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Feature Analysis of Sound Direction Perception Using Frequency Band-Limited Stmuli: Extension of a Directional Band Model

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Abstract

A directional band model of median-plane localization has been developed. Perception of sound direction for a narrow band noise in the median plane depends mainly on the center frequency and bandwidth. In median-plane localization, a frequency band limited stimulus gives perception associated with a given direction. Earlier studies were commonly implemented for the median plane and binaural hearing. No directional band model of monaural hearing, however, has been examined. Moreover, none for another plane has been examined sufficiently. For this research, we make an extension of a directional band model: we examine features in a different plane (e.g., the horizontal plane) and monaural hearing. For this study, stimuli were applied from loudspeakers on the upper hemisphere surface. Results of experiments conducted for direction recognition demonstrate that some frequency bands in monaural hearing correspond to specific directions. Additionally, we clarified features of the directional band model for binaural hearing aside from the median plane, which suggests the possibility of a directional band model of 3-D space localization.

Keywords: sound image localization, directional band, monaural hearing

1 INTRODUCTION

Blauert et al. reported the directional band model[1],[2]. Perception of sound direction for a narrow band noise in the median plane depends mainly on the center frequency and bandwidth. Itoh et al. also established that there was no distinct difference between directional bands for 1/3 and 1/6 octave band noises[3].

The discussion of the directional band is commonly directed to the median and sagittal planes, and not to the horizontal plane. This is because the conventional consideration of the directional band is intended for binaural hearing when interaural time difference (ITD) and interaural level difference (ILD) can be used as cues for direction recognition[4]. That is, when considering sound image localization for binaural hearing, it can be said that the peaks and notches of head-related transfer function (HRTF) in the horizontal plane have little influence.

However, in the case of monaural hearing, the used cues for direction recognition are different from those for binaural hearing. For monaural hearing such as the persons with UHL, ILD and ITD is not available to recognize the direction of the sound. Additionally it can be thought that the issue of the spectral cue on the horizontal plane by monaural hearing is similar to that of the median plane by binaural hearing. Therefore, there is a relationship between influence of the spectral cue on the horizontal plane by monaural hearing and that of the median plane by binaural hearing.

So far, various research institutes have conducted research on human's sound direction recognition, and many findings have been obtained[5]-[10]. At the same time, whereas the research on improving the quality of life (QoL) of deaf people has also been reported, some have focused on unilateral deafness. However, the knowledge about the direction recognition by monaural hearing is not sufficient. In this study, we investigate the influence of a directional band on the horizontal plane by monaural hearing, and extend a Directional Band Model by experimental analysis of sound direction perception using frequency band-limited stmuli.

2 FIRST EXPERIMENT

2.1 Method

2.1.1 Subject

Five subjects participated, ranging in age from 21-24 years. One of the subjects is a deaf person with a left ear (subject E) and the others are persons with normal hearing sensitivity (subject A, B, C, and D). We established a monaural listening condition by inserting an earplug (pura-fit, Moldex, NRR:33[dB])[11, 12].

2.1.2 Apparatus

The experiment was conducted in an anechoic chamber. Eight loudspeakers were located at every 45 degrees in the horizontal plane as shown in figure 1. The height of the loudspeaker was 1.1 m. The distance of the loudspeakers from the center of the subject's head was fixed at 1.0 m. The stimuli were noise signals of one third octave bandwidth, and presented from the loudspeakers. In all experiments, 20 different stimulus conditions were established. Our choice of frequency band is illustrated in figure 2. The sound pressure level of stimuli was 50 dB. Stimulus were randomly presented three times from each loudspeaker for one second, followed by an interval of two seconds.

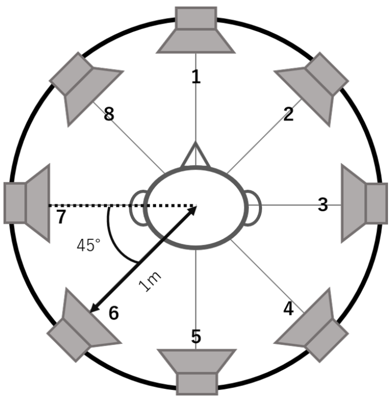


Figure 1. Arrangement of sound sources in the first experiment.

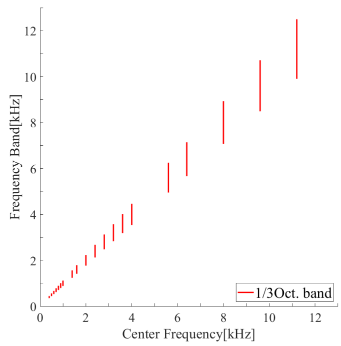


Figure 2. A diagramatic sketch of the noise stmuli

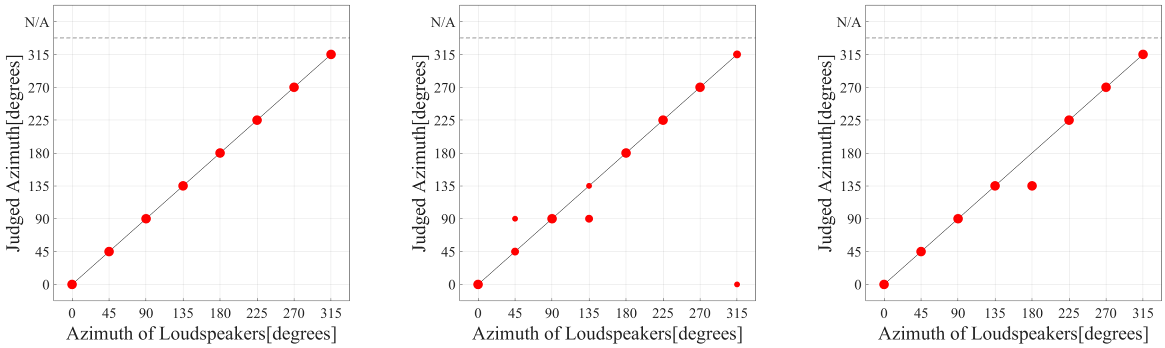
2.1.3 Procedure

Each subject was individually tested ,and it was instructed to face the front and keep his/her head fixed while stimuli were presented. The subjects verbally answer the loudspeaker number (from 1 to 8) closest to the direction where the sound image was localized during the stimulation interval (See figure 1). If the sound image was not localized, they was instructed to answer number 0. We performed sound image localization experiment of 20 sessions per one subject.

2.1.4 Broadband signal results

For comparison with narrowband signal results, the results of the broadband signal (white noise, 20 Hz to 20 kHz) are shown in figure 3. The experimental environment and procedure were set in the way as 2.1.2 and 2.1.3. Figure 3a shows the result of binaural hearing, figure 3b shows the result of left ear hearing by inserting the earplug to the right ear, and figure 3c shows the result of right ear hearing by inserting the earplug to the left ear. All figures are the results of subject A. The vertical axis shows the angle that subjects answered, and the horizontal one is the angle of the loudspeaker that presented the stimuli.

Filled red circles indicate responses, and unfilled ones indicate the case that the sound image was not local-



(a) Binaural hearing　　(b) Left ear hearing　　(c) Right ear hearing

Figure 3. Localization test results of broadband signal

ized (subjects answered 0). The size of the circles is proportional to the number of answers. The diagonal line rising to the right indicates the case where the presentation angle matches the judged angle.

As you can see figure 3a, the sound image localization of the broadband signal is usually correct for binaural hearing. The figures 3b and 3c show that localization error slightly occurs on the side direction where the earplug was inserted.

2.2 Results

2.2.1 Narrowband signal results

Figure 4 shows the results under the condition where the center frequency of the narrowband stimulus signal is 2.4, 6.4 and 11.2 kHz for subject A inserted the earplug into the left ear. Looking at figure 4a to figure 4c ,the localization is biased at 45 deg (right front) at a center frequency of 2.4 kHz, 90 to 135 deg (right side to right ear) at 6.4 kHz, and 135 deg (right rear) at 11.2 kHz, respectively. Similarly, from figure 5a to figure 5c, the localization is biased to 0 and 315 deg (left front) at a center frequency of 2.4 kHz, 270 to 315 deg (left side) at 6.4 kHz, and 225 deg (left rear) at 11.2 kHz.

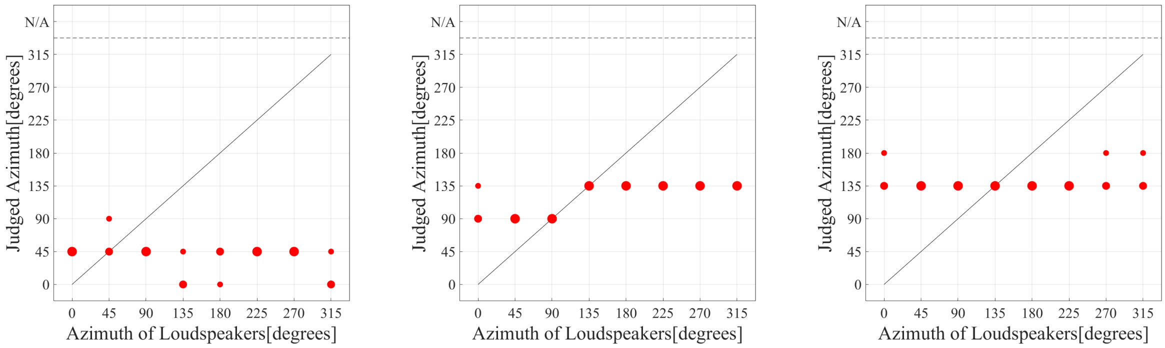
As depicted in figure 4, the responses for each frequency band are arranged at each different angle. It suggests that the responses for narrowband stimulus are concentrated in a particular direction, as compared to the broadband signal results in figure 3.

Therefore, it can be said that the sound image localization of narrow band signal in monaural hearing is biased in a specific direction for each center frequency regardless of the presentation direction of stimuli.

2.2.2 Test and discussion of results

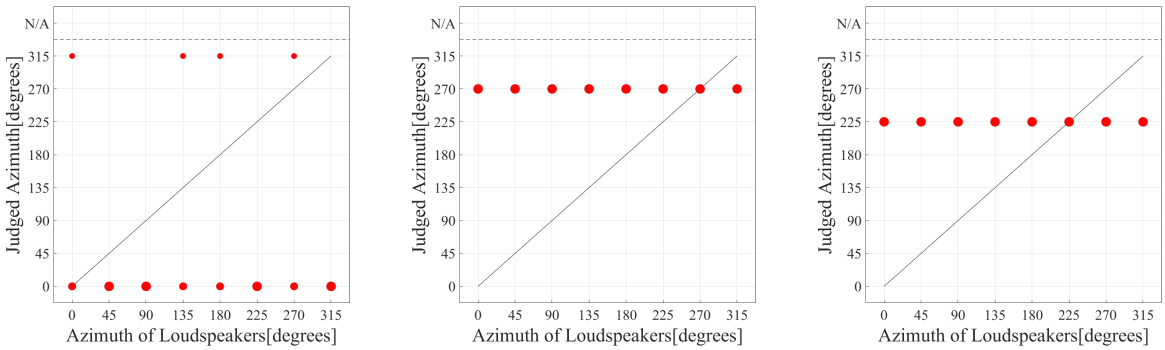
Binomial test was performed on the results of sound localization experiments of four subjects, and the horizontal directional band was determined. Table 1 shows the result of binomial test. We examine whether the answer (judged angle) is biased for narrowband stimulus. If the number of answers (direction of a judged angle including $\pm$ 45 deg) is more than that of responses of other angles, we paint the biased direction with a black arc. Here, the decision rule is defined to make the significance level 5 %. In addition, the cells of the center frequency f_c in the table are shaded according to the directional band in the median plane reported by Blauert[1].

Looking at Table 1, in the case of subject A, the localization direction is biased to the right front when the center frequency is 0.6 to 2 kHz, and to the right side from 2.4 to 4 kHz, and to the right rear from 8 to 11.2



(a) fc = 2.4 kHz (b) fc = 6.4 kHz (c) fc = 11.2 kHz

Figure 4. Localization test results of narrowband signal (Right ear hearing)



(a) fc = 2.4 kHz (b) fc = 6.4 kHz (c) fc = 11.2 kHz

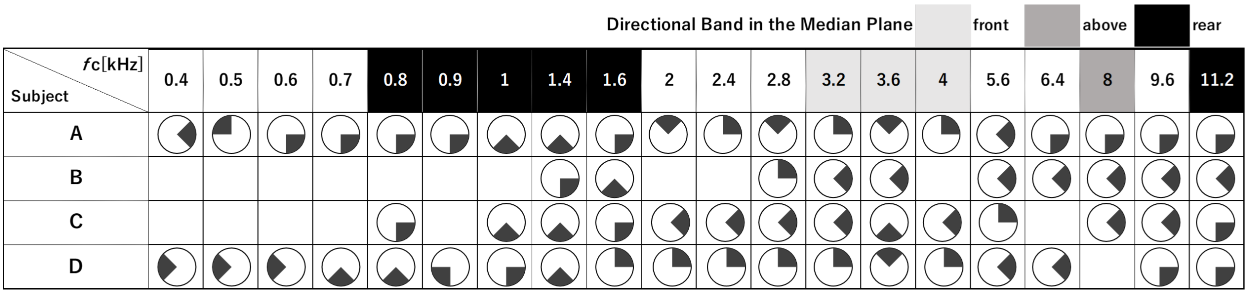
Figure 5. Localization test results of narrowband signal (Left ear hearing)

kHz. That is, the localization direction differs for each frequency band mainly on the open (audible) ear side. Similarly for other subjects, although there were individual differences, the frequency band causes deviation in direction perception of the narrow band signal. Therefore, it can be said that the directional band exists even in the state of monaural hearing and the horizontal plane.

3 SECOND EXPERIMENT

The second experiment extended the discussion of the horizontal directional band in monaural hearing, and we examined whether a deviation in direction recognition would occur even if the stimuli were presented from the upper hemisphere, not limited to the horizontal plane.

Table 1. Horizontal Directional Band of Monaural Hearing (Right ear hearing)



3.1 Methods

3.1.1 Subject

Five subjects participated, ranging in age from 21-24 years. One of the subjects is a deaf person with a left ear (subject E) and the others are persons with normal hearing sensitivity (subject A, B, C, D). We established a monaural listening condition by inserting an earplug as in the first experiment.

3.1.2 Apparatus

Sixteen loudspeakers were located in the anechoic chamber as shown in figure 6. Other conditions were the same as in the first experiment.

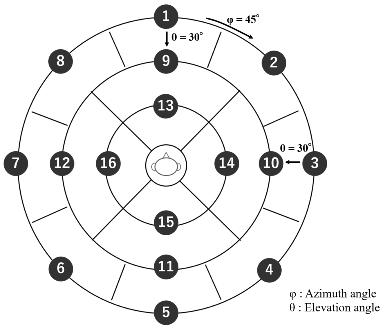


Figure 6. Arrangement of sound sources in the second experiment.

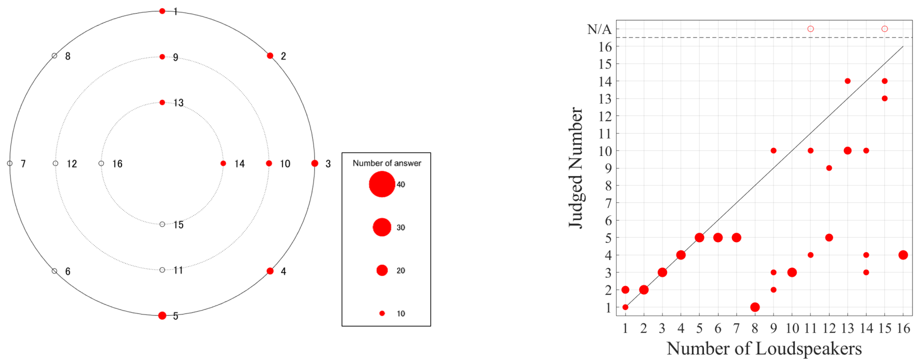
3.1.3 Procedure

Subjects were instructed to verbally respond to loudspeaker numbers from 1 to 16 during the stimulation interval (See figure 6). All other experiment procedures were the same as in the first experiment.

3.1.4 Broadband signal results

For comparison with narrowband signal results, the results from the broadband signal (white noise) are shown in figure 7. The experimental environment and procedure were set in the way as in 3.1.2 and 3.1.3.

Figure 7a is an overhead view of the experimental device (corresponding to figure 6), and shows the position answered in this experiment. Here, figure 7a shows the integrated number of each judged angle in the figure 7b. The size of the circles is proportional to the number of answers. In figure 7b, the vertical axis represents the loudspeaker number that subjects answered, and the horizontal one is the angle of the loudspeaker that presented the stimuli.



(a) (b)

Figure 7. Localization test results of broadband signal (Right ear hearing)

Filled red circles indicate responses, and unfilled ones indicate the case that the sound image was not localized (subjects answered 0). The size of the circles is proportional to the number of answers. The diagonal line rising to the right indicates is the position corresponding to the correct localization.

As you can see figure 7b, when the stimuli from the right side of the horizontal plane could be localized correctly. When the elevation angle in the presentation direction was greater than 0 deg, localization errors were often observed. However, it can be said that in the case of the broadband signal, the height could be recognized even in the monaural hearing.

3.2 Results

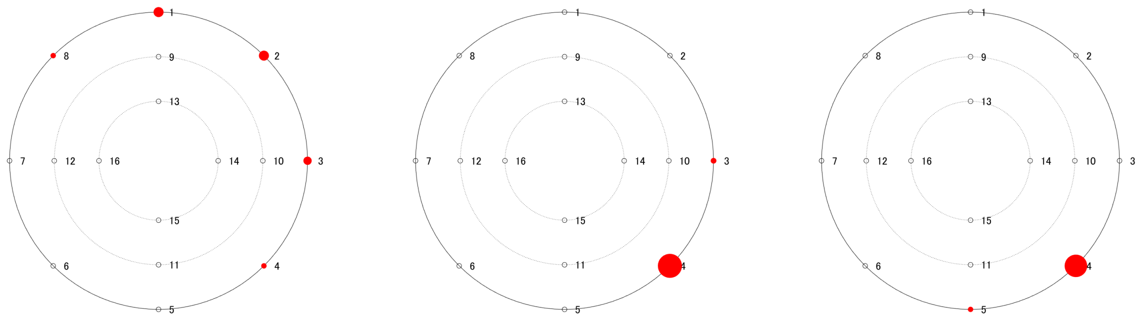
3.2.1 Narrowband signal results

Figure 8 shows the results when the center frequency of the stimulus is 2.4, 6.4 and 11.2 kHz for subject A inserted the earplug into the left ear. Looking at figures 8a to 8c, the localization is biased horizontal right front to back at a center frequency of 2.4 kHz, horizontal right side to rear at 6.4 kHz, and horizontal right rear at 11.2 kHz. Moreover, looking at figures 9a to 9c, the responses for each frequency band are arranged at a particular angle. It suggests that the responses for narrowband stimulus are concentrated in a particular direction, as compared to the broadband signal results in figure 7, which is same as the result of horizontal presentation in figure 4 and 5. The deviation of the localization is obviously confirmed.

Therefore, it can be said that the sound image localization of narrow band signal in monaural hearing is biased for each center frequency regardless of the presentation direction of stimuli in 3-D space.

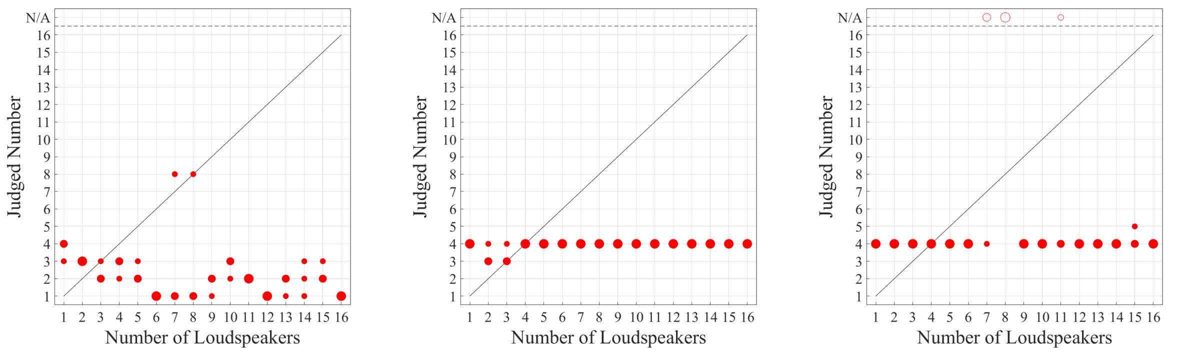
3.2.2 Test and discussion of results

Binomial test was performed on the results of sound localization experiments of subject A with right ear hearing, and the directional band was determined. Table 1 shows the result of binomial test. Here, the decision rule is defined in the same way as the Sec. 2.2.2. Looking at Table 1 and 2, it can be understood that there is no significant difference between two results in the tendency of the biased direction and transition of the angle judged. Consequently, even if the presentation direction of the stimuli is expanded to the upper hemisphere, it is considered that it does not affect the directional band in monaural hearing.



(a) fc = 2.4 kHz (b) fc = 6.4 kHz (c) fc = 11.2 kHz

Figure 8. Second localization test results of narrowband signal (Right ear hearing)



(a) fc = 2.4 kHz (b) fc = 6.4 kHz (c) fc = 11.2 kHz

Figure 9. Second localization test results of narrowband signal (Right ear hearing)

4 CONCLUSIONS

In this study, we investigate the influence of a directional band on the horizontal plane by monaural hearing. Although the directional band was argued in the median plane and binaural hearing reported in past studies, we conducted two experiments to extend and discuss a directional band model experimentally analyzing sound direction perception using frequency band-limited stimuli.

As a result, it's suggested that (1) there is a horizontal directional band in monaural hearing, and (2) the same phenomenon can be seen even if the stimulus presentation direction is not limited to the horizontal plane but expanded to the upper hemisphere.

ACKNOWLEDGEMENTS

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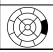
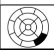
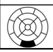
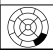
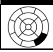
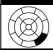
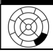
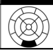
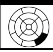
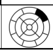
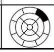
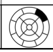
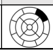
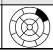
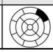
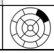
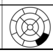
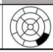
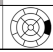
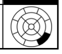
Table 2. Directional Band of Monoural Hearing (Right ear hearing)

Directional Band in the Median Plane front above rear

Subject \ fc[kHz]	0.4	0.5	0.6	0.7	0.8	0.9	1	1.4	1.6	2	2.4	2.8	3.2	3.6	4	5.6	6.4	8	9.6	11.2
A																				

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