Acoust. Sci. & Tech. **35**, 4 (2014)

PAPER

Influence of flattening of head-related transfer functions in low-frequency region on sound localization

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(*Received 1 May 2013, Accepted for publication 22 January 2014*)

Abstract: It is clear that applications such as virtual auditory displays can be achieved by synthesizing head-related transfer functions with high accuracy. However, in practice, their detailed spectral shapes over the entire frequency range are not likely to be essential to sound localization. For example, low-frequency sound has a tendency to diffract around the head and torso of the listener, which leads to low-frequency characteristics of head-related transfer functions (HRTFs) being largely independent of the position of the sound source. This may imply that HRTFs involve few localization cues in the low-frequency region. We have sought to clarify whether removing spectral cues from HRTFs affects horizontal localization [K. Watanabe *et al.*, *Acoust. Sci. & Tech.*, **32**(3), 121–124 (2011)]. In this paper, the low-frequency characteristics of the HRTFs of both ears were flattened below a certain frequency, termed the "boundary frequency," to investigate the influence of the low-frequency component of HRTFs. These flattening procedures were simultaneously applied to the HRTFs of both ears while the interaural level and time differences of the original HRTFs were retained. A localization test using such partially flattened HRTFs was carried out, and the results showed that the flattening of the HRTFs did not significantly affect sound localization at boundary frequencies of 0.5–2 kHz, except for the source direction of 60°. Those boundary frequencies differed depending on source direction. The low-frequency region below these boundary frequencies may be ignored, and some data reduction can be applied here without significant influence on sound localization.

Keywords: HRTF, Localization, Spectral cue, Flattening, Boundary frequency

PACS number: 43.60.−c, 43.66.−x [doi:10.1250/ast.35.192]

1. INTRODUCTION

Human beings obtain information about sound sources via sound signals incident on the right and left ears. One component of this information, the source position, is perceived using various physical cues. When sound travels in a free field from the source to the ear canal, its spectrum is transformed by reflection and diffraction around the external ear, the head, and the torso. This transformation is utilized as a spectral cue; such transformations are generally known as "head-related transfer functions" (HRTFs) [1]. A listener hearing a sound filtered with HRTFs can localize a virtual target. Many researchers have studied various applications of HRTFs, such as auditory display systems [2]. Many systems are able to reproduce virtual sound sources by the convolution of sound signals with HRTFs corresponding to the positions of sound sources. In such a system, computational load increases depending on the size and/or number of transfer functions. If the HRTFs could be represented by only a few parameters, this would greatly decrease computer memory and processing power requirements. Since the HRTFs have complicated spectral forms, the data size necessary for their accurate representation tends to be large. If we can clarify which features of HRTFs play a role in sound localization, a simpler representation of HRTFs becomes possible. This may reduce data size without influencing sound localization. Therefore, it is important to identify the feature or

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features of HRTFs that are related to localization cues. Researchers have used a variety of approaches to investigate the role of spectral cues in sound localization. One method is to use band-limited stimuli. Blauert [3] found that localization judgments in the median plane were related to the central frequency of the stimuli. Hebrank and Wright [4] reported that frontal elevation was cued by the lower cutoff frequency of a one-octave notch whose central frequency varied from 4 to 10 kHz, and that back elevation was cued by a small peak from 10 to 12 kHz. Morikawa and Hirahara [5] conducted the localization test using low- and high-pass stimuli and found that horizontal localization performance was degraded for stimuli consisting of only low-frequency components (below 2 kHz) or high-frequency components (over 12 kHz). Another approach is to use broadband stimuli, because these have features that vary with source direction and distance. Research has shown that the HRTFs include comprehensive localization cues. Wightman and Kistler [6] reported that front-back confusion was related to high-frequency cues derived from the anterior-posterior asymmetry of the pinna. Some groups have tried to identify important spectral cues by simplifying HRTFs. Asano *et al.* [7] reported that smoothing of the frequency characteristics of the HRTFs in high-frequency regions did not affect localization performance in the median plane. Kistler and Wightman [8] employed HRTFs modeled using low-order (1st–5th) principal components and showed that the primary peaks and dips in high-frequency regions were important for front-back discrimination. Iida *et al.* [9] represented HRTFs with one peak and two notches and demonstrated via a psycho-acoustical experiment, that the simplified HRTFs effectively controlled median plane localization. In these investigations, the HRTFs were simplified over the entire frequency range. An alternative approach is to partially remove spectral cues from HRTFs. The directional transfer function (DTF), which is the directional component of the HRTF, is important because it is thought that directional localization cues are directly represented [10,11]. Langendijk and Bronkhorst [12] removed cues from certain frequency bands of the DTF by flattening the magnitude characteristics of the bands. They reported that front-back confusion was significantly increased when spectral cues in the high-frequency region were removed. The spectral features for localization found in those studies [7–9,12] are likely to be essential in localization. However, it remains unclear whether other features also affect localization. If the simplification or elimination of such features is possible, it is not necessary to accurately reflect them in the representation of HRTFs. Results of earlier studies suggested that simplification can be adopted for a limited frequency region. Asano *et al.* [7] applied the autoregressive moving average (ARMA) model to HRTFs, which led to a reduction in the number of parameters. Most features of HRTFs were preserved because the modeled HRTFs still retained the same spectral outlines. Langendijk *et al.* [12] investigated the effect of simplification by partially eliminating the features of the DTF by flattening the profile in certain frequency bands. However, the frequency range considered was 2 kHz or higher, and the influence of lower frequency regions was not examined.

We investigated simplification in the high-frequency region and showed that in contralateral HRTFs, the frequency range above 8 kHz had no effect on localization [13]. On the other hand, the effect of low-frequency HRTF components is still unclear. In general, low-frequency sound waves arriving at both of the listener's ears diffract and propagate with little level difference between them because their wavelengths are long compared with the size of the listener's head. In other words, the magnitude of the HRTFs in the low-frequency region is nearly independent of source direction. This fact might help to simplify HRTFs. Therefore, it may be possible to partially remove spectral cues from the HRTFs in this region without any influence on sound localization. Some researchers have investigated the existence of low-frequency localization cues [14,15]. Morimoto *et al.* [14] performed a localization test using wide-band white noise that was divided into two frequency components at a cutoff frequency of 4.8 kHz. These components were presented from different directions in the median plane. They reported that the lower frequency components contributed only slightly to front-back discrimination compared with the higher frequency components. Algazi *et al.* [15] conducted a localization test using a low-pass noise burst and concluded that the low-frequency elevation cues existed at source directions away from the median plane, whereas Morimoto *et al.* [14] investigated only the median plane. Although Algazi *et al.* [15] targeted other directions in addition to the median plane, the stimuli did not have high-frequency components.

The influence on horizontal localization should be clarified to achieve effective data reduction. Algazi *et al.* [15] suggested that the cues for front-back discrimination depended on source directions. However, they used low-pass signals, that is, the subjects were not able to obtain any cues from high-frequency regions. In this study, we used broadband stimuli and HRTFs measured on a horizontal plane. We conducted a subjective test to clarify whether removing low-frequency cues from HRTFs affects horizontal localization.

2. FLATTENING PROCEDURE

2.1. HRTF Measurement

A set of HRTFs for each subject was measured using an optimized Aoshima's time-stretched pulse (OATSP) [16] with a sampling frequency of 48 kHz. Figure 1 shows the

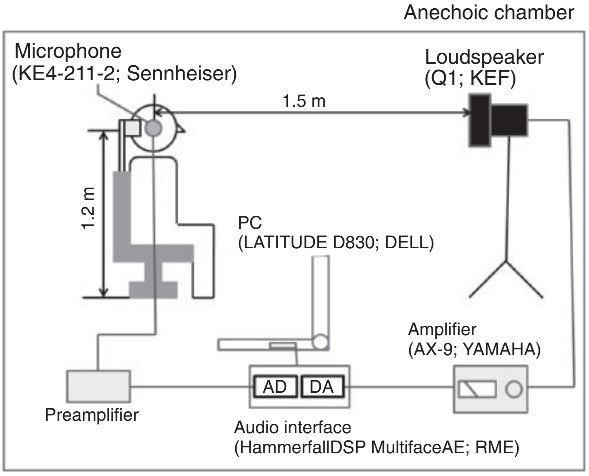
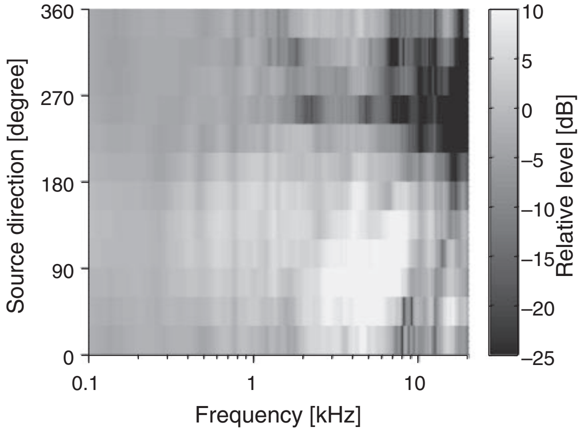
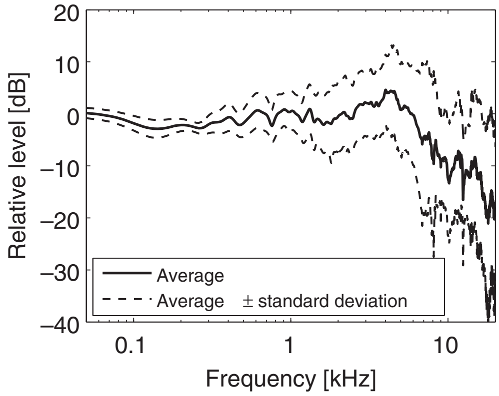


Fig. 1 The HRTF measurement system.



(a) Shading plot of azimuthal change in HRTFs



(b) Spatial average and standard deviation of HRTFs

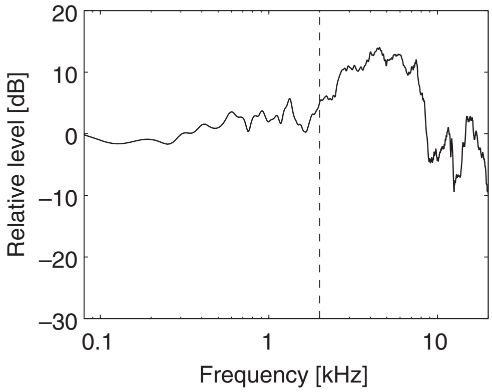
Fig. 2 Example plots of spatial change in HRTFs of one subject (right ear).

measurement system. A subject was seated in an anechoic chamber. A loudspeaker (Q1; KEF) was located 1.5 m from the center of the subject's interaural axis. The subject's ear canals were blocked [17], and miniature microphones (KE4-211-2; Sennheiser Electronic GmbH and Co. KG) were used to pick up the response to the OATSP signals. A headrest was mounted onto the chair in order to constrain the subject's head. The chair was rotated so as to measure HRTFs as the azimuth changed. In this measurement, the source at 0° is defined as front, and the other directions are defined by a clockwise rotation as viewed from above. An anti-alias filter with a cutoff frequency of 20 kHz was applied to each measured HRTF. Each HRTF was obtained as an impulse response. Because measured impulse responses contained possible reflections from the measurement setup, a rectangular window of 600 points was applied to each impulse response with its center corresponding to the response peak.

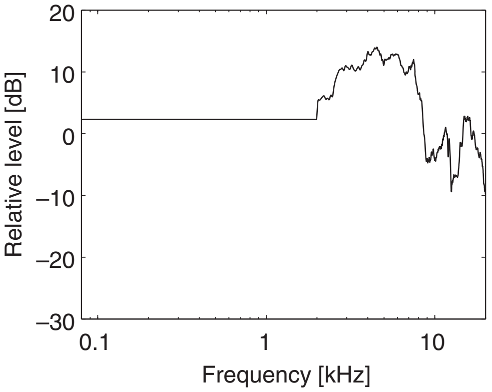
The HRTFs were obtained according to the definition described in [1]: the ratio of sound pressure measured at a point in the ear canal to that measured at a point corresponding to the center of the head while the subject was not present. Since the same setup was used for both measurements, characteristics specific to the measurement setup should have canceled each other out. After processing was complete, the length of the impulse response was set at 4,800 points with zero padding. Figure 2 illustrates the variations of the frequency spectra of a subject's measured HRTFs. Figure 2(a) shows the variations as a function of source direction and Fig. 2(b) shows the average and standard deviation of source directions calculated from the magnitude characteristics. The brightness indicates the relative level in the HRTFs in Fig. 2(a). As shown in this figure, the variation of a few dB to source directions is observed in low-frequency regions, such as the 0.1 to 1 kHz range. Differences of a few dB may be perceived and localization performance may be influenced by spectral forms in that region. Therefore, we investigated this influence by removing spectral features of HRTFs in the low-frequency range.

2.2. Flattening HRTFs in the Low-frequency Region

In this study, the magnitude of the HRTFs was flattened in the frequency region below a certain threshold. This frequency is referred to as the "boundary frequency." The phase characteristics of the frequency region to which flattening was applied were set so as to be linear and continuous at the boundary frequency. The level of the flattened region was set so as to retain the interaural level difference (ILD) calculated for the entire frequency range. After flattening the HRTF, the corresponding head-related impulse response (HRIR) was obtained by inverse Fourier transformation of the flattened HRTF. The interaural time difference (ITD) was maintained by restoring each initial delay included in the processed HRIR to that in the original one. An example of the method is presented in Fig. 3, where (a) shows the frequency characteristics of



(a) original HRTF



(b) flattened HRTF

Fig. 3 Example of HRTF flattening in the low-frequency region (source azimuth: 60°, right ear, boundary frequency: 2 kHz).

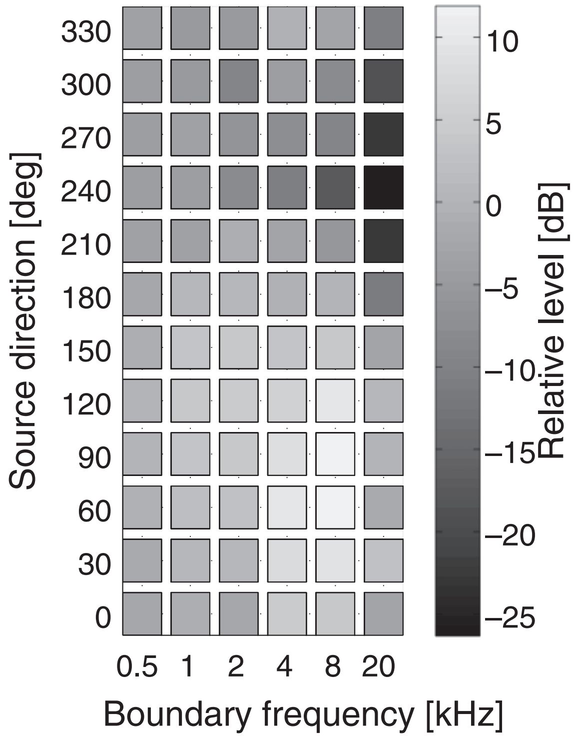


Fig. 4 Relative levels of the flattened region corresponding to the boundary frequencies set in the experiment (subject 3, right ear).

the original HRTF, and (b) shows the flattening of the spectral form in the frequency region lower than the boundary frequency of 2 kHz. The relative level in that region equaled the average level of the original HRTF in the frequency region corresponding to the flattened one. Consequently, the overall ILD was retained in all directions.

It should be noted that the sound pressure level within the flattened region varied somewhat across the source directions. In order to clarify this, change in the relative level of the flattened region for each boundary frequency condition (0.5, 1, 2, 4, 8, and 20 kHz, to be described in Sect. 3) and source direction is shown in Fig. 4. The characteristics of the right-ear HRTFs of subject 3 are represented in this figure. The levels are expressed relative to those derived from the transfer function measured at a point corresponding to the center of the head while the subject was not present. Spectral shape below the selected boundary frequency was flattened by adopting the procedures mentioned in this section. Figure 4 shows that the relative level of the flattened region varies within a few dB across the source directions, which might serve as a cue for sound localization.

3. EXPERIMENT

A localization test was conducted to evaluate the influence of flattening the HRTFs in the low-frequency region.

3.1. Subjects

Four male and one female subject aged between 22 and 24 years participated in the experiment. They had normal hearing acuity as reported by themselves.

3.2. Stimuli

A set of HRTFs was measured for each subject. The source directions were 30° apart, with 12 directions in total. The source signal was 1 s of pink noise with 100 ms raised-cosine on- and off-set ramps; the stimuli were made by convolving the signal with an HRTF or a flattened HRTF. The sound pressure level of the stimulus made by convolving the HRTF at 0° was approximately 70 dB; then each level of all stimuli was adjusted so that the relative level difference among source directions was maintained. The headphone compensation (equalization) was implemented by dividing the HRTFs by the individual (right and left) headphone transfer functions in the frequency domain. The gain of the inverse characteristics of the headphone transfer function in the frequency region near DC was excessively high because the sound barely radiated from

Table 1 Experimental conditions.

Subjects	Four males and one female
Source direction [deg.]	0–330 (intervals of 30°)
Source signal	Pink noise (duration of 1 s)
Boundary frequency [kHz]	0 (original), 0.5, 1, 2, 4, 8, 20
Frequency range of stimuli [kHz]	0.08–20

the headphones in that region. Therefore, a high-pass filter with a cutoff frequency of 80 Hz was applied to the equalization filter.

The boundary frequencies were set at 0, 0.5, 1, 2, 4, 8, and 20 kHz. The boundary frequency of 20 kHz corresponds to a flattening of the entire audible frequency region, and that at 0 kHz corresponds to no flattening (i.e., the original spectrum). Each stimulus was evaluated five times in random order.

3.3. Procedures

Subjects seated in an anechoic chamber listened to a stimulus presented through headphones (HD-650; Sennheiser Electronic GmbH and Co. KG). Each stimulus was a sound signal convolved with the subject's own HRTFs or the processed HRTFs, as described in the previous section. The subjects were asked to report the perceived direction in the horizontal plane by clicking a mouse button after moving the cursor over the corresponding location on a circle displayed on a computer screen, where the center of the circle corresponded to the subject's head. As a preliminary session, a localization test using real sound sources (loudspeakers) was conducted for the subjects to become familiar with the procedure of this experiment. The main experimental conditions are summarized in Table 1. In this experiment, the subjects were not asked to state whether they perceived a sound image inside or outside their heads.

3.4. Results

The results for five subjects under each condition are presented in Fig. 5. The abscissa is the simulated direction and the ordinate is the subject's perceived direction. In each panel, the size of the marker represents the number of judgments in a 30-degree-wide interval. If the responses are plotted around the diagonal, this indicates that the subject perceived the direction accurately. The boundary frequency is shown at the right of the figure. Four of the five subjects show similar localization performance in terms of the influence of flattening; the higher the boundary frequency, the more degraded the subjects' localization performance. Under the original condition, the responses of subjects 1 to 4 lie roughly along the diagonal, while those of subject 5 show that the subject perceived a sound image from the front as being from the rear, i.e., there was front-back confusion. Moreover, subject 5 showed frequent front-back confusion under all conditions. Therefore, the localization tendency is subject-dependent. Figure 5 also shows that each subject's answers were scattered widely for boundary frequencies above 4 kHz, i.e., the localization performance was degraded.

To evaluate the localization results for the flattened HRTFs with respect to lateral angle localization and front-back discrimination, we analyzed localization errors and front-back confusion rates, respectively using the same method as applied in [13]. Localization error was defined as the absolute value of the difference between a source direction and a perceived direction; if front-back confusion occurred, the perceived direction was reversed relative to the direction that was symmetrical about the interaural axis [12]. Errors were calculated for all source directions. Front-back confusion rates were calculated for all source directions except 90° and 270°. As shown in Fig. 5, subject 5 showed front-back confusion even under the original (i.e., no flattening) condition. Because the purpose of this study was to determine the effect of removing spectral cues from original HRTFs, subject 5's results were excluded from the following analysis. Figure 6 shows localization errors for each source direction, averaged over subjects. The abscissa is the boundary frequency, whereas the ordinate is the average localization error. The upper panel of the figure shows the results for source directions in the front, and the lower panel shows the results for those in the rear. The effects of flattening and source directions were analyzed by analysis of variance (ANOVA). The main effect of flattening was significant ($F(6, 1596) = 7.06$, $p < 0.01$), as was that of source direction ($F(11, 1596) = 6.10$, $p < 0.01$). The interaction of these two factors was insignificant. Since the main purpose of this study to investigate the effect of flattening HRTFs, we focused on the difference between errors under the original condition and those under each of the other conditions. We performed multiple comparison tests by the least significant difference (LSD) method. The results showed that only the error for the boundary frequency of 20 kHz differed significantly from the others (significance level was 5%).

Figure 7 shows the front-back confusion rates for each source direction, averaged over subjects. The abscissa is the boundary frequency, while the ordinate is the front-back confusion rate for all source directions except 90° and 270°. The upper panel of the figure shows the results for source directions in the front, and the lower panel shows the results for those in the rear. The ANOVA for the effects of flattened HRTF and source directions showed a significant interaction ($F(54, 210) = 2.63$, $p < 0.01$). Be-

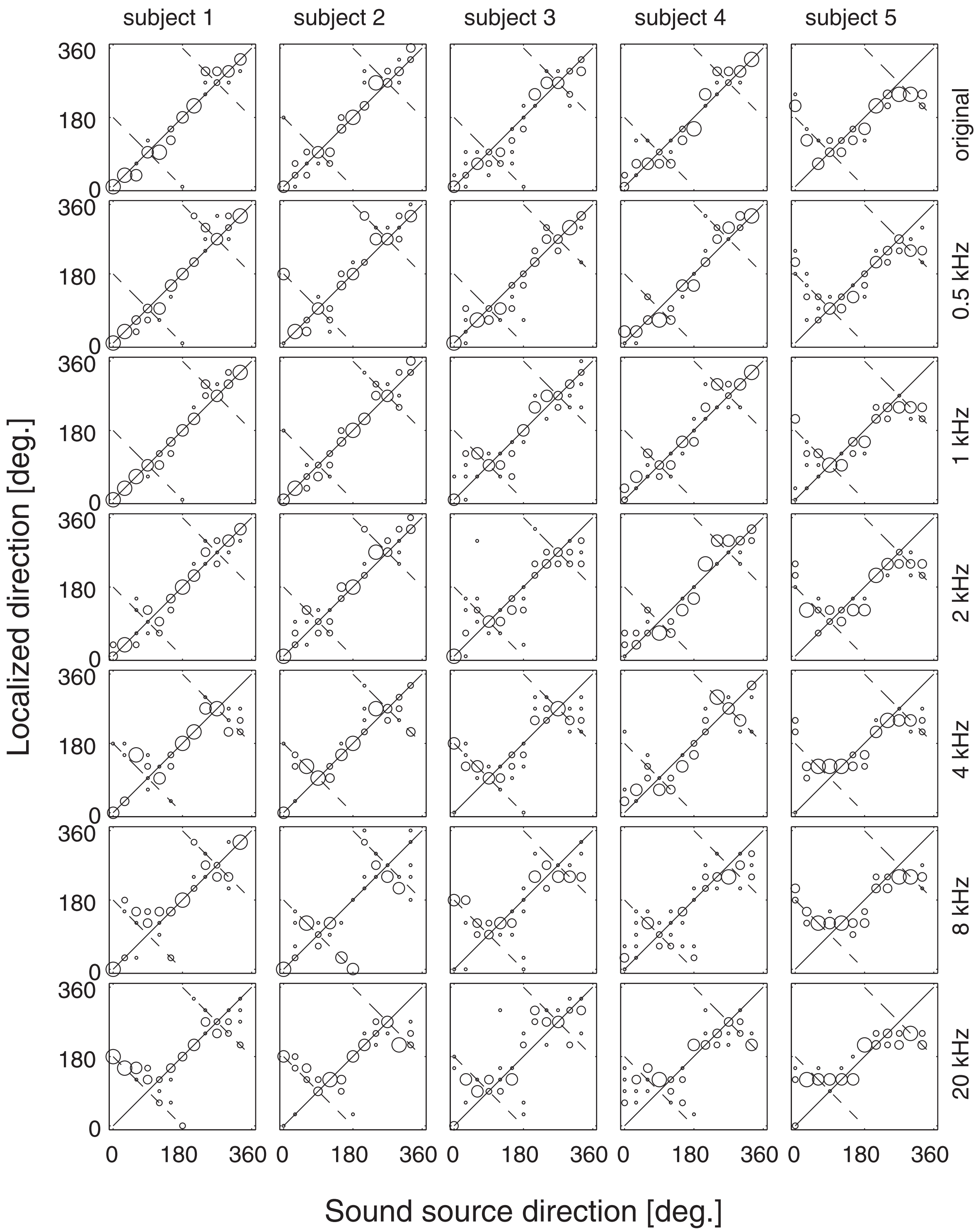


Fig. 5 Scatterplots of simulated directions versus the subject's perceived directions.

cause the simple main effect was significant for flattening when source directions were frontal (0, 30, 60, 300, and 330°), we performed multiple comparison tests by the LSD method. The conditions associated with significantly higher front-back confusion rates than in the case of 0 kHz (the original condition) are indicated with asterisks in Table 2 (significance level was 5%).

4. DISCUSSION

The results of ANOVA for localization errors showed that lateral angle identification was difficult when all spectral cues were removed from HRTFs. Although the cause of this phenomenon is unknown, lateralization should occur because no spectral cues were included in

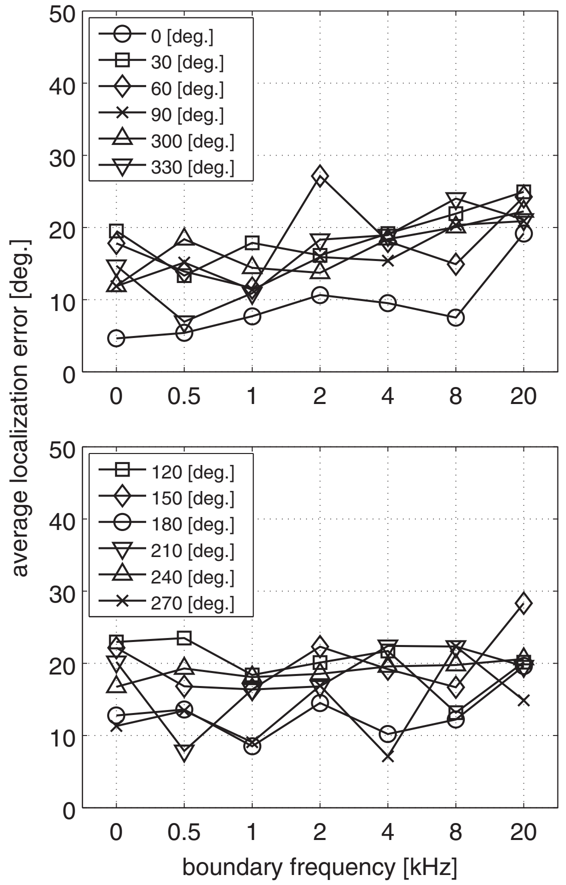


Fig. 6 Average localization error for front (upper panel) and rear (lower panel) source directions.

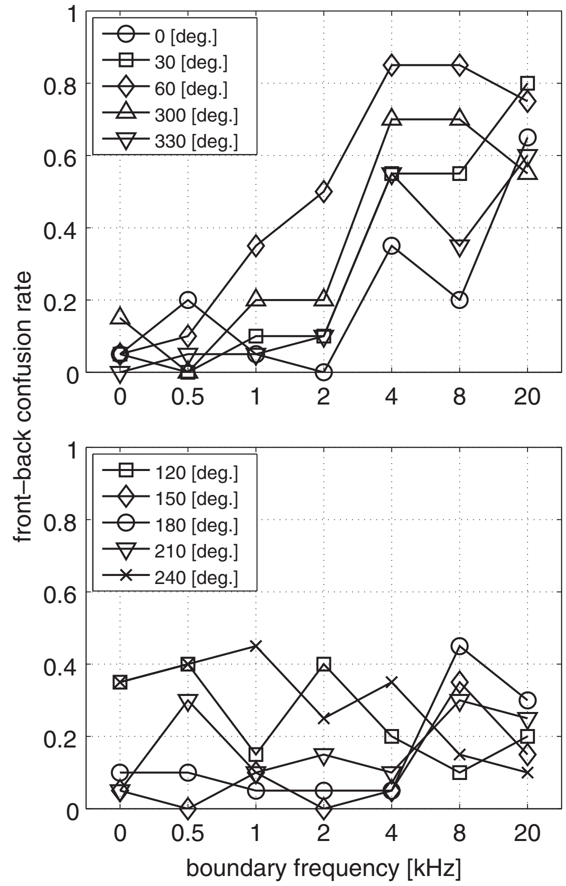


Fig. 7 Front-back confusion rates for front (upper panel) and rear (lower panel) source directions.

flattened HRTFs. These results might suggest that subjects were able to discriminate between lateral angles using some spectral cues. In addition, subjects used the ILDs and ITDs as cues, because they were retained in the flattened HRTFs.

As seen in Fig. 7, front-back confusion rates tended to increase if the frequency region in which the flattening was performed was wide. That is, flattening influenced front-back discrimination. The spectral structure of HRTFs is generally thought to be important as a cue in front-back discrimination [4,18]. Our results, however, suggest that it is not necessary to accurately synthesize the spectral structure of HRTFs in all frequency regions. The spectral forms of the HRTFs for frequencies below 2 kHz may be flattened, except for the source direction of 60°, independent of the high-frequency region, as can be seen in the results obtained by statistical analysis shown in Table 2. Asano *et al.* [7] concluded that the important cues for front-back judgment exist in microscopic spectral cues below 2 kHz. Our own results were inconsistent with this conclusion. The HRTFs used in the experiment performed by Asano *et al.* were simplified by smoothing, that is, there was distortion of spectral features such as peaks and dips whose variation was larger than the directional

Table 2 Results of LSD test. Asterisks denote the boundary frequency conditions under which front-back confusion rate was significantly different (significance level was 5%) from that obtained for the original signal for each source direction.

Source direction [deg.]	Boundary frequency [kHz]					
	0.5	1	2	4	8	20
0				*		*
30				*	*	*
60		*	*	*	*	*
300				*	*	
330				*	*	*

variation observed in Fig. 2. These spectral features might influence localization. On the other hand, the HRTFs used in this study were simplified by flattening, that is, there were no spectral features that could be used by the subjects. Therefore, the subjects may have achieved front-back discrimination by using cues only in high-frequency region.

As shown in Table 2, the influence of flattening differed among source directions. Algazi *et al.* [15] reported that the spectral cues in low-frequency regions existed at source directions away from the median plane. Although Table 2 shows that only the results for the 60° direction showed a different significance from those for the other directions, our results might be consistent with the results reported by Algazi *et al.* [15]. In this study, the spectral forms of the HRTFs in the frequency region below 2 kHz did not influence the subjects' ability to discriminate front from back, except for the source direction of 60°. In addition, our results imply that the simplification of HRTFs might be possible without the degradation of localization performance; if an appropriate data reduction method is applied, the region below 0.5–2 kHz, where depends on source direction, can be disregarded.

5. CONCLUSIONS

In this work, we investigated the role of spectral cues in the low-frequency region of HRTFs, by verifying whether flattening influenced sound localization performance. A localization test was conducted using HRTFs that were partially flattened in frequency. The results showed the following.

(1) The spectral forms of HRTFs below 8 kHz did not influence horizontal localization when front-back confusion was ignored. The subjects were likely to base their judgments on the ITD and ILD cues.
(2) With respect to front-back discrimination, flattening HRTFs in low-frequency regions might have an effect depending on source direction; flattening HRTFs at directions away from the median plane had greater influence than those near the median plane.
(3) Except for the source direction of 60°, the low-frequency region below 2 kHz did not influence front-back discrimination.

The results of our experiment suggest that the auditory system is unlikely to utilize the spectral information in the low-frequency region if cues regarding interaural differences in the overall frequency range are adequately reproduced. The results also suggest an efficient representation of HRTFs, such as data reduction, without a significant effect on localization performance.

Our previous work showed that removing spectral cues in contralateral HRTFs in the high-frequency region had no effect on localization. An issue that remains for future study is the influence of flattening HRTFs in both high- and low-frequency regions. Subjects might perceive a sound image inside their head under some flattening conditions, and verifying this possibility is another potential topic of future work.

ACKNOWLEDGEMENTS

This work was partially supported by a Grant-in-Aid for Young Scientists (B) (21700140, 24700120).

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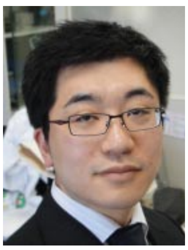

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