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Signal bandwidth necessary for horizontal sound localization

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ABSTRACT

This paper clarifies how much signal bandwidth is necessary for horizontal sound localization. Horizontal sound localization experiments were conducted with sixteen listeners using white noise, and fourteen listeners using high-pass noise whose cut-off frequency (*Fc*) was 2, 4, 8, 12, or 16 kHz, or low-pass noise whose *Fc* was 0.5, 1, 2, 4, or 8 kHz. Four listeners participated in an experiment on band-pass noise whose *FcL-FcH* was 2-12, 4-12, 2-8, 2-4, 4-8, or 8-12 kHz. It was very difficult to localize sound for high-pass noise whose *Fc* was high. Sound localization performance was 64% for 12-kHz high-pass noise while it was 27% for 16-kHz high-pass noise. In contrast, sound localization was possible even for 500-Hz low-pass noise. Sound localization performance was 81% for 1-kHz low-pass noise and 67% for that at 500-Hz. It was also difficult to localize sound for narrowband band-pass noise. Sound localization performance was 56% for 2-4-kHz band-pass noise and 67% for that at 8-12-kHz. These results suggest that the interaural time difference, mainly calculated from low-frequency components, the interaural level difference, mainly calculated from high-frequency components, and spectral cues, mainly calculated from middle-frequency (5-10 kHz) components each play roles in sound localization for band-limited noise. We clarified that signal bandwidth from 2 kHz to 12 kHz is necessary to perform good horizontal-sound localization.

INTRODUCTION

Three-dimensional (3-D) sound can be reproduced either with binaural, transaural, wave-field synthesis, or multichannel surround-sound technologies. The perceptual characteristics of these 3-D sounds have been extensively investigated. It is well known that the interaural time difference (ITD), interaural level difference (ILD), and spectral cues, which are involved in HRTF or HRIR, greatly contribute to 3-D sound localization [1]. However, there have been few reports on how broad the bandwidth needs to be to reproduce sound as 3-D sound. With regard to the real sound source, Morimoto and Saito reported that a signal bandwidth from 4.8 to 9.6 kHz was the minimum necessary for sound localization in the median plane [2]. Nakabayashi reported that horizontal localization is incomplete with one octave bandwidth noise [3]. Blauert reported on a directional band, viz., certain frequency band signals are subject to becoming localized in a certain direction [1]. Kondou *et al.* re-examined this directional band phenomenon [4]. Morimoto *et al.* investigated the role of low-frequency components in localization on the median plane. They found that higher frequency components are dominant in median plane, whereas lower-frequency components do not contribute significantly to localization [5]. Nojima *et al.* recently demonstrated that front/back judgment is difficult for 500-Hz low-pass noise when head movement is not allowed [6]. With regard to the virtual sound source, Arrabito and Mendelson reported that 14-kHz high-pass noise contributes little to vertical- or horizontal-sound localization [7]. This article clarifies the signal bandwidth necessary for horizontal-sound localization using band-limited noise from real sound sources.

EXPERIMENTAL SYSTEM

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 12 loudspeakers were placed around a chair in a horizontal circumference at a 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, whose walls and ceiling were covered with sound-absorbing materials. The A-weighted noise-floor level of the room was 53 dB.

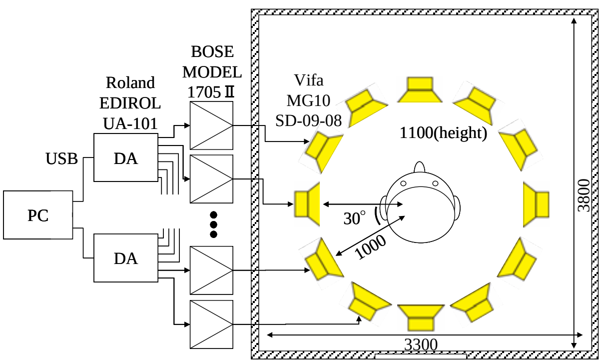

Figure 1. Experimental system and setup

Stimuli

Broadband noise, *i.e.*, Gaussian distributed random noise, high-pass (*Fc* = 2, 4, 8, 12, 16 kHz), low-pass (*Fc* = 0.5, 1, 2, 4, 8 kHz) and band-pass (*FcL-FcH* = 2-12, 4-12, 2-8, 2-4, 4-8, 8-12 kHz) filtered noise were used as the stimuli. The high-pass, low-pass and band-pass filters were 512 tap FIR filters with –60-dB stop-band attenuation. The FIR filters were designed with the window method [8].

The stimulus duration and inter-stimulus intervals were 3 sec. A 30-ms linear taper window was applied at the beginning and end of the stimuli. As the frequency response of the loudspeakers was 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, low-pass and band-pass filtered noise stimuli decreased depending on the filter bandwidth.

Procedure

The experimental procedure was as follows. Subjects sat on a chair placed in the center of the speaker array. The subjects listened to stimuli reproduced from one of the loudspeakers. They were asked to horizontally localize the sound-image positions of the real sound sources and to mark the located position on an answer sheet. The subjects were instructed to close their eyes and keep their heads 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. The experiments were conducted separately for each low-pass, high-pass and broadband noise stimulus.

Subjects

Sixteen subjects participated in the sound-localization experiments. Table 1 lists the details on the number of subject for all the stimulus experiments. Five subjects could not hear the stimulus of 16-kHz high-pass noise due to severe hearing loss above 16 kHz. Of these, three subjects who were in their 20s, 40s and 50s each participated in the sound-localization experiments on 16-kHz high-pass noise. Subjects who could hear the stimulus were placed in group E, and subjects who could not hear the stimulus were placed in group D.

RESULTS

Broadband Noise

Figure 2(a) plots the pooled sound-localization results for the sixteen subjects for broadband noise. The sound localization was almost perfect for broadband noise. Sound localization performance, *i.e.*, the correct rate for localizing sound stimuli, was 94%. The sound images were, of course, localized away from the head. There were no differences in sound localization performances by the different age groups.

High-pass Noise

Fig. 2(b) plots the pooled sound localization results for fourteen subjects for 12-kHz high-pass noise. The sound images were localized away from the head for all high-pass noise. Fig. 2(c) plots the results for nine subjects who could hear the stimulus for 16-kHz high-pass noise. Localization was poorer for high-pass noise than for broadband noise. As seen in Fig. 2(c), sound localization was vague for stimuli that only contained very-high-spectral components. Fig. 2(d) plots the results for three subjects who could not hear the stimulus for 16-kHz high-pass noise. Sound localization was impossible for subjects who could not hear the stimulus.

Low-pass Noise

Figures 3 (a) and (b) plot the pooled sound-localization results for fourteen subjects for 1-kHz and 500-Hz low-pass noise. Sound localization was also poorer for low-pass noises than for broadband noise. As seen in Fig. 3, many stimuli were localized with front-back confusion. Sound images were localized away from the head for all low-pass noise.

Figure 4 plots the mean sound localization performance and standard deviations for the fourteen subjects against the filter cut-off frequency for high-pass and low-pass noise. Sound localization performance was over 85% 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 85% for 8-, 4-, and 2-kHz low-pass noise, and it dropped gradually when the cut-off frequency of the low-pass filter was lowered.

Table 1. Details on subjects for each stimulus

Noise╲Age group	20s	30s	40s	50s	Total
Broadband	10	1	2	3	16
High and low-pass	8	1	2	3	14
16-kHz high-pass (E)	7	1	1	0	9
16-kHz high-pass (D)	1	0	1	1	3
Band-pass	4	0	0	0	4

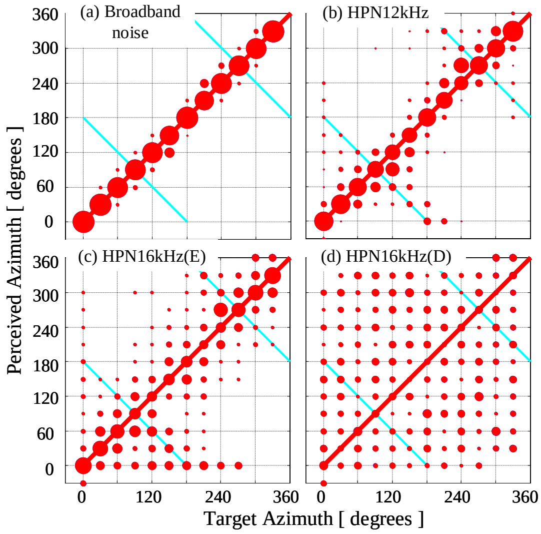

Figure 2. Horizontal-sound localization results for broadband and high-pass noise

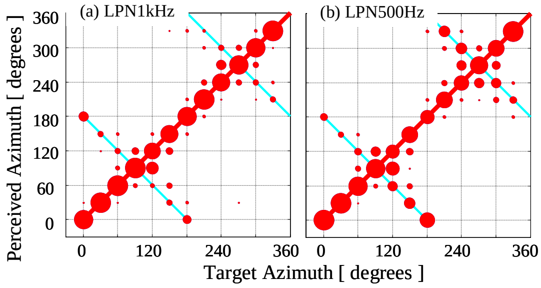

Figure 3. Horizontal-sound localization results for low-pass noise

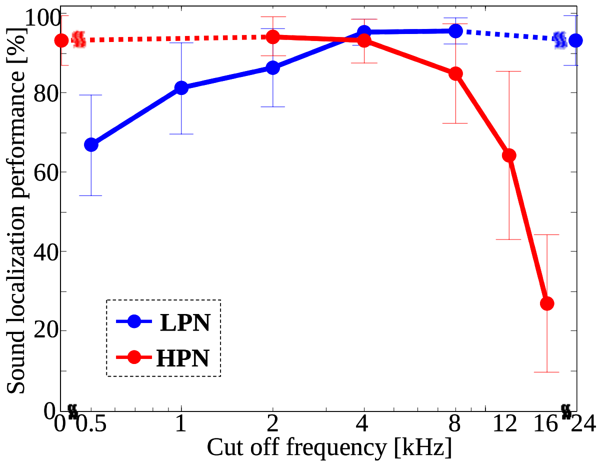

Figure 4. Mean sound localization performance and standard deviations for band-pass, high-pass, and low-pass noise

Band-pass Noise

Figures 5 (a) and (b) have the pooled sound-localization results for four subjects for 2-12-kHz and 2-4 kHz band-pass noise. The sound localization was almost perfect for 2-12-kHz band-pass noise. The sound localization performance was 95%. Localization was poorer for narrowband band-pass noise than for 2-12-kHz band-pass noise. As seen in Fig. 5(b), many stimuli were localized with front-back confusion.

Figure 6 plots the mean sound localization performance and standard deviations for the four subjects against the filter cut-off frequency of band-pass noise. The sound localization performance was over 85% with the 2-12 and 4-12-kHz band-pass noise, and the performance dropped gradually as the pass-bandwidth of the filter narrowed. Sound images were localized away from the head. However, the same stimuli presented at the front were localized very close to the head except for 2-12- and 4-12-kHz band-pass noise. The 2-4-kHz band-pass noise was particularly localized that way by all subjects.

Figure 7 compares the mean sound localization performance and standard deviations for the four subjects for band-pass noise and high-pass noise, and band-pass noise and low-pass noise. The sound localization performance of 8-12-kHz band-pass noise was poorer than 8-kHz high-pass noise. The sound localization performance for 2-4-kHz band-pass noise was poorer than that for 4-kHz low-pass noise. The narrower the bandwidth, the poorer the performance.

DISCUSSION

As seen in Fig. 4, sound localization is difficult for stimuli that only consist of high-frequency components over 12 kHz. Sound localization performance largely decreases for 16-kHz high-pass noise (27%), *i.e.*, sound localization is very difficult for stimuli that only have very high-spectral components.

One reason for poor sound localization performance with 16-kHz high-pass noise is that there are no low spectral components. The sound-image locations for this stimulus have to be calculated only from the ILD of the high-spectral components. ITD cannot be used as a cue because it is calculated from low-spectral components below 4 kHz at the medial superior olive (MSO) [9]. The spectral notches around 5-10 kHz also cannot be used as a cue for sound localization in the stimulus

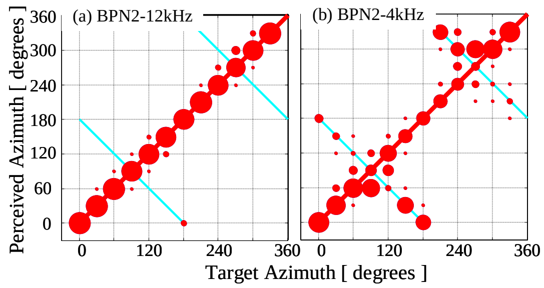

Figure 5. Horizontal-sound localization results for band-pass noise

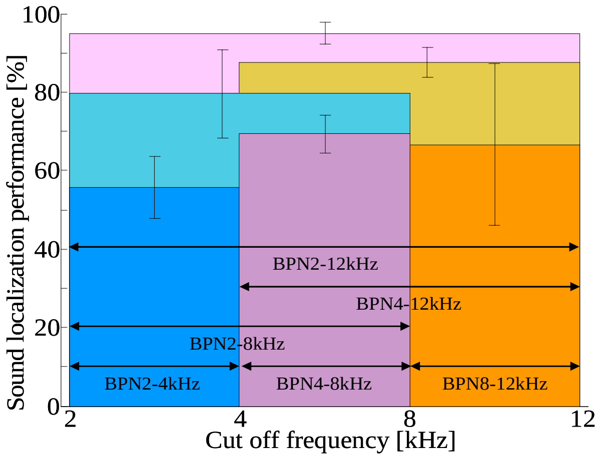

Figure 6. Mean Sound localization performance and standard deviations for band-pass noise

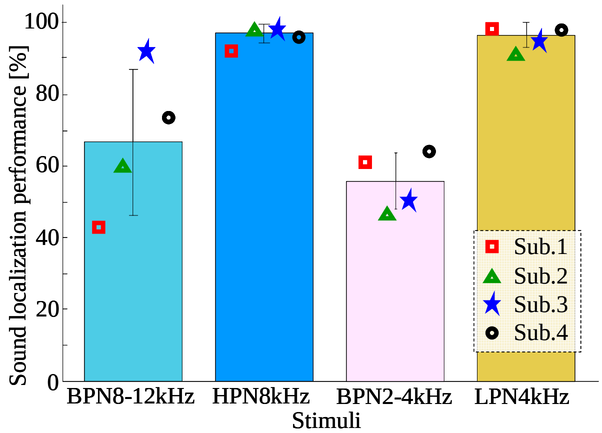

Figure 7. Comparison of band-pass noise with high- and low-pass noise

Another reason for the poor sound localization performance with 16-kHz high-pass noise could be attributed to the low sensation level (SL) of the stimuli. Hebrank and Wright found localization performance was level independent for white-noise stimuli presented over 40 dB SL, but decreased for stimuli below 40 dB SL [10]. Inoue reported that sound localization performance for white-noise stimuli was low at 0 to 20 dB SL [11]. The sound pressure level of the 16-kHz high-pass noise used in our experiment was actually 72 dB and its SL was 0 to 30 dB depending on subjects. The low SL of the stimuli, thus, is a possible cause for the low sound localization performance of the stimulus.

Some visually impaired people who cannot see are able to predict the locations of visual stimuli and this is known as blind sight [12]. Our experiment revealed that subjects who could not hear 16-kHz high-pass noise could not localize sound at all. The hearing loss of the three subjects at high frequency is most likely the result of malfunctions at the sensor stage due to aging. Thus, it is not surprising that they could not hear the stimuli and they also could not localize the stimuli.

As seen in Fig. 4, sound localization is difficult for stimuli that only consist of low-frequency components below 1 kHz. Sound localization performance decreases for 500-Hz low-pass noise (64%); however, it is still better than that for 16-kHz high-pass noise. The major cue for sound localization of 500-Hz low-pass noise was the ITD calculated from the low-spectral components. The ILD of the low-spectral components can be used as another cue, yet ILD was mainly calculated from the high-spectral components at the lateral superior olive (LSO**)** [9]. The spectral notches around 5-10 kHz also cannot be used as cues in the sound localization of the stimuli. The ITD and possibly some ILD from low-spectral components give better estimates of the location of the sound image than the ILD from high-spectral components alone gives.

As shown in Fig. 6, sound localization is difficult for stimuli that only consist of middle-frequency components between 2-4 kHz, 4-8 kHz, or 8-12 kHz. Sound localization performance largely decreases for 2-4-kHz band-pass noise (56%), *i.e.*, sound localization is very difficult for stimuli that have narrow-spectral components. Fig. 6 also supports the finding that the signal bandwidth necessary to perform horizontal sound localization is from 2 to 12 kHz.

As seen in Fig. 7, Localization is poorer for 8-12-kHz band-pass noise than for 8-kHz high-pass noise. The reason for the poor sound localization performance with 8-12-kHz band-pass noise is that there were no low-spectral components or narrow-spectral components. The major cue for this stimulus for sound localization is the ILD calculated from the high spectral components from 8 to 12 kHz. The spectral notches around 5-10 kHz can be used as another cue. However, this stimulus does not include spectral components above 8 kHz. The ILD information from 8-12-kHz band-pass noise is insufficient compared with that from 8-kHz high-pass noise. Spectral components over 12 kHz contributed to the calculations of ILD.

In addition, Fig. 7 shows that individual differences in sound localization performance for 8-12-kHz band-pass noise are large. The reason for this is shat the weight of ILD and spectral cues used to localize this stimulus may vary from person to person.

As seen in Fig. 7, Localization is poorer for 2-4-kHz band-pass noise than for 4-kHz low-pass noise. The reason for the poor sound localization performance with 2-4-kHz band-pass noise is that there are no high-spectral components. The sound-image locations for this stimulus only have to be calculated from the ITD of the low spectral components from 2 to 4 kHz. However, this stimulus does not include spectral components below 2 kHz. The ITD information from 2-4 kHz band-pass noise is insufficient compared with that from 4-kHz low-pass noise. Spectral components below 2 kHz contributed to the calculations of ITD.

CONCLUSION

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

(1) It was necessary to have a bandwidth from 2 to 12 kHz to perform horizontal-sound localization.

(2) Low-frequency components below 2 kHz or high-frequency components over 12 kHz contributed little to horizontal-sound localization.

(3) Horizontal-sound localization was very difficult for high-pass noise. Sound localization performance dropped to 64% for 12-kHz high-pass noise and 27% for 16-kHz high-pass noise.

(4) Horizontal-sound localization was impossible for high-pass noise with subjects who could not hear the stimuli due to severe hearing loss above 16 kHz.

(5) Horizontal-sound localization was difficult for low-pass noise with a 500-Hz cut-off frequency. Sound localization performance dropped to 81% for 1-kHz low-pass noise and 67% for 500-Hz low-pass noise.

(6) Horizontal-Sound localization was difficult for narrow band-pass noise. Sound localization performance dropped to 56% for 2-4-kHz band-pass noise, 69% for 4-8-kHz band-pass noise, and 67% for 8-12-kHz band-pass noise.

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