4aPPb10. Sound-localization performance with the hearing protectors

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Hearing-protection system that provide level-dependent sound attenuation can protect the ear against potentially damaging sounds (such as loud impulsive noises), while at the same time allowing the perception of moderate-level signals (such as speech). Such systems come in two forms: passive (nonlinear-attenuation earplugs) and active (talk-through system). This study sought to quantify the effect of these systems on spatial hearing. To this aim, sound-localization performance was measured in twenty subjects, with and without ear protectors on. Five protectors (two passives and three actives) were tested. The results showed significant increases in the proportions of errors during the use of one of the systems tested. To clarify the origin of this effect, "protected head-related transfer functions" (PHRTFs), i.e., HRTFs obtained with the ear-protectors on, were measured in the horizontal plane for each of the systems tested. The comparisons of these measures between PHRTFs with HRTFs were found to be in agreement with the subjective tests.

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INTRODUCTION

In many situations, it is very important to communicate as well as to perceive and to interpret the sound environment while being protected against the noise. In hearing protection, one distinguishes two types of hearing protection devices (HPDs): protectors with a fixed attenuation which is not depending on noise level and those with a variable attenuation depending on noise level. For this second type of protectors two principles exist:

Passive-protection systems are nonlinear-attenuation earplugs [3]. This type of protector is usually very effective for protection against impulsive noises because the attenuation increases with the peak pressure level of the sound. Nonlinear-attenuation "filters" consist of a cylindrical cavity with a small perforation at either side, which are inserted into an earplug. The acoustic impedance of the cavity is related to its viscous resistance, which has a nonlinear component which is proportional to the particle velocity [3].

Active protection systems are electronic “talk-through” systems. In these systems, sound is recorded using an external microphone and played back at an adapted level via a miniature speaker placed underneath the protector’s shell. The input/output gain is reduced as sound level increases.

HPDs in which the attenuation depends on the noise level protect the ear against loud continuous and impulsive noises while allowing almost unaltered perception of faint or moderate-level sounds. These systems facilitate oral communication. However, their impact on sound-localization performance is not well known.

To localize sound sources, listeners make use of various cues which result from physical phenomena, which occur as sound propagates from its source to the listener’s ear. For the localization of sound sources in the horizontal plane, the inter aural time differences (ITDs) and the inter aural level differences (ILDs) are used [1;4]. However, ITDs and ILDs do not allow the listener to determine the elevation of the source and may lead to front-back confusion. In order to resolve these directions, listeners make use of implicit knowledge of the acoustic effects of their body on incoming sounds. Moreover, reflections added to the direct sound, and absorption provide cues for the perception of the distance of the source [5;10]. In this study only influence of the hearing protector on the directional perception was taken into account.

Five HPDs were tested: P1 and P2 (two different nonlinear earplugs); P3 and P4 (two different earplugs with electronic talk-through systems); P5 (headset with electronic talk-through system).

In the first part, the tests consisted of determining localization performance when wearing these devices. In the second part we have searched for a relationship between head related transfer functions (HRTF), measured on a artificial head with these devices, and the localization performance.

LOCALIZATION PERFORMANCE TEST

Material and methods

Twenty participants (10 male, 10 female, aged 24-51 years, mean age = 33.5 +/- 7 years) participated in the study. All participants had normal hearing for their age and were checked for abnormal cerumen build-up inside the ear canal prior to the experiment. Participants were paid for their participation in the study.

Participants were individually seated in an elevated chair (2-m elevation) surrounded by 8 speakers inside the center of an anechoic chamber. They held in their hands a ball-shaped device equipped with eight buttons on its surface, each button corresponding to one speaker. The number of correct responses was recorded.

During the present experiment, participants took part in 13 test sessions. During three of the 13 sessions, participants did not wear a HPD; for the other 10 sessions, participants wore a HPD; two test sessions for each HPD. During each of these sessions, participants were exposed sequentially with 80 sounds (10 sounds per loudspeaker) in random order.

Each participant received a pair of HPDs. Except for P5 (headphones), the device size was selected on an individual basis in an attempt to provide the best possible fit for each participant’s ear. For the device labeled P3, the tightness of the fit is evaluated using an active (acoustic) system, which “beeps” every minute if the fit is not sufficiently tight. For four of the 20 participants, no tight fit could be obtained, whichever of the three available ear piece sizes was used. As a result, these four participants could not be tested with this device, and the mean results reported below for P3 are based on results from 16 participants only; for all other HPDs, mean results are based on 20 participants.
Results: Localization performance

The figure 1 shows the mean percent-correct scores for each of the conditions tested in the localization task. Percentages of correct responses measured with active devices (P1 to P5) were generally lower than those measured with passive ones. The table 1 gives the mean proportions of different types of localization errors for each test condition. The most common types of errors were up-down confusions, followed by front-back confusions. These two types of confusions also occurred frequently in combination. Left-right confusions were rare and, when they did occur, they were almost always associated with up-down or front-back confusions, which is why they were grouped with the latter two types of confusions in this analysis. Anova statistic analysis confirms these results. Additional details and individual results can be found in an internal report [9].

FIGURE 1: Mean percentage of correct scores in the localization task for the different test conditions. Without: without HPD; P1-P5: with HPD. Error bars show +/- 1 standard deviation of the mean across participants in the considered gender group (male or female).

TABLE 1: Percentage of correct responses and the percentage of different types of confusion.

<table>
<thead>
<tr>
<th>Percent correct</th>
<th>Percent front-back errors</th>
<th>Percent up-down errors</th>
<th>Percent top-down errors + front-back error</th>
<th>Percent left-right errors</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>96.1%</td>
<td>1.4%</td>
<td>1.5%</td>
<td>0.9%</td>
</tr>
<tr>
<td>P1</td>
<td>61.3%</td>
<td>11.5%</td>
<td>16.8%</td>
<td>10.0%</td>
</tr>
<tr>
<td>P2</td>
<td>67.6%</td>
<td>9.9%</td>
<td>15.8%</td>
<td>6.4%</td>
</tr>
<tr>
<td>P3</td>
<td>57.5%</td>
<td>8.3%</td>
<td>23.8%</td>
<td>10.2%</td>
</tr>
<tr>
<td>P4</td>
<td>49.3%</td>
<td>12.2%</td>
<td>24.6%</td>
<td>13.6%</td>
</tr>
<tr>
<td>P5</td>
<td>39.8%</td>
<td>15.3%</td>
<td>27.2%</td>
<td>17.7%</td>
</tr>
</tbody>
</table>

Localization performance discussion

The results of this study show that HPDs have a significant detrimental impact on sound-localization performance. This is the case for all of the tested systems in this study, including nonlinear earplugs, talk-through earplugs, and talk-through earmuff. Nonlinear earplugs were found to have the smallest impact on sound-localization performance, with an average score of 63%, which still corresponds to a decrease of 33 percentage points relative to the naked-ear condition. Importantly, HPDs were found to increase both front-back confusions, in addition to up-down confusions. Front-back confusions are usually more detrimental than up-down confusions in real-life situations, where sound signals of interest are usually located around, rather than above or below, the listener. The two nonlinear earplugs were found to show the less up-down confusions. Finally, very few left-right confusions were observed and, when such confusions did occur, they were often accompanied by front-back or up-down confusions. In particular for the earmuff (P5), there is no left-right confusion. This can be explained by the fact that, with the earmuff, the distance between the two ears is virtually increased (corresponding to the distance between two microphones).
HRTF

To gain information about the effects of HPDs on spectral cues for sound localization, we measured and compared head-related transfer functions (HRTFs) in the horizontal plane without, and with, HPDs. HRTFs provide a representation of alterations introduced by the listener’s body (in particular, the torso and the head, including the pinnae) on sound spectra.

HRTF measurement procedure

In the context of this study, it was important to measure HRTFs with the HPD in the ear (PHRTF). However, due to physical (volume and shape) constraints, it was not possible to place the microphone used to measure the HRTF underneath the HPD (earplug). To circumvent this problem, the HRTFs were measured using an artificial head (ISL [6]) in which the “eardrums” are materialized by microphones, mounted in a way that the acoustic impedance is close to that in a real ear. The artificial head was used to measure HRTFs without an HPD, and for each of the HPDs tested in the study. The sound source (loudspeaker) used for these measurements was located in the horizontal plane of the head. Measurements were performed for eight different orientations of the head (relative to the sound source) in the horizontal plane, spanning 0-315° in steps of 45° (Figure 2), and for each ear (left and right). Measures were performed in an audiometry room.

FIGURE 2: Illustration of the different head orientations for which HRTFs were measured

Results: HRTF curves

The figure 3 shows, for eight orientations of the artificial head, the HRTFs measured in the right ear, without an HPD in place. These HRTFs are used as reference in this study. It can be seen that there is very little influence for frequencies below 400 Hz. Therefore, only the ITDs can be used for localizing low frequency sounds. With increasing frequency, the HRTF becomes more and more sensitive to the orientation of the head. This increasing sensitivity may be explained by the fact that with increasing frequency (decreasing acoustic wavelength) more and more morphological details of the head will influence the HRTF. These orientation-dependent level changes at the eardrum correspond to ILD cues, which can be used for localizing sound sources in the horizontal plane.

FIGURE 3: HRTFs measured in the right ear without an HPD, for the eight orientations of the artificial head relative to the noise source. Different colors correspond to different orientations, as indicated in the key.
In order to understand the relationship between the effects of HPDs on HRTFs and their effects on front-back confusions, we compared HRTFs for orientations of 45° and 135°. These two orientations correspond to front-right and back-right source locations, respectively. In particular we computed the differences between the HRTFs measured in the left and right ear for these two head orientations. This was done for the naked ear and for each HPD, separately. The results, which are shown in FIGURE 4, illustrate the ILD cues that may be available to the listener for distinguishing between front sources and back sources for the different HPDs.

**FIGURE 4**: Differences between the HRTFs of the left and the right ear, for head orientations of 45° (blue) and 135° (red). The different graphs correspond to different HPDs, and to the without-HPD condition (upper-left graph).

Note that, for the no-HPD condition, differences (of up to 5 dB) between the ILD curves corresponding to the two orientations were observed over a wide range of frequencies (above about 500 Hz). Such differences provide a potential basis for the ability of listeners to distinguish between front and back locations. Differences between the two curves were also observed for measurements performed with HPDs in both ears. However, the magnitude and shape of these differences differ largely, depending on the HPD. This is most easily seen in FIGURE 5, which...
shows, in the same plot, the differences between the 45° and 135° ILD curves for the different HPDs. It can be seen that the ILD-difference curves most similar to the reference (no-HPD) curve are for P1, P2, and P3; for P4, and even more so, for P5, large deviations from the reference curve are observed.

**Discussion**

This observation is confirmed quantitatively by comparing the mean squared differences between the ILD-difference curve for the naked-ear and the ILD-difference curves for each HPD, in the 0.5-10 kHz range (TABLE 2); the mean squared difference is largest for P5. This indicates that the normal (naked-ear) pattern of ILD cues for front-back distinctions is more severely altered by P5 than by the other HPDs, and is in line with the behavioral results described above, which show a larger number of front-back confusions for P5 than for the other HPDs.

**TABLE 2**: Mean squared differences between ILD-difference curve of the naked ear condition and each of the HPD conditions (FIGURE 5)

<table>
<thead>
<tr>
<th></th>
<th>P1</th>
<th>P2</th>
<th>P3</th>
<th>P4</th>
<th>P5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean square difference (dB²)</td>
<td>4.05</td>
<td>3.81</td>
<td>1.74</td>
<td>12.24</td>
<td>57.90</td>
</tr>
</tbody>
</table>

**CONCLUSION**

The results of this study demonstrate significant impact of HPDs on sound-localization performance. The impact was more or less marked, depending on the HPD. Indeed, the rate of confusion is less than 30% (in average) for nonlinear earplugs and less than 46% for talk-through systems. However, front-back confusions for nonlinear earplugs (P1 and P2) and for one of the talk-through systems (P3) are almost the same.

Comparisons between HRTFs measured with and without HPDs provide some information about the origin of the impact of HPDs on localization performance in the horizontal plane, as well as some information about the origin of the larger number of front-back confusions with the earmuff-based system (P5). In particular, when comparing the pattern of ILD cues for distinguishing between the 45° (front right) and 135° (back right) locations, we find that this pattern is more severely altered by P5 than by any of the other HPDs tested in this study. Moreover, this analysis shows that P1, P2, and P3 has a smaller impact on ILD cues than P4 and P5, which is consistent with the fact that localization performance is less adversely impacted by P1, P2, and P3 than by P4 and P5.

**REFERENCES**