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Impact of head movement on sound localization with band-limited noise

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ABSTRACT

This paper clarifies the relationship between head movement and sound localization with band-limited noise (12-kHz high-pass, 500-Hz low-pass and 2-4-, 4-8-, 8-12-kHz band-pass filtered noise). 12-kHz high-pass noise mainly provides interaural level difference (ILD) information, while 500-kHz low-pass noise mainly provides interaural time difference (ITD) information. Band-pass noises provide a mixture of ILD and spectral cue information depending on the bandwidth. Four subjects listened to each band-limited noise in head-still and head-movement conditions. Regarding horizontal plane, sound localization was difficult in the head-still condition, while it was possible in the head-movement condition. These results suggest that temporal variation of ITD and ILD caused by head movement impacts horizontal sound localization. Regarding the median plane, sound localization was also difficult in the head-still condition, while it was sometime possible in the head-movement condition. However, improvement in sound localization performance varied from bandwidth to bandwidth of the stimuli. These results suggest that temporal variation of the spectral cue caused by head movement impacts median sound localization.

Keywords: Sound localization, Signal bandwidth, Head movement

1. INTRODUCTION

Three-dimensional (3-D) sound can be reproduced by either binaural, transaural, wave-field synthesis, or multi channel surround sound technology. It is known that the interaural time difference (ITD), interaural level difference (ILD), and spectral cues, which are involved in the head-related transfer function (HRTF) or head-related impulse response, greatly contribute to 3-D sound localization [1]. There have been, however, few reports on how broad bandwidth is necessary to perceive reproduced sound as 3-D sound. Regarding the horizontal plane localization, Nakabayashi reported that the signal bandwidth over 8 kHz is important [2]. In addition Arrabito *et al.* reported that the signal bandwidth over 14 kHz is not necessary [3]. We have confirmed that signal bandwidth from 2 to 12 kHz is necessary and sufficient [4]. Regarding the median plane localization, Morimoto *et al.* reported that the signal bandwidth from 4.8 to 9.6 kHz is necessary [5]; whereas, Hebrank *et al.* reported that the signal bandwidth from 4 to 16 kHz is necessary [6]. All these values were obtained in the head-still condition. However, it is known that head movement greatly impacts sound localization [7-11]. We clarify the impact of head movement on horizontal as well as median sound localization with high-pass, low-pass and band-pass noises which are difficult to localize in the head-still condition.

2. EXPERIMENTAL SYSYEM

2.1 System

Figure 1 shows the experimental system. The system consisted of a Windows-based PC, three

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8-channel digital-to-analog converters (DACs) (Roland, UA-101), 12 power amplifiers (BOSE, 1705II), and 17 loudspeakers (Vifa, MG10SD-09-08). The sampling frequency of the DACs was 48 kHz. The loudspeakers were placed around a chair in a horizontal and upper hemisphere in the median of 1-m radius at 30-degree intervals. The height of these horizontal loudspeakers was 1.1 m. The sound localization experiment was carried out in an experimental room with the walls and ceiling covered with sound absorbing materials. The A-weighted sound pressure level of the room was 23 dB and reverberation time was less than 50 ms.

2.2 Stimuli

Broadband noise, *i.e.*, Gaussian distributed random noise, high-pass (cut-off frequency: *fc* = 12 kHz), low-pass (*fc* = 500 Hz) and band-pass (*fc* = 2-4, 4-8, 8-12 kHz) filtered noise were used as stimuli. The high-, low-, and band-pass filters were 512-tap finite impulse response (FIR) filters with 60-dB stop-band attenuation. The stimulus duration and inter stimulus interval were both 3 s. A 30-ms linear taper window was applied at the beginning and end of the stimuli. As the frequency responses of the loudspeakers are fairly flat (±8.7 dB) between 0.1 to 20 kHz, no inverse filter was used to correct the speaker response in the experiment. The sound pressure level of the broadband noise was 70 dB, while those of the high-pass, low-pass and band-pass filtered noises decreased according to the filtering.

2.3 Procedure

The experimental procedure was as follows. Subjects sat on a chair placed in the center of the speaker array and listened to stimuli reproduced from one of the loudspeakers. In the head-still condition, subjects were instructed to close their eyes and keep their head still when a stimulus was reproduced. In the head-movement condition, subjects were instructed to close their eyes and move their heads in a horizontal direction when a stimulus was reproduced.

Regarding the horizontal plane sound localization experiment, subjects were asked to localize the sound image position of real sound sources and to mark the localized angle from one of 12 directions on an answer sheet. Each session consisted of 60 trials, and the stimuli were presented in random order from the 12 loudspeakers. Regarding the median plane sound localization experiment, subjects were asked to localize the sound image position of real sound sources and to speak the localized angle from one of 7 directions on a microphone. Each session consisted of 35 trials, and the stimuli were presented in random order from the 7 loud speakers. One experiment consisted of 4 sessions, resulting in 20 answers from each direction. Experiments were conducted separately for each broadband, high-pass, low-pass and band-pass noise stimulus in the head-still and head-movement conditions.

2.4 Subjects

Four normal-hearing males in their 20s, whose hearing thresholds had been measured, participated in the sound localization experiments.

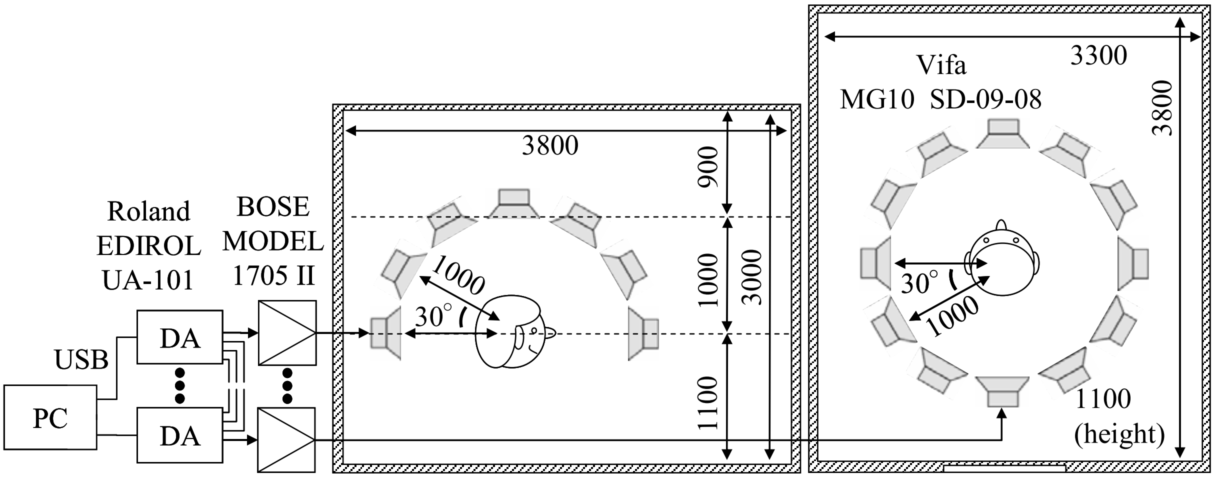

Figure 1 – Experimental system and setup

3. RESULTS

3.1 Horizontal Sound Localization

Figure 2 is the pooled horizontal sound localization results for the four subjects for each stimulus. The ordinate of each panel represents the perceived azimuth, and the abscissa, the target azimuth. The size of each circle is proportional to the number of answers. The sound images were localized away from the head for all stimuli. Regarding the head-still condition, localization was almost perfect for broadband noise. However, sound localization was difficult with other stimuli. As seen in the results of the 12-kHz high-pass noise, localization was vague. For the 500-Hz low-pass noise, many stimuli were localized with front-back confusion. From the results of the band-pass noises, many stimuli were localized to neighboring angles and some stimuli were localized with front-back confusion. Regarding the head-movement condition, localization was almost perfect with all stimuli.

Figure 3 plots the mean sound localization performance, *i.e.*, the correct rate for localizing sound stimuli, and the improvement rate for the four subjects for each stimulus. Localization performance was 96% for broadband noise in the head-still condition. In addition, localization performance was poorer for the 12-kHz high-pass, 500-Hz low-pass, and band-pass noises than for broad band noise in the head-still condition. Localization performance was 76, 69, 64, 69 and 70% for the 12-kHz high-pass, 500-Hz low-pass, 2-4-, 4-8, and 8-12-kHz band-pass noises, respectively. In contrast, localization performance was over 93% with each stimulus in the head-movement condition. Localization performances improved 17 to 35% for band-limited noises due to head movement.

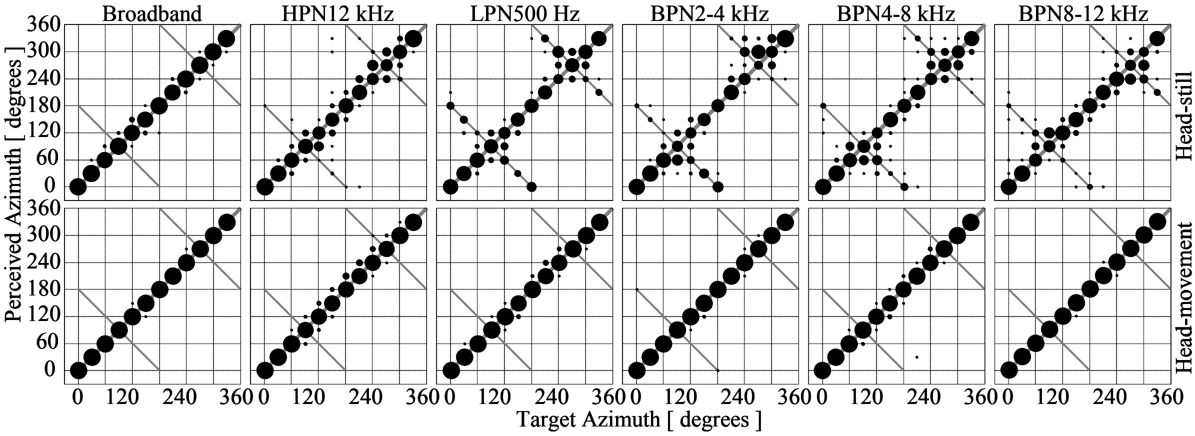

Figure 2 – Horizontal sound localization results

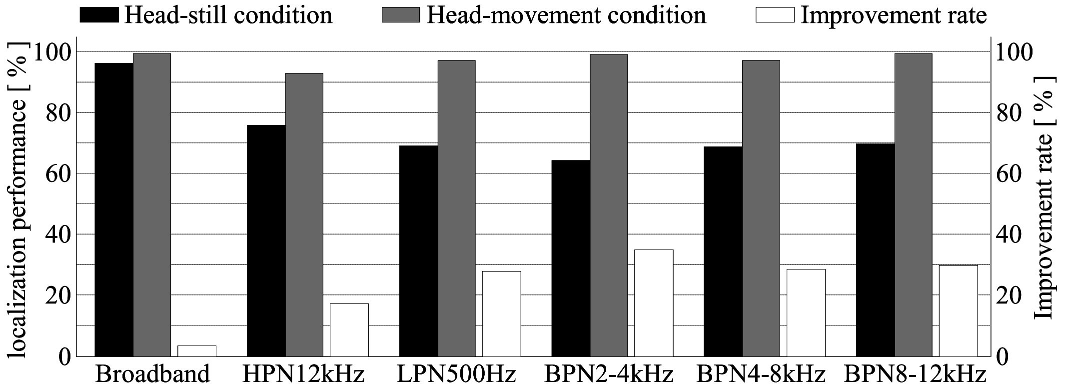

Figure 3 – Horizontal sound localization performance and improvement rate

3.2 Median Sound Localization

Figure 4 is the pooled median sound localization results for the four subjects for each stimulus. The sound images were localized away from the head for all stimuli. Regarding the head-still condition, localization was difficult with all stimuli. From the results of the 12-kHz high-pass and 8-12-kHz band-pass noises, localization was vague with stimuli from the front. However, localization was very difficult with stimuli from the rear. For the 500-Hz low-pass noise, localization was impossible with the stimuli. For the 2-4-kHz band-pass noise, localization was possible only front or back. For the 4-8-kHz band-pass noise, localization was vague with the stimuli. Regarding the head-movement condition, localization improved with all stimuli.

Figure 5 plots the mean localization performance and improvement rate for the four subjects for each stimulus. Localization performance was 72, 40, 17, 28, 25% and 29% for the broadband, 12-kHz high-pass, 500-Hz low-pass, 2-4-, 4-8-, and 8-12-kHz band-pass noises. In contrast, localization performance was 92, 71, 70, 55, 83 and 70% for the broadband, 12-kHz high-pass, 500-Hz low-pass, 2-4-, 4-8-, and 8-12-kHz band-pass noises. Localization performances improved 28 to 57% for the band-limited noises due to head movement. However, localization performance was poorer, less than 15%, for the 2-4-kHz band-pass noise than for other stimuli.

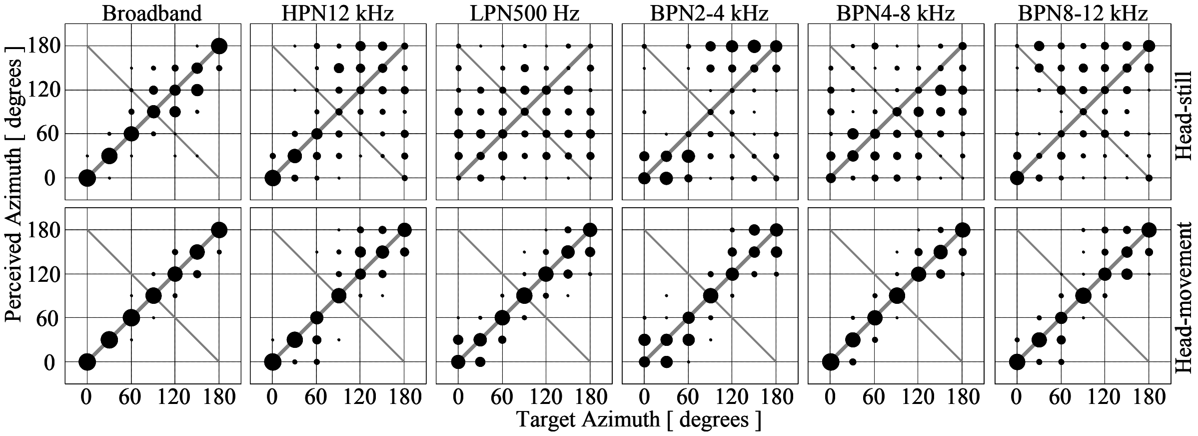

Figure 4 – Median sound localization results

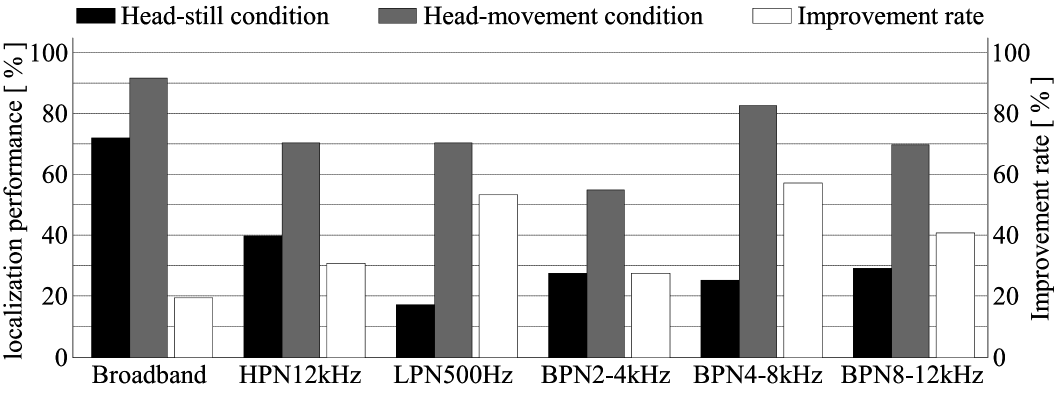

Figure 5 – Median sound localization performance and improvement rate

4. DISCUSSION

Figure 6 shows the frequency range of the acoustical cues, ITD, ILD, and spectral cues, to be calculated. The ITD is calculated from the low-frequency component below 1.5 kHz [1]. The ILD is mainly calculated from the high-frequency component above 1.5 kHz [1]. The spectral cues are calculated from the middle-frequency component, from 5 to 10 kHz [1] or 6 to 16 kHz [12]. Therefore, the 500-Hz low-pass noise mainly provides ITD information, the 12-kHz high-pass noise and band-pass noises provide a mixture of ILD and spectral cue information depending on its bandwidth. It is known that ITD and ILD greatly contribute to horizontal plane localization. By contrast, spectral cues are known to be important for median sound localization.

Regarding the horizontal sound localization, localization performance was poorer, 20% or more, for the high-pass, low-pass and band-pass noises than the broadband noise in the head-still conditions because the 500-Hz low-pass noise does not have frequency components to calculate ILD. Therefore, a number of front-back confusions occurred with these stimuli. Likewise, the 12-kHz high-pass and band-pass noises do not have frequency components to calculate ITD. Therefore, a number of localization errors to neighboring angles occurred for these stimuli. By contrast, sound localization was quite possible in the head-movement condition for all stimuli. Front-back confusions and miss localization to neighboring angles disappeared almost completely. These results clearly show that the temporal variation of ITD and ILD caused by head movement has greatly impacts horizontal sound localization.

Regarding the median sound localization, localizations were more difficult with all median plane stimuli in the head-still condition because all stimuli have the same ITD and ILD (= 0). It is the only spectral cue that can be used for localization. Thus, the bandwidth of the stimuli is important for localization. Localization was very difficult with the 500-Hz low-pass noise because it lacks a frequency band for calculating the spectral cues. In contrast, localization was better than those of the other band-limited noises for stimuli presented from the front for the 12-kHz high-pass and 8-12-kHz band-pass noises because they have enough frequency components to calculate ILD and spectral cues.

By contrast, sound localization was possible in the head-movement condition because ΔITD and ΔILD can be caused by head movement. Sound localization was most difficult with the 2-4-kHz band-pass noise in the head-movement condition. This is because it does not have frequency components to calculate spectral cues compared with the stimuli in which both ΔILD and spectral cues are available, or the 500-Hz low-pass noise in which ΔITD is only available. These results clearly show that temporal variation of the ITD, ILD, and spectral cues caused by head movement impacts in median sound localization.

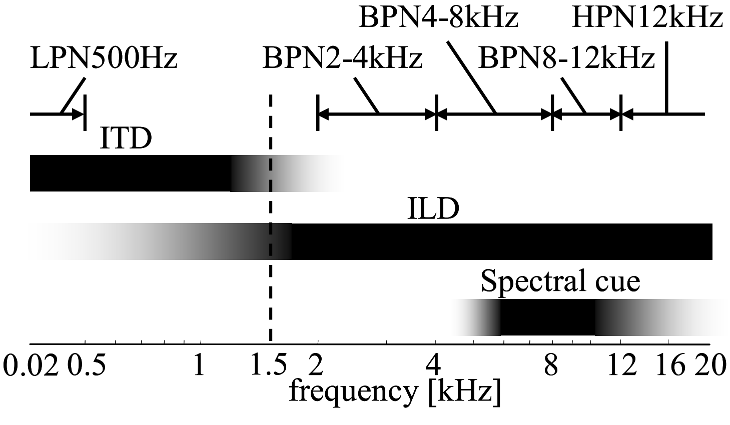

Figure 6 – Relationship between frequency components and localization information

5. CONCLUSION

Horizontal and median sound localization experiments for broadband, high-pass, low-pass, and band-pass noises were conducted with four subjects. The obtained results are as follows:

(1) Horizontal sound localization performance was 96, 76, 69, 64, 67 and 70% for the broadband, 12-kHz high-pass, 500-Hz low-pass, 2-4-, 4-8-, and 8-12-kHz band-pass noises, respectively, in the head-still condition.

(2) Horizontal sound localization was over 93% for all stimuli in the head-movement condition.

(3) Median sound localization performance was 72, 40, 17, 28, 25 and 29% for the broadband, 12-kHz high-pass, 500-Hz low-pass, 2-4-, 4-8-, and 8-12-kHz band-pass noises, respectively, in

the head-still condition.

(4) Median sound localization performance was 92, 71, 70, 55, 83 and 70% for the broadband, 12-kHz high-pass, 500-Hz low-pass, 2-4-, 4-8-, and 8-12-kHz band-pass noises, respectively, in the head-movement condition.

(5) Head movement improves localization performance for all stimuli.

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