Signal frequency range necessary for horizontal sound localization

Daisuke Morikawa* and Tatsuya Hirahara

Faculty of Engineering, Toyama Prefectural University,
Kurokawa 5180, Imizu, 939-0398 Japan

(Received 11 May 2010, Accepted for publication 7 July 2010)

Keywords: Horizontal sound localization, Signal frequency range, Low-pass noise, High-pass noise

PACS number: 43.66.Qp [doi:10.1250/ast.31.417]

1. Introduction

Three-dimensional (3-D) sound can be reproduced by binaural, transaural, wave-field synthesis, or multi channel surround sound technology. It is well known that the interaural time difference (ITD), interaural level difference (ILD), and spectral cues, which are involved in head-related transfer function (HRTF) or head-related impulse response, greatly contribute to 3-D sound localization [1]. However, there are few reports on a how broad bandwidth is necessary to perceive reproduced sound as 3-D sound. Nakabayashi reported that horizontal localization for a real sound source is incomplete with one octave of bandwidth noise [2]. Blauert reported that on a directional band, certain frequency band signals are subject to localized in a certain direction [1]. Arrabito and Mendelson reported that 14-kHz high-pass noise contributes little to vertical and horizontal sound localization with a virtual auditory display [3]. With regard to median plane sound localization, Morimoto and Saito reported that the signal bandwidth from 4.8 kHz to 9.6 kHz is necessary [4], whereas Hebrank and Wright reported that the signal bandwidth from 4 kHz to 16 kHz is necessary [5]. Brungart and Simpson reported that low-pass filters have a profound effect on localization accuracy in the vertical dimension [6]. King and Oldfield reported that 0 to 13 kHz is required in order for listeners to accurately localize signals actually presented from a range of spatial locations [7]. In this article, we clarify the signal bandwidth necessary for horizontal sound localization using high- and low-pass-filtered noise of real sound sources.

2. Experiment

2.1. Experimental system

Figure 1 shows the experimental system. The system consisted of a Windows-based PC, two 8-channel digital-to-analog converters (DACs) (Roland, UA-101), 12 power amplifiers (BOSE, 1705II), and 12 loudspeakers (Vifa, MG10SD-09-08). The sampling frequency of the DACs was 48 kHz. The loudspeakers were placed around a chair in a horizontal circumference of 1-m radius at 30 degree intervals. The height of the loudspeakers was 1.1 m. The sound localization experiment was carried out in an experimental room having the walls and ceiling covered with sound-absorbing materials. The A-weighted level of the background noise of the room was 53 dB.

2.2. Stimuli

Broadband noise, *i.e.*, Gaussian distributed random noise and high-pass (cut-off frequency: $F_c = 2, 4, 8, 12, 16$ kHz) and low-pass ($F_c = 0.5, 1, 2, 4, 8$ kHz) filtered noise were used as stimuli. The high- and low-pass filters were 512 tap finite impulse response (FIR) filters with a -60 -dB stop-band attenuation. The FIR filters were designed by a window method. 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 response of the loud speakers are fairly flat (± 8.7 dB) between 0.1 kHz to 20 kHz, no inverse filter was used to correct the speaker response in the experiment. The sound pressure level of the broadband noise stimuli was 80 dB at the head center position. The sound pressure level of the high-pass and low-pass filtered noise stimuli decreases depending on the filtering.

2.3. Subjects and procedure

Five subjects (four males and a female) in their 20 s, whose hearing thresholds had been measured, participated in the sound localization experiments. Compared with the absolute hearing threshold curve of ISO 226:2003 [8], subjects showed small hearing losses, less than 25 dB, from 125 Hz to 18 kHz.

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. They were asked to localize horizontal sound image positions of the real sound sources and to mark the located position on an answer sheet. The method was a forced choice method of one of 12 directions in the horizontal plane. Subjects were instructed to close their eyes and keep their head still when a stimulus was reproduced.

Each session consisted of 60 trials, and the stimuli were presented in random order from the 12 loudspeakers. One experiment consisted of four sessions, resulting in 20 trials from each of the 12 directions. Experiments were conducted separately for each low-pass, high-pass and broadband noise stimulus.

3. Results

Figure 2 shows the pooled sound localization results for five subjects for (a) 1-kHz low-pass noise, (b) 500-Hz low-pass noise, (c) broadband noise, (d) 12-kHz high-pass noise, and (e) 16-kHz high-pass noise. The ordinate of each panel represents the perceived azimuth, and the abscissa, the target azimuth. The size of each circle plotted is proportional to the number of answers.

*e-mail: t074001@st.pu-toyama.ac.jp

Fig. 1 Experimental system and setup.

First of all, sound images were localized away from the head for all stimuli. Localization was almost perfect for broadband noise. The sound localization performance, *i.e.*, the correct rate of stimuli sound localization, was 98%. Localization was poorer for high-pass noise than for broadband noise. As shown in the result for 16-kHz high-pass noise, sound localizations were vague. Localization was also poorer for low-pass noise than for broadband noise. As shown in the result for 500-Hz and 1-kHz low-pass noise, many stimuli were localized with front-back confusion. The front-back error rate in total localization error was 61%, 58%, 51%, 36%, and 43% for 0.5-, 1-, 2-, 4-, and 8-kHz low-pass noise, respectively. There was no front-back error for 2-, 4-, and 8-kHz high-pass noise, while front-back error rate in total

Fig. 3 Mean sound localization performance and standard deviations for the five subjects.

localization error was 14% and 29% for 12- and 16-kHz high-pass noise. These results suggest that the increase in the total error rate owing to narrowing of the stimulus bandwidth is not necessarily caused by the increase in front-back confusion [1].

Figure 3 shows the mean sound localization performance and standard deviations for the five subjects against the filter cut-off frequency for all stimuli. Sound localization was almost perfect (98%) when the stimulus bandwidth was not limited. The sound localization performance was over 90%

Fig. 2 Horizontal sound localization results. (a) 1-kHz low-pass noise, (b) 500-Hz low-pass noise, (c) broadband noise, (d) 12-kHz high-pass noise, (e) 16-kHz high-pass noise.

with 2-, 4- and 8-kHz high-pass noise. The performance dropped rapidly for 12- and 16-kHz high-pass noise. In contrast, the sound localization performance was over 90% for 8- and 4-kHz low-pass noise, and the performance dropped gradually with the lowering of the cut-off frequency of the low-pass filter.

4. Discussion

As shown in Fig. 3, sound localization at 30 degree intervals is difficult, *i.e.*, the sound localization performance was below 90%, for stimuli which consist of only low-frequency components below 2 kHz or high-frequency components over 12 kHz.

The sound localization performance largely decreases for 16-kHz high-pass noise (45%), *i.e.*, sound localization is very difficult for stimuli that have only very high spectral components. The reason for the poor sound localization performance with 16-kHz high-pass noise is that there are no low spectral components. For this stimulus, sound image locations must be calculated from only the ILD of the high spectral components. The ITD cannot be used as a cue because the ITD is calculated from low spectral components below a few kHz at the medial superior olive in mammals [9–11]. The HRTF spectrum around 3–14 kHz, in which several prominent spectral peaks and notches appear [3], cannot be used.

Sound localization is also difficult for stimuli that consist of only low-frequency components below 1 kHz (80%). The sound localization performance for 500-Hz low-pass noise (64%), however, is better than that for 16-kHz high-pass noise. For the 500-Hz low-pass noise, the major cue for sound localization is the ITD calculated from the low spectral components. The ILD of the low spectral components can be used as another cue, but the ILD is calculated mainly from high spectral components at the lateral superior olive [9]. The HRTF spectrum around 3–14 kHz also cannot be used as a cue for sound localization for the stimuli. The ITD and possibly some of the ILD from low spectral components give better estimations of the sound image location than that given by the ILD from high spectral components alone.

In addition, the results show that the individual differences in performance for 16-kHz high-pass noise sound localization is large. This variation may depend on the subjects' hearing threshold level variation. Detailed investigation of the relationship between hearing threshold levels and sound localization performances remains as a future work. The individual sound localization performance difference for low-pass noise is large compared with those of high-pass noise, except for 16-kHz high-pass noise. Hearing threshold levels of each low frequency are approximately the same among subjects. Therefore, the weights of ITD and ILD used to localize low-pass noise may vary from person to person.

5. Conclusions

Horizontal sound localization experiments for low-pass, high-pass and broadband noise were conducted with five subjects. The obtained results are as follows.

- (1) Sound localization performance dropped rapidly with increasing cut-off frequency of the high-pass filter. The performance was 84% for 12-kHz high-pass noise and 46% for 16-kHz high-pass noise.
- (2) Sound localization performance dropped gradually with lowering of the cut-off frequency of the low-pass filter. The performance was 80% for 1-kHz low-pass noise and 64% for 500-Hz low-pass noise.
- (3) The horizontal sound localization performance at 30 degree intervals was below 90% for stimuli consisting of only low-frequency components below 2 kHz or high-frequency components over 12 kHz.

References

- [1] J. Blauert, *Spatial Hearing* (The MIT Press, Cambridge, Mass., 1997), pp. 36–176.
- [2] K. Nakabayashi, "Sound Localization on the Horizontal Plane," *J. Acoust. Soc. Jpn. (J)*, **30**, 151–160 (1974) (in Japanese).
- [3] G. R. Arrabito and J. R. Mendelson, "The relative impact of generic head-related transfer functions and signal bandwidth on auditory localization: Implications for the design of three-dimensional audio displays," *Aviat. Space Environ. Med.*, **72**, 624–631 (2001).
- [4] M. Morimoto and A. Saito, "On sound localization in the median plane —Effects of frequency range and intensity of stimuli—," *Trans. Tech. Comm. Psychol. Physiol. Acoust.*, H-40-1-3, pp. 12–17 (1977) (in Japanese).
- [5] J. Hebrank and D. Wright, "Spectral cues used in the localization of sound sources on the median plane," *J. Acoust. Soc. Am.*, **56**, 1829–1834 (1974).
- [6] D. S. Brungart and B. D. Simpson, "Effects of bandwidth on auditory localization with a noise masker," *J. Acoust. Soc. Am.*, **126**, 3199–3208 (2009).
- [7] R. B. King and S. R. Oldfield, "The impact of signal bandwidth on auditory localization: Implications for the design of three-dimensional audio display," *Hum. Factors*, **39**, 287–295 (1997).
- [8] H. Takeshima, Y. Suzuki, M. Kumagai, T. Fujimori and H. Miura, "Threshold of hearing for pure tone under free-field listening conditions," *J. Acoust. Soc. Jpn. (E)*, **15**, 159–169 (1994).
- [9] J. O. Pickles, *An Introduction to the Physiology of Hearing*, 2nd ed. (Academic Press, London, 1988), pp. 87, 179–188.
- [10] B. Grothe and G. Neuweiler, "The function of the medial superior olive in small mammals: Temporal receptive fields in auditory analysis," *J. Comp. Physiol. A*, **186**, 413–423 (2000).
- [11] D. McAlpine and B. Grothe, "Sound localization and delay lines — Do mammals fit the model?," *Trends Neurosci.*, **26**, 347–350 (2003).