Evaluation of Sound Localization under Conditions of Covered Ears

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In this paper, we examine how covering one or both external ears affects sound localization on the horizontal plane. In our experiments, we cover subjects’ pinnae and external auditory canals with headphones, earphones and earplugs, and conduct a sound localization test. The results indicate that front-back confusion rates increase when covering both external ears with open-air headphones, and one ear with an inner earphone and an earplug. Furthermore, the incorrect answer rate is high when sound sources and an occluded ear are on the same side when putting on an inner earphone and an earplug. We consider that factors causing front-back confusion could be clarified by comparing these results with characteristics of HRTFs.

1 Introduction

We regularly hear many kinds of sound such as conversation, music and so on, and these sounds give us spatial, temporal and meaningful information. The spatial information contains the direction of arrival (DOA) and the distance between the sound source and the listener. The DOA is mainly determined by the interaural time difference (ITD) and the interaural level difference (ILD) [1], both of which are correlated with the head, ears and other physical body parts. It can be considered that a change in ITD and ILD due to covering the ears would affect localization ability. Previous researchers have verified that the directions of the sound source and auditory event coincide much more rarely when using short rubber hoses inserted into the external ears than when not using them [2]. Furthermore, the ability to localize on the median plane decreases with increasing occlusion of the pinnae [3]. It is clear, therefore, that the effect provided by the external ears plays an important role in sound localization.

This paper describes sound localization from subjective and objective perspectives when external canals and pinnae are occluded. The experiments have been designed to clarify the roles of both pinnae and ears concerning the determination of DOA. In the experiments, we employ widely and commonly used equipment such as open-air headphones, ear-hook headphones, earphones, inner earphones and earplugs to occlude ears.

This paper is organized as follows. In Section 2, we report on and discuss the subjective sound localization test. This experiment took place under 12 different conditions. In Section 3, we report on and discuss the objective test, with head-related transfer functions (HTRFs) measured under the same 12 conditions. Section 4 includes concluding remarks.

2 Sound localization test

2.1 Experimental conditions

The subjective test was performed to examine the performance of sound localization when subjects put on equipment to cover their ears. The experiment was conducted in a reverberant room at a reverberant time of 150 ms. A circular loudspeaker array was set up in this room. The radius of this circular array was 2.1 m, and 24 loudspeakers (TEAC S-300 Extra) were located at 15° intervals. The heights of all the loudspeakers were the same. To reduce the visual effects, only half of them (every second speaker) actually made a sound. Figure 1 illustrates the experiment configuration. The stimulus was a white noise of 1.0s duration, and the sampling frequency was 48 kHz. The stimuli were presented to subjects randomly from 12 directions. The azimuth corresponded to the following directions: in front of the subject, 0°; in a clockwise direction from the front, at negative angles; in a counterclockwise direction, at positive angles.

We used the following five types of equipment to cover the subjects’ ears: open-air headphones (STAX NOVA), ear-hook headphones (audio-technica ATH-EQ3), earphones (audio-technica ATH-C31), inner earphones (Etymotic Research ER-6), and earplugs (3M 1100RP). As Table 1 shows, each piece of equipment was fitted to a single ear or both ears. Each subject wore the equipment for 11 of the 12 conditions, and for the other condition no equipment was used for comparison.

Since five stimuli were presented from every direction, the total number of stimuli for one subject was 720 (12 conditions × 12 directions × 5 stimuli). 12 subjects with normal hearing participated in the experiments.

2.2 Experimental results

The answers are evaluated by a correct rate and a front-back confusion rate. In our study, a correct answer is one in which the presented direction and the perceived direction are the same. It is called a front-back confusion when the presented stimulus is perceived in the direction...
symmetrical to the bitragion diameter.

Table 2 shows the results. The highest correct rate was obtained in the case of #12 (no equipment). The test of significance was performed for these subjective results. The correct rates and the front-back confusion rates were evaluated by the $\chi^2$ test, with the significance level of 5%. Table 3 shows the result of a two-side significance test on the correct rates, while Table 4 presents the result of a two-side test on the front-back confusion rates. In these tables, the numbers on each axis represent the experimental conditions. The character “A” means the null hypothesis is accepted; that is, there is no significant difference between the two conditions.

At first, the effects of putting on a piece of equipment are examined by the $\chi^2$ test on the correct rates between #12 and the others. The results show a significant difference between #12 and the others except #9 (the inner earphone (right)). We consider that the effect due to pinnae concerning the determination of DOA is diminished by pinna occlusion. In the cases of using inner earphones and earplugs, subjects perceived the source directions correctly when sound sources and an unoccluded ear were on the same side. However, the number of incorrect answers increased when the sound source and an occluded ear were on the same side. Considering these results, the ear that is closer to the sound source plays a superior role whereas the ear on the opposite side plays an inferior role in sound localization. However, we need to conduct further experiments to confirm this.

### 3 Measurement of HRTFs

#### 3.1 Measurement conditions

We measured head-related transfer functions (HRTF) to evaluate the results of the sound localization test from the perspective of acoustic characteristics. In such a measurement, an HRTF is a transfer function between the sound source and the entrance of the eardrum. The HRTFs were measured with a head-and-torso simulator (HATS, B&K 4128) in the same room as that in which we conducted the sound localization. The distance between the HATS and the sound source (BOSE ACOUSTIMASS) is 2.1 m. The microphones (B&K 4158, 4159)
were positioned at the HATS’ eardrum. The equipment conditions for HRTF measurement were the same as in table 1. Other conditions are shown in Table 5.

### 3.2 The characteristics of HRTFs

The decrease of correct answers in the cases of open-air headphones, inner earphones and earplugs should be correlated with the changes of HRTF characteristics, such as sound attenuation and spectral changes.

Figure 5 shows comparisons of sound pressure on the right ear. The sound pressure level is given by

\[ P = \sqrt{\sum_{n=0}^{1023} [h[n]]^2} \]  

Table 5: Measurement conditions of HRTFs

<table>
<thead>
<tr>
<th>Background noise level</th>
<th>13.1 dB(A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>16.5 °C</td>
</tr>
<tr>
<td>Signal</td>
<td>Swept sine [4]</td>
</tr>
<tr>
<td>Sound pressure level (2.1m)</td>
<td>68.7 dB(A)</td>
</tr>
<tr>
<td>Sampling frequency</td>
<td>48 kHz</td>
</tr>
<tr>
<td>Azimuth</td>
<td>-175 – 180°, divided into 5° intervals</td>
</tr>
</tbody>
</table>
where $h[n]$ is a measured HRTF (impulse response), and $n$ is the duration of the HRTF.

As a result, a sound attenuation of 50 dB occurred with an earplug, while 40 dB occurred with an inner-earphone, suggesting that sound attenuation by external ear occlusion has a negative influence on sound localization.

Though open-air headphones completely cover the ears, they do not block lateral sound [5]. Therefore, there is less sound attenuation in the case of open-air headphones. This suggests that the decrease of the correct rate is not because of sound attenuation, but due to spectral changes.

Figure 6 displays a comparison of the right ear’s front (0°) and back (180°) HRTFs in the frequency domain without any equipment, while Figure 7 shows a comparison of the right ear’s front (0°) and back (180°) HRTFs in the frequency domain with open-air headphones. The sound pressure level at the front is attenuated with open-air headphones, and levels from 10 to 15 kHz are inverted by comparing the front and the back. The sound direction is determined by comparing the acquired memory of sound localization and the information obtained from the current sound. Assuming the HRTF without equipment is the acquired memory and the HRTF with open-air headphones is the current information, the changes of the spectrum from 10 to 15 kHz cause an increase in front-back confusion.

4 Conclusions

In this paper, we described sound localization under several conditions of covered ears. From the results of the subjective test, we found that localization accuracy deteriorates by covering the ears with any type of equipment. This effect was especially true when subjects wore open-air headphones, inner earphones and earplugs. In the case of covering ears with open-air headphones, the front-back confusion rate was extremely high, while for inner earphones and earplugs, subjects perceived the source directions correctly when the sound sources and an unoccluded ear were on the same side. However, the number of incorrect answers increased when the sound sources and an occluded ear were on the same side. These results were influenced by sound attenuation and changes in the spectrum.

Future work will involve clarifying the role of both ears in sound localization, and applying that knowledge to a method for evaluating HRTFs.

References