**, where no devices were worn.

Procedure: At the start of each experimental session, the experimenter supervised the insertion of the correct devices into the listener's ears before taking them into the ALF facility. Once in the facility, the listener's first task was to put on a hat equipped with an electromagnetic position sensor (Polhemus Fastrak) and calibrate the headtracker by fixating on an LED at the loudspeaker at 0° azimuth and 0° elevation and pressing a handheld response switch. After this initial calibration, head position information was polled every 100 ms by the control computer and used to illuminate an LED cursor at the loudspeaker located directly in front of the listener's head. At the same time, a long or short stimulus was presented at approximately 70 dB SPL from a loudspeaker that was randomly selected from the 232 speaker locations that were above -45° in elevation. The listener then responded to this stimulus by moving the head-slaved cursor to the perceived location of the sound and pressing the response switch. The response location was then recorded, and the listener was prompted to reorient the head-slaved LED cursor to the loudspeaker at 0° azimuth and 0° elevation and press the response switch to start the next trial.

The listeners from Group A participated in one 50-trial block of long stimuli and one 50-block trial of short stimuli in each of

[1] The high-pass noise masker was added as an extra precaution to make sure that the listeners were unable to take advantage of any transient high-frequency components that would have been filtered out by the bandlimited pass-through listening devices.

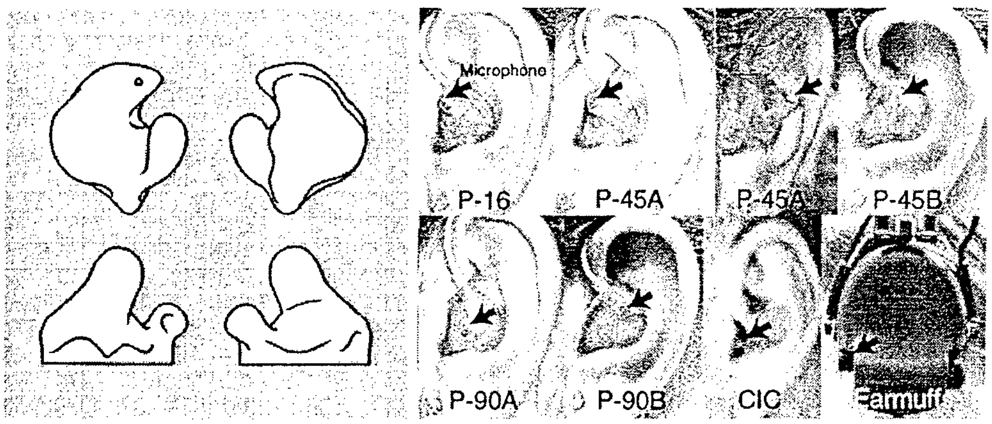

Figure 2: *The left panel shows four profile views of the Westone No. 40 Earmold Style, which is similar to the one used for the plugs tested in this study (picture used with permission from Westone Laboratories, Inc.). The right panel shows microphone placement in the different electronic pass-through listening devices tested in the experiments. The first six subpanels (P-16 to P-90B) show side-on views of the five different custom plug configurations tested in the main experiment, as well as a front-on view of the P-45A configuration. The last two subpanels show the microphone placement with the CIC hearing aid, where the microphones were recessed inside the ear canals, and with the electronic earmuffs, where the microphones were located in front of the lower portions of the earcups.*

the seven conditions of the experiment, with the order of the conditions randomized across subjects. The listeners from Group B participated in one 150-trial block of long stimuli and one 150-trial block of short stimuli in each condition. These longer blocks were separated into three 50-trial sub-blocks, with short rest periods between.

3. RESULTS AND DISCUSSION

The overall results of the experiment are illustrated in Figure 3. The top panel shows the overall angular error, which was defined by the angle of the arc between the stimulus location and the response location on the surface of the sphere. The second panel shows the left-right error, which was determined by projecting the stimulus and response locations into the front hemifield and measuring the absolute azimuth difference between the two projected locations. The third panel shows the front-back error, which was determined by projecting the stimulus and response locations into the left hemifield and measuring the absolute azimuth difference between the two projected locations. And the last panel shows the up-down error, which was defined by the absolute difference in elevation between the stimulus and response locations.

The data for each type of error were also analyzed with two-factor within-subject repeated-measures ANOVAs. These ANOVAs were conducted separately for the Group A and Group B listeners, with stimulus length and type of listening device serving as the two independent variables in each analysis. The results of these ANOVAs showed that the main effect of stimulus length was significant at the $p < 0.05$ level for all types of errors in both groups except for the up-down error in Group B, and that the main effect of listening device was significant for all types of errors in both groups except for the left-right error in Group A. The interaction between stimulus length and listening device was not found to be significant for any type of error in Group A, but it was significant for the angular, left-right, and front-back errors in group B. In cases where significant effects were found, a Fisher LSD post-hoc analysis was used to determine which listening conditions were significantly different from one another. The horizontal bars in Figure 3 indicate groups of conditions that were not significantly

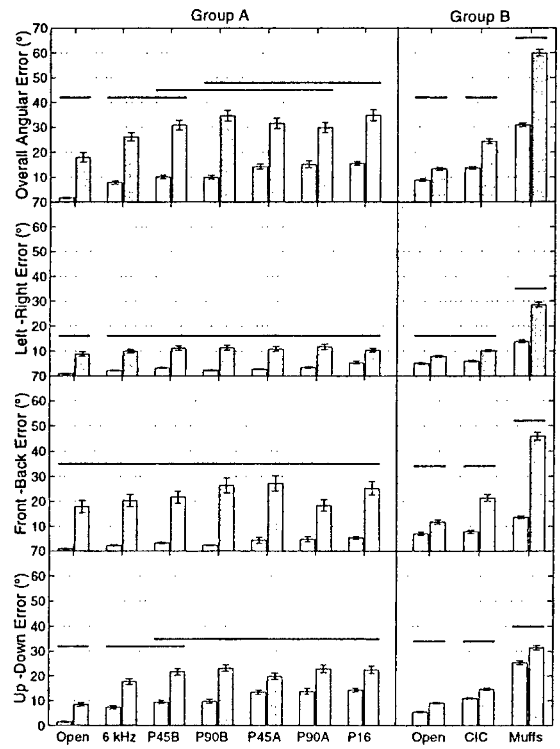

Figure 3: *Overall localization performance in the ten different listening conditions tested in the experiment. The white bars show performance in the long stimulus conditions, and the gray bars show performance in the short stimulus conditions. The top panel shows the overall angular errors, and the bottom three panels show the mean absolute errors in the left-right, front-back, and up-down dimensions. The error bars represent 95% confidence intervals calculated from the raw data, and the horizontal bars show groups of conditions that were not significantly different from one another at the p< 0.05 level in either the short or long stimulus conditions.*

different from one another (at the $p>0.05$ level) for either the short or the long stimuli.

From the overall results of the experiments, a number of general observations can be made:

- The overall errors were generally lower in the left-right condition than in the front-back or up-down conditions, especially for the short stimuli. This reflects the fact that left-right localization is dominated by low-frequency interaural time difference cues that are relatively robust to the distortions caused by pass-through listening devices.
- In every condition, overall performance was better with the long stimuli (white bars) than it was with the short stimuli (gray bars). However, the difference in performance between the two types of stimuli was much greater in the front-back dimension than it was in the up-down dimension. The large reductions in the front-back errors with the continuous stimuli reflect the fact that these stimuli were on long enough to allow the listeners to orient their heads toward the sound sources and use low-frequency interaural time difference cues to determine their front-back locations. These exploratory head movements were much less effective in helping the listeners determine the elevations of the sound sources. A similar effect was reported by Noble [4] in a paper that examined the effects of electronic earmuffs on sound localization.

Looking specifically at the data from the Group A listeners, note the following important findings:

- In every dimension except front-back error, the error in the open-ear condition was significantly better than in any other condition.
- Although the overall angular errors and the up-down errors in the 6 kHz condition were significantly lower than in four of the five earplug conditions, this difference in performance was small relative to the difference in performance between the 6 kHz condition and the open-ear condition. This suggests that most of the disruptions in localization performance that occurred when the earplugs were worn were caused by transducer bandwidth limitations and not by distortions in the head-related transfer functions.
- The effects of this bandwidth limitation were most apparent in the up-down dimension, which accounted for almost all of the overall angular error with the continuous stimuli. This is consistent with the results of King and Oldfield [2], which showed that elevation perception is most sensitive to the elimination of the frequency components above 8 kHz in an audio stimulus.
- Although performance was nominally better with the P45B plug configuration than with the other plug configurations (it was the only configuration that was not significantly different than the 6 kHz condition), the only significant difference was a decrease in overall angular error relative to the P16 plug. This suggests that differences in microphone configuration have relatively little impact on localization performance in pass-through systems that are band-limited to 6 kHz. Note, however, that larger performance differences could and probably would occur in systems with bandwidths greater than 6 kHz.

In listener Group B, performance with the CIC devices was slightly but significantly worse than the open-ear condition in the front-back and up-down dimensions, and performance with the earmuffs was much worse than with the CIC hearing aids in every error dimension tested. Comparisons across the two groups of listeners are difficult, particularly in light of the fact that the Group B listeners were substantially worse than the Group A listeners in the open-ear condition with the long stimulus. However, the following general observations appear to be justified by the data:

- Relative to the open-ear conditions, the CIC devices tested in Group B performed at least as well in every error dimension as any of the earplug devices tested in Group A, and in the up-down dimension with short stimuli the CIC devices performed substantially better than any of the Group A earplugs. This result seems reasonable when one considers that the CIC plugs used a microphone configuration that should not have interfered with the HRTF and that the reported bandwidth of the CIC plugs (7.4 kHz) was slightly higher than the 6 kHz bandwidth of the plugs tested in Group A. Indeed, in light of these factors, it is somewhat surprising that the CIC plugs did not exhibit an even larger performance advantage over the plug configurations tested in Group A. Again, the explanation seems to be that earplug configuration has little effect on localization performance in bandlimited electronic pass-through listening devices.
- Localization performance with the electronic earmuffs was dramatically worse than with any other listening device. The earmuffs essentially eliminated all of the natural localization cues associated with the external ears, and this particular set of earmuffs also shifted the input microphones much further away from the ear canal openings than any of the earplugs. While one cannot exclude the possibility that the performance of the earmuffs could have been improved by better microphone placement, additional electronic processing of the audio signals, or possibly by the use of an array of microphones instead of a single microphone on each earcup, these results suggest that it is more difficult to preserve natural localization cues with an earmuff pass-through listening device than with an earplug pass-through listening device.

In conclusion, the results of this experiment suggest that bandwidth tends to be the limiting factor in determining the localization performance of pass-through earplugs constructed from conventional hearing aid components, and that microphone configuration is really of secondary importance for systems that are limited to operating frequencies below 6 kHz. However, the poor results obtained with earmuffs in this experiment suggest that physical configuration cannot be completely discounted even for relatively low-bandwidth systems. Further research is now required to determine the frequency range where microphone placement begins to have an important effect on localization accuracy with pass-through earplugs, and how earplugs should be configured to optimize localization performance with broadband pass-through listening devices.

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