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TECHNICAL REPORT

Sound localization under conditions of covered ears on the horizontal plane

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Abstract: In this paper, we examine how covering one or both external ears affects sound localization on the horizontal plane. In our experiments, we covered subjects' pinnae and external auditory canals with headphones, earphones, and earplugs, and conducted sound localization tests. Stimuli were presented from 12 different directions, and 12 subjects participated in the sound localization tests. The results indicate that covering one or both ears decreased their sound localization performance. Front-back confusion rates increased, particularly when covering both outer ears with open-air headphones or covering one ear with an intraconcha-type earphone or an earplug. Furthermore, incorrect answer rates were high when the sound source and the occluded ear that had an intraconcha-type earphone or an earplug were on the same side. We consider that the factors that cause poor performance can be clarified by comparing these results with characteristics of head-related transfer function.

Keywords: Binaural hearing, Monaural hearing, Sound localization, Head-related transfer function

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1. INTRODUCTION

We are exposed to many kinds of sounds including conversation and music, and these sounds give us spatial, temporal, and meaningful information. Spatial information contains the direction of arrival and the distance between the sound source and the listener.

On the horizontal plane, the sound source direction is mainly determined by the interaural time difference (ITD) and the interaural level difference (ILD), both of which correlate to the head, ears, and other physical body parts. Covering the ears causes changes in the ITD and ILD and affects localization ability. Previous researchers verified that the direction of the sound source and the auditory event coincide much more rarely when short rubber hoses are inserted into the external ears [1]. The ability to localize decreases by increasing pinnae occlusion [2,3].

From previous research and daily experience, it is easy to infer that sound localization performance deteriorates when wearing a sound device. However, examining how the sound localization performance degrades when wearing a sound device is important because the ways of covering ears and the insulation used differ for various kinds of equipment. It is also valuable to investigate whether ordinary equipment influences sound localization. Sound localization performance has been examined when various equipment was worn, including earmuffs and headgear [4–6]. It is clear, therefore, that external ears play an important role in sound localization. Many people walk, drive, etc, while using headphones, earphones, and other sound devices. In such cases, the characteristics of sound signals reaching our ears are changed when wearing sound devices, which cause deterioration in sound localization performance. Of course, the distraction of another sound, such as music, in our ears also influences sound localization performance.

In this paper, we describe sound localization from subjective and objective perspectives when the external canals and pinnae are occluded. We designed experiments to clarify the roles of both pinnae and ears in determining the sound source direction. In the experiments, we used commonplace equipment, such as open-air headphones, ear-hook headphones, earphones, intraconcha-type earphones, and earplugs, to occlude ears.

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This paper is organized as follows. In Sect. 2, we describe the experimental conditions of the subjective sound localization tests. We report on and discuss the results in Sects. 3 and 4. Sect. 5 contains our concluding remarks.

2. EXPERIMENTAL CONDITIONS

2.1. Sound Localization Test

Subjective tests were performed to examine sound localization performance when subjects covered their ears with various kinds of equipment. We conducted the experiment in a reverberant room with dimensions of 7 m × 7 m and a ceiling height of 4.5 m. Because the walls and ceiling contained acoustic material, the reverberant time in the room was 150 ms. The background noise level was 13.3 dB(A).

We set up a circular loudspeaker array in the room. The radius of the circular array was 2.1 m, and 24 loudspeakers (TEAC S-300 Extra, 128 mm diameter) were located at 15° intervals. The loudspeakers were all the same height. To reduce the visual effects, only half the speakers (every second speaker) actually made a sound. The stimulus was a white noise of 1.0 s duration, and it was transduced by a loudspeaker. There was an 8.0 s interval between the stimuli. The sound pressure level of stimuli was 71.5 dB(A) at a distance of 2.1 m, and the difference between maximum and minimum sound pressure was within 1.0 dB(A). We did not compensate for the characteristics of the loudspeaker, because subjects reported that they did not perceive the difference in sound pressure. We presented the stimuli to subjects randomly from 12 directions (30° intervals). The azimuth corresponded to the following directions: in front of the subject, 0°; in a clockwise direction from the front, negative angles; and in a counter-clockwise direction, positive angles. Figure 1 illustrates the experimental configuration.

Subjects sat in a chair at the center of the circular loudspeaker array. We instructed subjects not to move their heads, but did not fix them with any equipment. To cover the subjects' ears, we used the following five types of equipment: open-air headphones (OAH, STAX Λ NOVA), ear-hook headphones (EHH, Audio-Technica ATH-EQ3), earphones (EPH, Audio-Technica ATH-C31), intraconcha-type earphones (ICE, Etymotic Research ER-6), and earplugs (EPL, 3M 1100RP). Each piece of equipment was fitted to a single ear or to both ears. The subjective tests were performed under the 12 conditions shown in Table 1. Each subject wore the equipment for 11 conditions, but as comparison, they wore no equipment for the 12th condition. We expected that subjects would not be able to perceive a stimulus when intraconcha-type earphones or earplugs were worn on both ears, because they have higher sound insulation. Therefore, the "both ears" fitting condition was not conducted.

Table 1 Experimental conditions.

Condition	Equipment
OAH_B	open-air headphones (both ears)
EHH_B	ear-hook headphones (both ears)
EPH_B	earphones (both ears)
EHH_L	an ear-hook headphone (left ear)
EHH_R	an ear-hook headphone (right ear)
EPH_L	an earphone (left ear)
EPH_R	an earphone (right ear)
ICE_L	an intraconcha-type earphone (left ear)
ICE_R	an intraconcha-type earphone (right ear)
EPL_L	an earplug (left ear)
EPL_R	an earplug (right ear)
NoEQ	no equipment

Since five stimuli were presented from every direction, the total number of stimuli for one subject was 720 (12 conditions × 12 directions × 5 stimuli). The subject wrote the perceived direction of the stimuli on answer sheets that consisted of a circle and twelve lines at intervals of 30°. Therefore, the answers include a ±15° error. We originally installed 24 loudspeakers to reduce the visual effect. However, this installation had no effect because answer sheets had twelve lines at intervals of 30°.

Twelve subjects with normal hearing participated in the experiments.

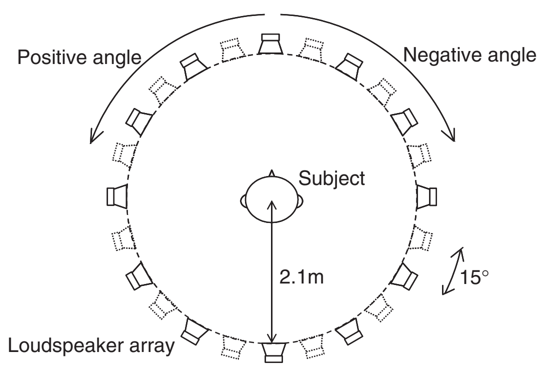

Fig. 1 Experiment configuration.

2.2. HRTF Measurement

When a subject wears equipment such headphones, earplugs, etc, the sound that arrives at the subject's ears has different acoustic characteristics. These characteristics influence the subjects' sound localization performance and the head-related transfer function (HRTF).

We measured HRTFs to evaluate the acoustic characteristics and to discuss the sound localization performance. The HRTFs were measured using a head-and-torso simulator (HATS, B&K 4128) in the same room as that in which we conducted the sound localizations. In our experiments,

Table 2 Measurement conditions of HRTFs.

Background noise level	13.1 dB(A)
Temperature	16.5°C
Signal	Swept sine [7]
Sound pressure level (2.1 m)	68.5 dB(A)
Sampling frequency	48 kHz
Azimuth	−175–180°, intervals at 5°

the HRTF is the transfer function between the sound source and the eardrum. Therefore, the microphones (B&K 4158, 4159) were positioned at the HATS' eardrum. The distance between the HATS and the sound source (BOSE Acoustimass cube speaker, 63 mm diameter) was 2.1 m. A swept sine signal [7] of 0.683 s was transduced by the loudspeaker. The experimental conditions for the HRTF measurement were the same as those in Table 1. The other conditions are shown in Table 2.

3. RESULTS

3.1. Sound Localization

We evaluated the answers using a correct rate (the percentage of correct answers) and a front-back confusion rate. In our experiment, a correct answer is one in which the presented direction and the perceived direction are the same. Front-back confusion is when the presented stimulus is perceived in a direction symmetrical to the bitragion diameter.

Figures 2 to 13 show the answers for all conditions. In every figure, the area of each circle corresponds to the number of answers. The correct answers lie on the solid diagonal line, while answers showing front-back confusion lie on the dashed-and-dotted lines. Figure 14 shows the correct rates and Fig. 15 shows the front-back confusion rates. The highest correct rate was obtained in the case of the "no equipment" condition.

We performed tests of significance for these subjective results. We evaluated the correct rates and the front-back confusion rates using the χ^2 test, with a significance level of 5%. Table 3 shows the results of a two-side test on the correct rates, and Table 4 shows the results of a two-side test on the front-back confusion rates. In both tables, the symbols 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.

First, we examined the effects of wearing a piece of equipment using the χ^2 test on the correct rates between NoEQ and the other conditions. There was a significant difference between NoEQ and the other conditions except for EHH_R. This suggests that sound localization performance deteriorates as a result of wearing any type of equipment. In terms of the difference among equipment types, there was no significant difference between the ear-hook headphones and the earphones (EHH_B vs. EPH_B, EHH_L vs. EPH_L and EHH_R vs. EPH_R). Furthermore, the correct rate was comparatively high for both these types of equipment.

There is significant difference between left and right in the case of ear-hook headphones and intraconcha-type earphones. Since two subject answers were considerably different when the ear-hook headphone was worn, a significant difference was found. One subject scored 83.3% for EHH_L and 95.0% for EHH_R. The other scored 68.3% for EHH_L and 85.0% for EHH_R. On the other hand, five subjects' answers were different for intraconcha-type earphones. These subjects were not the same in the case of the ear-hook headphones. Their answers were compared with those for EPG_L and EPG_R; however, there was no distinct pattern.

In contrast, the correct rates were significantly lower when the ears were covered with open-air headphones, intraconcha-type earphones and earplugs. In the case of open-air headphones, front-back confusion was particularly high for sounds at the front. In the cases of using intraconcha-type earphones and earplugs, the subjects perceived the source direction correctly when the sound source and the unoccluded ear were on the same side. The results for the intraconcha-type earphone and earplug conditions did not differ from those in previous research [8–10].

As Table 4 shows, there was a significant difference between OAH_B and the other conditions except for ICE_R. In the case of OAH_B, pinnae were completely occluded by the open-air headphones, and the sound waves arrived to the external ear canals by lateral apertures. Therefore, the acoustic path from the sound source to the external ear canal was similar for sounds from the front and the back, which increased the front-back confusion rate. However, pinnae were not completely occluded for the other conditions. Moreover, the sound waves could arrive at various apertures. Therefore, we think that the ability of determine sound source direction is diminished by pinna occlusion.

3.2. HRTF Characteristics

Figure 16 shows differences in the right ear's HRTF between the front (0°) and the back (180°) in the frequency domain. These differences in magnitude response were calculated by subtracting the magnitude response at the back from that at the front. We removed loudspeaker characteristics by subtracting the back response from the front response in the frequency domain. In this figure, the solid line represents the difference in the magnitude response for open-air headphones, while the dotted line denotes no equipment.

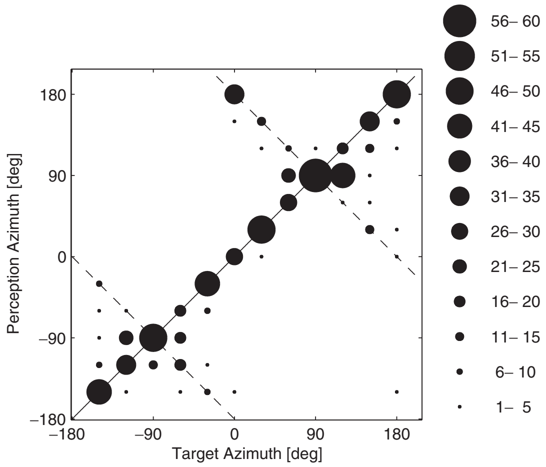

Fig. 2 Result of sound localization test for open-air headphones (OAH_B, correct: 60.8%, f/b confusion: 14.4%).

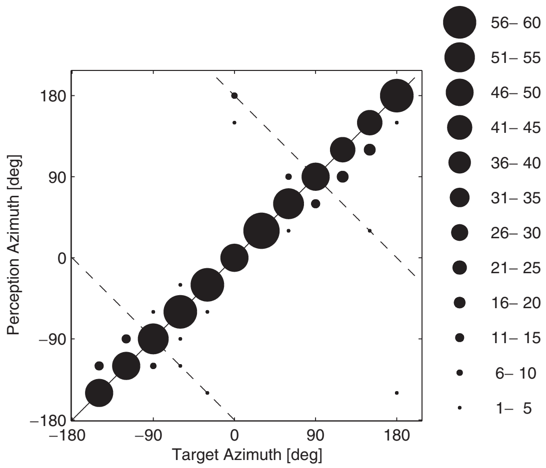

Fig. 3 Result of sound localization test for ear-hook headphones (EHH_B, correct: 85.0%, f/b confusion: 1.8%).

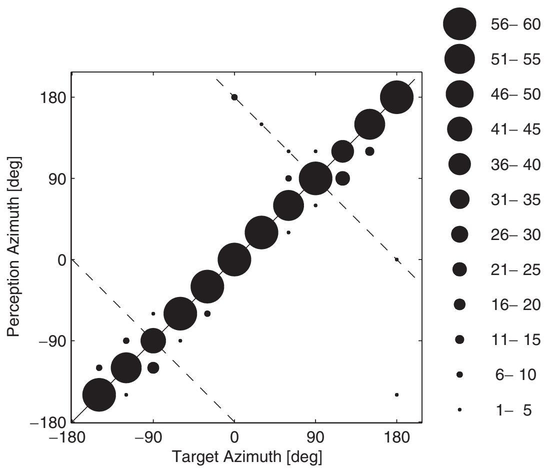

Fig. 4 Result of sound localization test for earphones (EPH_B, correct: 87.1%, f/b confusion: 1.4%).

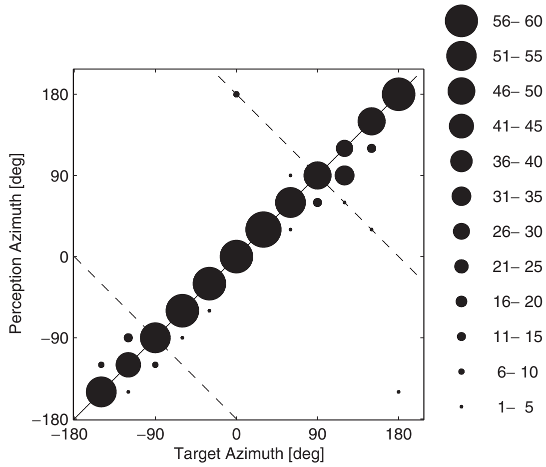

Fig. 5 Result of sound localization test for an ear-hook headphone (EHH_L, correct: 84.7%, f/b confusion: 1.1%).

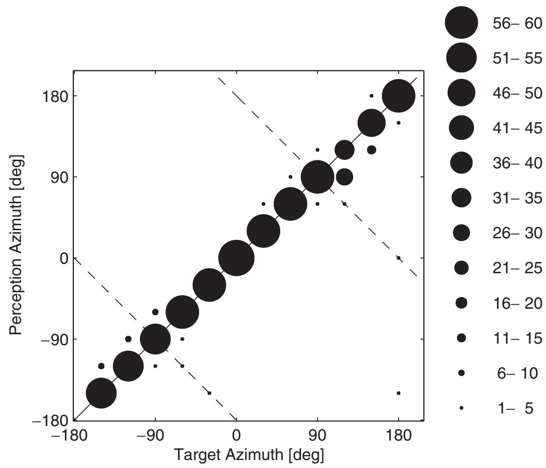

Fig. 6 Result of sound localization test for an ear-hook headphone (EHH_R, correct: 89.4%, f/b confusion: 0.7%).

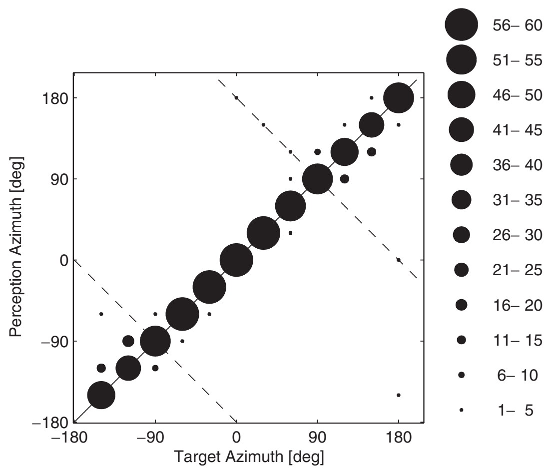

Fig. 7 Result of sound localization test for an earphone (EPH_L, correct: 86.5%, f/b confusion: 1.1%).

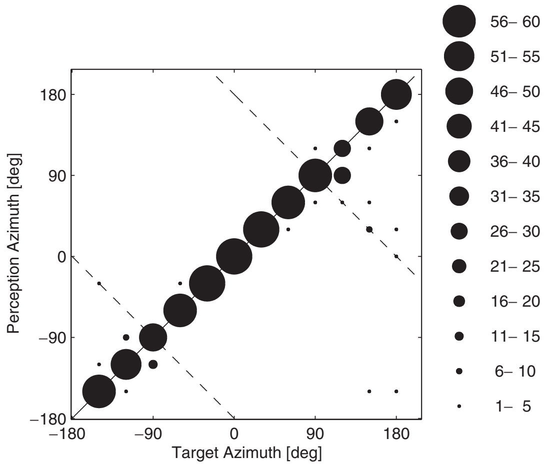

Fig. 8 Result of sound localization test for an earphone (EPH_R, correct: 88.6%, f/b confusion: 1.9%).

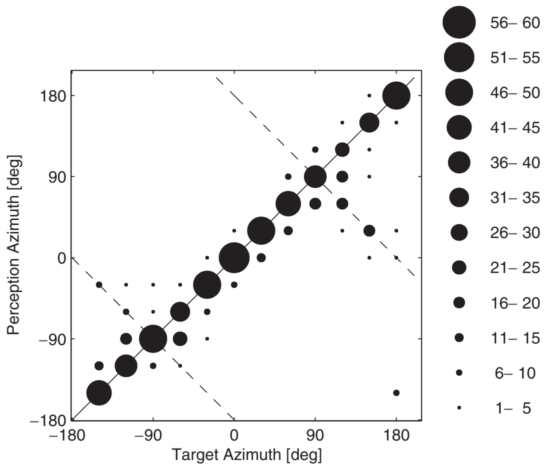

Fig. 9 Result of sound localization test for an intra-concha-type earphone (ICE_L, correct: 68.0%, f/b confusion: 6.9%).

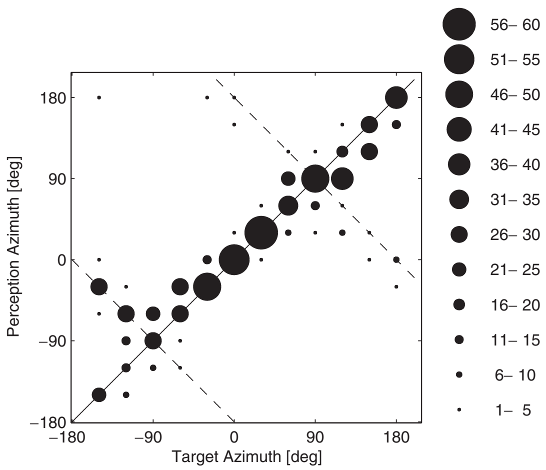

Fig. 10 Result of sound localization test for an intra-concha-type earphone (ICE_R, correct: 56.4%, f/b confusion: 11.1%).

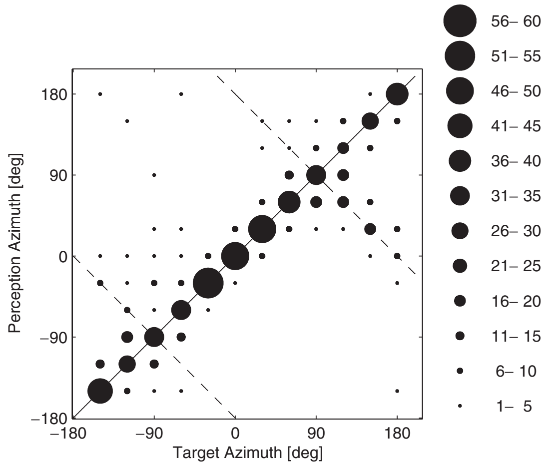

Fig. 11 Result of sound localization test for an earplug (EPL_L, correct: 59.3%, f/b confusion: 8.1%).

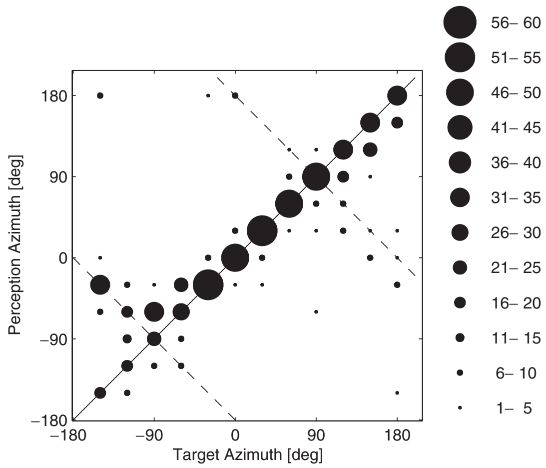

Fig. 12 Result of sound localization test for an earplug (EPL_R, correct: 58.8%, f/b confusion: 9.6%).

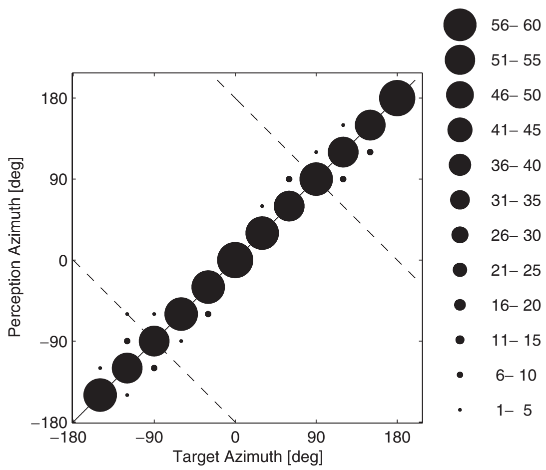

Fig. 13 Result of sound localization test without any equipment (NoEQ, correct: 92.8%, f/b confusion: 0.1%).

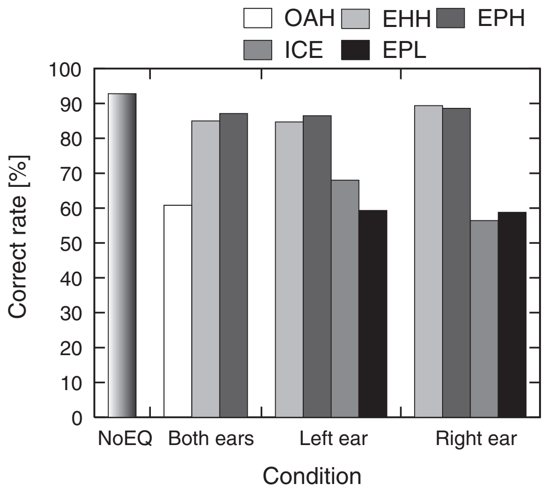

Fig. 14 Correct rate of sound localization test.

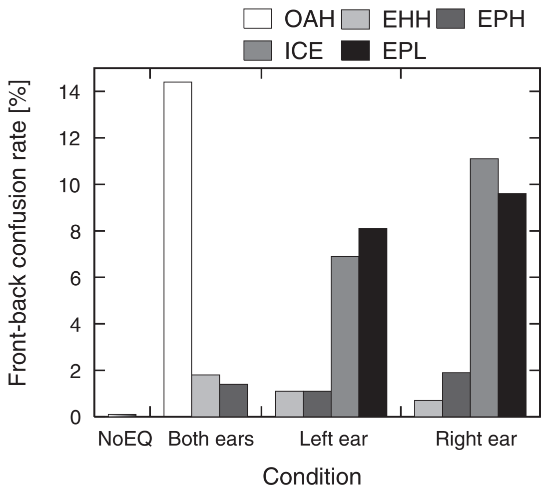

Fig. 15 Front-back confusion rate of sound localization test.

Table 3 Result of two-side test on the correct rates. The character "A" means that there is no significant difference between the two conditions.

	OHA_B	EHH_B	EPH_B	EHH_L	EHH_R	EPH_L	EPH_R	ICE_L	ICE_R	EPL_L	EPL_R	NoEQ
OHA_B									A	A	A	
EHH_B			A	A	A	A	A					
EPH_B				A	A	A	A					
EHH_L						A	A					
EHH_R						A	A					A
EPH_L							A					
EPH_R												
ICE_L												
ICE_R										A	A	
EPL_L											A	
EPL_R												
NoEQ												

Table 4 Result of two-side test on the front-back confusion rates. The character "A" means that there is no significant difference between the two conditions.

	OHA_B	EHH_B	EPH_B	EHH_L	EHH_R	EPH_L	EPH_R	ICE_L	ICE_R	EPL_L	EPL_R	NoEQ
OHA_B									A			
EHH_B			A	A	A	A	A					
EPH_B				A	A	A	A					
EHH_L					A	A	A					A
EHH_R						A	A					A
EPH_L							A					A
EPH_R												
ICE_L										A	A	
ICE_R										A	A	
EPL_L											A	
EPL_R												
NoEQ												

Figure 17 shows a comparison of sound pressure on the right ear. The sound pressure level is given by

$$P = 20\log_{10}\sqrt{\sum_{n=0}^{1023} h[n]^2} \text{ [dB]}, \qquad (1)$$

where $h[n]$ is measured HRTF (impulse response) and n is the sample index.

The result show that a sound attenuation of 50 dB occurred using the earplug, while 40 dB occurred using the intraconcha-type earphone, suggesting that sound attenuation during external ear occlusion has a negative influence on sound localization performance.

4. DISCUSSION

The results of subjective tests indicate that sound localization performance declines when the ears are covered with any sort of equipment. However, ear-hook headphones and earphones do not cover whole ear; thus, they inhibit sound localization to a lesser degree.

Table 5 shows a comparison of the number of errors between the left and right sides. Significance tests were conducted for error rates with a significance level of 5%. For open-air headphones (OAH_B), there is no significant difference between the left and right sides. However, this is not true in the cases of intraconcha-type earphones (ICE_L and ICE_R) and earplugs (EPL_L and EPL_R). The number of incorrect answers increased when the sound source and the occluded ear were on the same side, and error rates between the left and right sides for identical equipment (ICE_L vs ICE_R and EPL_L vs EPL_R) had no significant difference. These results and the front-back confusion rates suggest that front-back confusion occurs everywhere using the open-air headphones. For intraconcha-type earphones and earplugs, front-back confusion generally occurred more easily when the sound source and the occluded ear were on the same side.

We observed a correlation between the decrease in correct answers in the cases of open-air headphones,

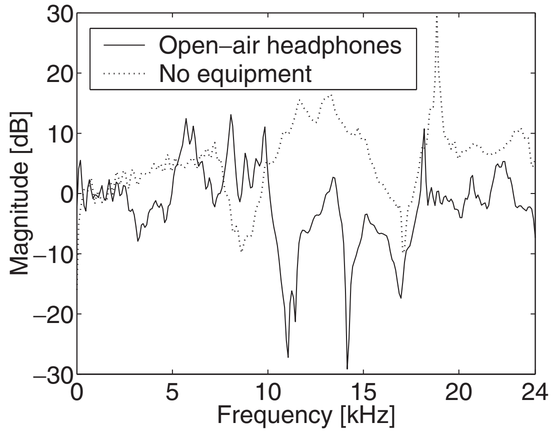

Fig. 16 Comparison of the right ear's front (0°) and back (180°) HRTFs in the frequency domain. The solid line shows open-air headphones, and dashed line shows no equipment.

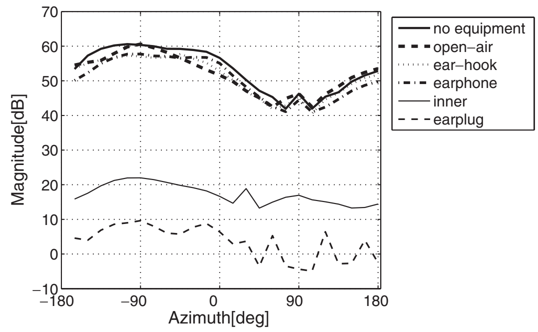

Fig. 17 Comparison of sound pressure on the right ear.

intraconcha-type earphones and earplugs and the changes in HRTF characteristics, such as spectral changes and sound attenuation.

Although open-air headphones completely cover the ears, they do not block lateral sound [11]. Therefore, there is less sound attenuation in the case of open-air headphones. This suggests that the decrease in the correct rate is not because of sound attenuation, but is actually due to spectral changes. Figure 16 shows the difference in magnitude response between the front and back HRTFs. In this figure, a positive magnitude denotes that the magnitude response of the front is greater than the back, and negative denotes that the magnitude response of the back is greater than the front. Differences in magnitude response from 3 to 5 kHz and from 10 to 15 kHz were inverted between open-air headphones and no equipment. We determined the sound direction by comparing the acquired memory of sound localization and the information obtained from the current sound [12,13]. Assuming the HRTF without equipment represents the acquired memory and the HRTF for open-air headphones represents the current information, spectrum changes from 3 to 5 kHz and from 10 to 15 kHz, respectively, increase front-back confusion.

Table 5 Comparison of the number of errors between left and right sides.

Condition	Number of errors (left side)	Number of errors (right side)
OAH_B	122	115
ICE_L	118	90
ICE_R	121	165
EPL_L	143	116
EPL_R	95	164

Considering the results for intraconcha-type earphones and earplugs, it appears that in sound localization, the ear that is closer to the sound source plays a more important role whereas the ear on the opposite side plays a less important role. However, we need to conduct further experiments to confirm this.

5. CONCLUSIONS

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

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

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