Measuring sound-image trajectory of a moving sound source approaching a reflective wall in steps

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1. Introduction

Sound-localization experiments are usually conducted in an anechoic room to approximate a free-field environment. However, humans spend most of their time in spaces that are surrounded by acoustically reflective walls, such as rooms and cars. In such echoic environments, the perception of spatial sound is different from that in a free field, since the reflected waves from the walls affect binaural cues. For example, one perceives the sound image to be moving along a straight line if the sound source is moving along a straight line in free-field conditions. However, when one stands near a wall and listens to a sound approaching straight toward the wall, the sound image is perceived to bend around the head [1–3].

To investigate this illusion quantitatively, we performed a psychophysical experiment to measure the trajectory of the perceived sound image formed by a moving sound source as it approaches a reflective wall. Subject's perceptions of the sound image were quantified as they pointed at the perceived location of the sound source using a hand-held motion tracker.

2. Method

Sound-image trajectories were recorded within a sound-proof room (W : 320 cm, D : 350 cm, and H : 230 cm), equipped with sound-absorbing material on the walls and ceiling. Acoustically absorbent carpets were tiled on the floor. A 3-inch full-range loudspeaker with a spherical enclosure (Anthony Gallo, Micro Satellite) was moved stepwise on a rail perpendicular to one of the walls of the room, on which an acoustically reflective 2-mm-thick vinyl chloride board (W : 182.2 cm and H : 91.2 cm) was hung. The loudspeaker was moved from 115 to 15 cm away from the wall at a velocity of 0.1 m/s, and its motion was paused for 5 s at seven positions, 115, 90, 65, 52.5, 40, 27.5, and 15 cm, as measured from the wall. The center of the loudspeaker was 110 cm away from the floor (Fig. 1).

In each experimental session, the subject sat facing the rail on which the loudspeaker was moved. The distance between the center of the subject's head and rail and that between the center of the subject's head and the wall was 25 and 65 cm, respectively. Chair's height was adjusted so that

the center of the subject's outer ear entrance was 110 cm away from the floor.

In each session, a one-third-octave band-pass noise (1/3-oct. BPN) with various center frequencies (f_c) values was emanated from the moving loudspeaker and the subject was asked to track the center position of the perceived sound image using a magnetic motion tracker (POLHEMUS, Liberty) held in his hand. The sampling frequency of the motion sensor was 240 Hz. Nine normal-hearing adult male subjects participated in the experiments and they kept their eyes closed during the session.

In a preliminary experiment, we moved the loudspeaker continuously toward the wall at a velocity of 0.2 m/s. Although the tracking of a sound image was possible, untrained subjects found it very difficult, and variances in the trajectory data were large. Thus, we decided to move the loudspeaker at a slower rate and stepwise.

Stimuli of 1/3-oct. BPN with f_c values of 375, 750, 1,500, 3,000, and 6,000 Hz were presented. Each stimulus was D/A converted (RME, Fireface UC) at a sampling frequency of 48 kHz, after which it was amplified (Creek, Evolution 50A) and fed to the loudspeaker. The sound pressure level of the stimuli was 70 dB when measured 25 cm in front of the loudspeaker.

Each subject repeated the tracking the task thrice for each f_c value, and the position of the motion tracker and the actual position of the loudspeaker were recorded. The azimuthal angle of the sound source (θ_s) was calculated from the seven coordinates at which the loudspeaker stopped. Since the subjects' tracking was always delayed due to the movement of the loudspeaker by some amount, the azimuthal angle of the sound image (θ_i) was calculated by averaging the coordinates of the tracker when it was held still. θ_i and θ_s are defined as increasing clockwise, with the direction pointing perpendicular to the loudspeaker rail from the center of the subject's head defined as 0° .

3. Results

Figure 2 shows the typical sound-image trajectories of the 1/3-oct. BPNs. For high- f_c values, i.e., 6, 3, or 1.5 kHz, θ_i always matched θ_s even when the loudspeaker was close to the wall. In this case, the sound-localization illusion did not occur. The sound-image trajectories did not trace straight lines

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Fig. 1 Experimental setup.

Fig. 2 Typical sound-image trajectories of the 1/3-oct. BPN stimuli.

in the x - y plane because the subjects unconsciously adjusted the tracker so as to avoid it from hitting their noses. On the contrary, for the low- f_c stimuli (750 or 375 Hz), θ_i was more negative than θ_s when the loudspeaker was close to the wall. The sound image of the sound source near the wall was localized near the side of the head, causing the sound-image trajectory to bend around the head.

Figure 3 plots the relation between the mean sound image angle ($\bar{\theta}_i$) and f_c of the stimuli emanated from the loudspeaker when it was closest to the wall. $\bar{\theta}_i$ matched θ_s for the high- f_c stimuli, whereas $\bar{\theta}_i$ takes a larger negative value than θ_s for the low- f_c stimuli.

The results of the analysis of variance of $\bar{\theta}_i$ showed a significant difference [$F(4, 40) = 7.77, p < 0.01$]. Post hoc analysis of the result, using Tukey's honestly significant difference test revealed that $\bar{\theta}_i$ of the low- f_c stimuli (750 or

Fig. 3 Relation between $\bar{\theta}_i$ and f_c of the stimuli emanated from the loudspeaker position closest to the wall ($\theta_s = -63.4^\circ$).

375 Hz) was significantly lower than that of the high- f_c stimuli (3 or 6 kHz) ($p < 0.01$).

4. Discussion

This illusion occurred only with stimuli for which f_c is relatively low, i.e., at 750 Hz or 375 Hz. This result suggests that the interaural time difference (ITD) plays an important role in the illusion because it is known to be computed from low-frequency components within the brain [4].

When a low- f_c 1/3-oct BPN is emanated from the loudspeaker positioned near the wall, both the direct wave and the wave reflected from the wall reach the left and right ears. Since the wavelength of the stimulus is longer than the size of the subject's head, ILD is small so that the combinations of the direct and reflected waves to the left and right ears generate four ITD values. Among them, the ITD given by the direct wave to the left ear and by the reflected wave to the right ear should be longer than that given by direct waves to the both ears. This long ITD can be the cue that leads the subjects to judge the direction of the sound image to be at the left side of the head.

When a high- f_c 1/3-oct BPN is emanated from the loudspeaker near the wall, the direct wave reaches both ears. The reflected wave from the wall reaches the left ear without attenuation, but reaches right ear after being greatly attenuated due to the occlusion of the head. Thus, the ILD cue provided by the sum of the direct and reflected wave can be somewhat larger than that provided by the direct wave. As subjects perceived the sound image near the sound-source position, the increase in ILD due to the reflected wave is likely to be small. Each high- f_c 1/3-oct BPN has an envelope that contains low-frequency components, and these low-frequency envelope modulations could yield the envelope ITD [5]. However, the influence of the envelope ITD is also likely to be small, since subjects localized the sound image of the high- f_c 1/3-oct BPNs close to the sound-source position, not at the left side of the head.

Actual ITDs and ILDs of the stimuli can be calculated from impulse responses between the sound source and the

both ears. Measuring the impulse responses with a subject's head, calculating the ITDs and ILDs, and revealing the cues that cause the illusion remain as future works.

5. Summary

We recorded subjects' perceptions of the sound-image trajectory of a one-third-octave band-pass noise moving in a straight line toward a wall. The sound image moved in a straight line if the stimulus had f_c greater than or equal to 1.5 kHz, but it was bent around the head if stimulus had f_c less than or equal to 750 Hz. The long ITD caused by the difference in the timing of the direct wave reaching the left ear and the reflected wave from the wall reaching the right ear likely explains this sound-localization illusion.

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