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Effect of Active Self-Motion on Auditory Space Perception

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This study investigated how auditory space is represented during linear self-motion. Results of several studies suggest that whether the listener's motion is active or passive affects sound localization. Therefore, we investigated whether the style of the self-motion affects the perceived auditory space. As the passive condition, observers were transported automatically forward by a robotic wheelchair. In contrast, observers controlled the movement of the robotic wheelchair or walked straight ahead in active conditions. The observers indicated the direction in which the sound was perceived relative to their coronal plane (i.e., a two-alternative forced-choice task). The results of experiments demonstrated that the sound position aligned with the subjective coronal plane was displaced backward relative to the observers' physical coronal plane both in active and passive motion conditions. These results suggest that perceived self-motion itself affects auditory space representation irrespective of the intention of the movement.

KEYWORDS: linear acceleration, auditory space perception, active and passive motion, multimodal perception

1. Introduction

We can perceive stable auditory spatial information, even when we are moving, which implies that inputs from the auditory periphery are interpreted in the brain by integrating those inputs with information about the movements of the head and whole body. Such movement signals used for sound localization can be derived from vestibular information [1].

Several reports have described the influence of rotatory self-motion on auditory localization. Most preceding studies have demonstrated large systematic errors, especially during rapid head motion [2, 3]. These findings suggest that the vestibular semicircular-canal system plays an important role in spatial perception.

Aside from information originating in the semicircular-canal system, sensory information from the macular receptors of the otolith system (utricle and saccule) might also play a role in this respect. The otolith system can detect linear acceleration, whereas the semicircular-canal system can detect rotatory acceleration. Therefore, it is important to investigate the effect of linear self-motion on auditory space representation. Our earlier research revealed that the sound position aligned with the subjective coronal plane (SCP) was displaced in the direction of linear self-motion [4]. This effect was observed even when linear self-motion was provided only by visual information [5].

In the previous study, the experimenter controlled the listeners' movements. Listeners were unable to ascertain when and where they were moving. Therefore, their movement can be regarded as passive movement. Observed phenomena might be different if listeners had been able to control their movements intentionally. Actually, prior research has pointed out that the difference between active and passive head rotation affects the sound localization improvement [6].

In this study, we specifically addressed the effects of different modes of linear motion (active or passive) on auditory space representation of near space. As the active movement, participants controlled the motion of a robotic wheelchair by stepping on the footpedals in Exp. 1, whereas they actually walked in Exp. 2. By comparing these motions with passive motion, the amount of the displacement of the SCP was analyzed.

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2. Experiment 1: Effects of active and passive movement on the distortion of auditory space representation [7]

2.1 Experimental apparatus

The experiments were conducted in a corridor at the Research Institute of Electrical Communication, Tohoku University (Fig. 1(a)). Sound-absorbing materials were placed on the sidewalls in the part of the corridor in which the experiments were conducted (about a 5-m section) to attenuate the sound reflection. The observers were transported using a robotic wheelchair (iXs Research Corp., Fig. 1(b)). To reduce the reflection from a seatback of the chair, the seatback was removed. A participant's head was fixed to a small and thin headrest. Small footpedals (Saitek Pro Flight Rudder Pedals; Saitek) were connected to the wheelchair. The amount of the acceleration was changed in response to the degree of downward pressure on the pedal. The maximum A-weighted sound pressure level of ambient environmental noise, including noise from the wheelchair, was 60 dB while the wheelchair was in operation.

Auditory stimuli were presented using 17 full-range loudspeakers (30 mm, 0254-7N101; Hosiden Corp.) installed in small cylindrical plastic boxes (108 cm^3). These loudspeakers were on the right-hand side, aligned with the direction of movement of the wheelchair at 10-cm intervals and at a height of 1.32 m (almost equivalent to the height of the seated participant's ears). The auditory stimulus was presented at the moment the wheelchair intersected an orthogonal laser set beside the baseline (Fig. 1(a)). Specifically, analog signals from the laser were converted to digital signals using a data acquisition device (NI USB-6289; National Instruments Corp.) connected to a laptop computer. The inputs were processed using a LabVIEW program (National Instruments Corp.). The audio data were output through audio interfaces (UA-25EX and Marantz, PM-54DS; Roland Corp.). The system delay from sensing the position of the wheelchair to the onset of the auditory stimulus was 3 ms or less.

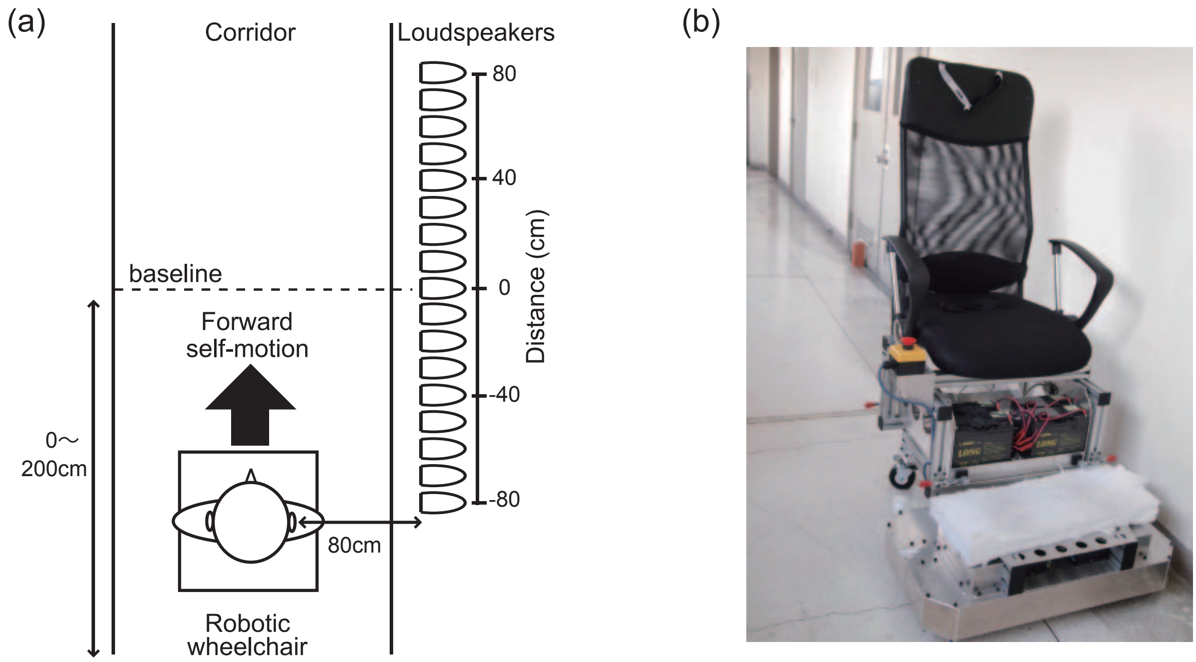

Fig. 1. Schematic diagram of (a) the experimental setup and (b) a robotic wheelchair.

2.2 Experimental Procedure

Six participants participated in this experiment. All had normal hearing with no history of vestibular deficiency.

Three conditions were no motion (reference), active motion, and passive motion conditions. Before the experiment, participants sat on the wheelchair and experienced passive forward motion at acceleration of $0.4\,m/s^2$. Then, in an active motion condition, they were asked to reproduce the wheelchair movement they had experienced by stepping down on the pedal. The movement was recorded at the sampling rate of 16 Hz. Figure 2 presents an example of the profile of the actual movement in active motion condition. One of the recorded movements was selected randomly in each trial and used as the passive motion. The auditory stimulus was presented when the wheelchair reached a baseline, which was set at the position of 1 m. The auditory stimulus consisted of 30 ms of pink noise modulated by a 5-ms Hanning onset and offset windows at an average sound pressure level of 80 dB (sampling frequency: 44.1 kHz).

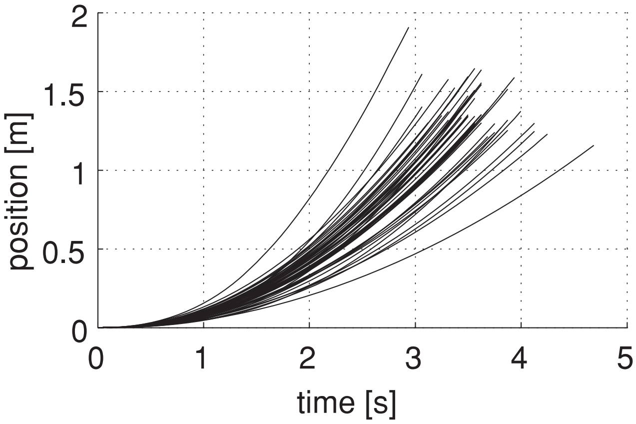

Fig. 2. Example of the movement of the robotic wheelchair in active motion condition (Participant A).

The participants were sitting blindfolded on the wheelchair. In each condition, they were asked to answer whether they perceived the sound “backward” or “forward” relative to their coronal plane (i.e., a two-alternative forced-choice task). A test sound was presented from one of the loudspeakers when the chair reached the baseline. The distance was defined as the physical distance between the baseline and test sound. The test sound position was −80 cm to 80 cm in 10-cm intervals. The actual sound position varied from trial to trial according to a randomized maximum likelihood sequential procedure [8]. In the procedure, the loudspeaker position of the next variable stimulus was determined randomly within a range centered at the loudspeaker position that yields the maximum likelihood of PSE (0, ±10, ±20 cm).

2.3 Results and discussion

The mean sound positions aligned with the participants’ SCPs are presented in Fig. 3. The baseline denotes a sound position aligned with the participants’ physical coronal plane. Negative and positive values respectively denote rear and frontal spaces. A repeated-measures analysis of variance (ANOVA) with one within-participant factor (no motion, active motion and passive motion conditions) revealed a significant effect of the experimental condition ($F(2, 10) = 7.91$, $p < .009$, $\eta^2 = .48$, $\beta = .32$). Multiple comparison (Ryan’s method, $p < .05$) revealed that the mean sound positions aligned with the participants’ SCPs moved significantly backward in the opposite direction of self-motion for the active and passive motion conditions compared with SCP in the no motion condition. No significant difference was found between active and passive motion conditions (active-passive: $d = .165$, $\beta = .578$, active-no motion: $d = 1.847$, $\beta = .821$, passive-no motion: $d = 2.662$, $\beta = 0.985$).

3. Experiment 2: Difference of the perceived auditory space between walking and passive self-motion

3.1 Experimental apparatus

Figure 4 presents a schematic diagram of the experimental setup. The same loudspeaker array as that used in the previous experiment was used to provide auditory information to participants. To record the movement during experiment, a position sensor (TX-4; Fastrak) was put on the head of participants.

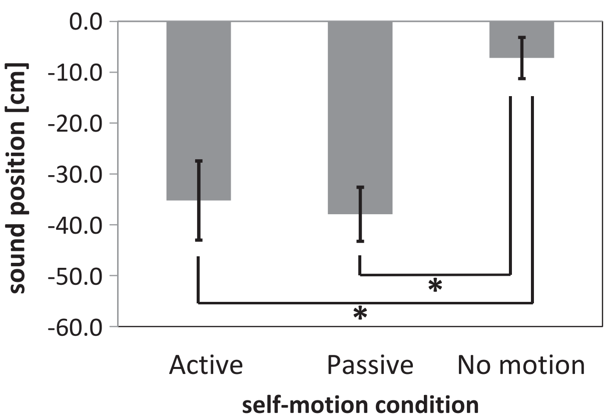

Fig. 3. Effects of active and passive movements on auditory space representation.

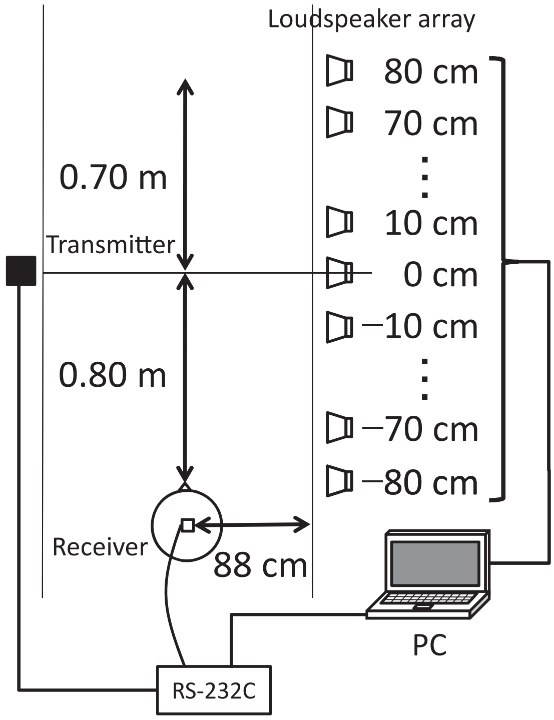

Fig. 4. Schematic diagram of the experimental setup.

3.2 Experimental procedure

Six participants took part in this experiment. All had normal hearing with no history of vestibular deficiency.

The three conditions were no motion (reference), active motion, and passive motion conditions. In the active motion condition, participants stood 80 cm behind the baseline and then started to walk straight ahead at the distance of 150 cm. They were asked to walk at the velocity of around 3 m/s. Before the experiment, they trained this motion for a few times. Figure 5 presents an example of the profile of the actual movement in walking condition. In the figure, 0 s means the time when the auditory stimulus was presented.

The movement was recorded at the sampling rate of 120 Hz. One of the recorded movements was selected randomly in each trial and was used as the passive motion. In the passive motion condition, observers were transported forward by the robotic wheelchair according to the selected movement. The auditory stimulus consisted of 30 ms of pink noise modulated by 5-ms Hanning onset and offset windows at an average sound pressure level of 80 dB (sampling frequency: 44.1 kHz).

The participants were blindfolded during the experiment. A test sound was presented from one of the loudspeakers when the body (active motion condition) or the chair (passive motion condition) reached the baseline. The loudspeaker position of the next variable stimulus was decided using the same procedure as that used in the previous experiment. In each condition, a participant was asked to report whether they perceived the sound as "backward" or "forward" relative to their coronal plane (i.e., a two-alternative forced-choice task).

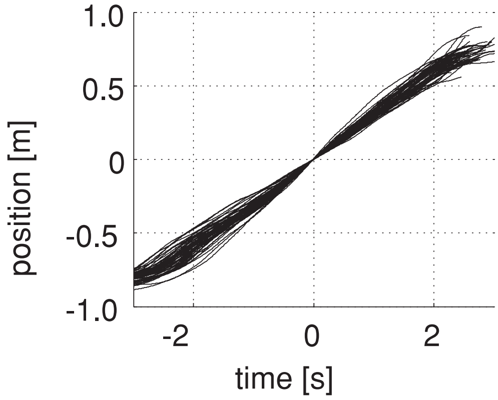

Fig. 5. Example of the movement in walking condition (Participant A).

3.3 Results and Discussion

The mean sound positions aligned with the participants' SCPs are presented in Fig. 6. The baseline denotes a sound position aligned with the participants' physical coronal plane. Negative and positive values respectively denote rear and frontal spaces. Repeated-measures analysis of variance (ANOVA) with one within-participant factor (no motion, active motion and passive motion conditions) revealed a significant effect of the experimental condition ($F(2, 10) = 17.62$, $p < .001$, $\eta^2 = .45$, $\beta = .29$). A multiple comparison (Ryan's method, $p < .05$) revealed that the mean sound positions aligned with the participants' SCPs moved significantly backward in the opposite direction of self-motion for the active and passive motion conditions compared with SCP in the no-motion condition. No significant difference was found between active and passive motion conditions (active-passive: $d = .402$, $\beta = .097$, active-no motion: $d = 1.731$, $\beta = .771$, passive-no motion: $d = 2.025$, $\beta = 0.884$).

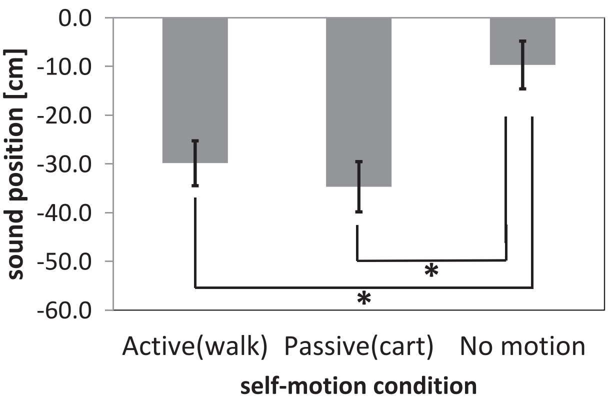

Fig. 6. Obtained SCPs in walking and passive movement conditions.

4. General Discussion

In this study, we demonstrated that the sound position aligned with the SCP was displaced compared with the baseline irrespective of the style of the self-motion (active or passive). In Exp. 2, participants' movement was almost uniform motion as shown in Fig. 5. Nevertheless, the perceived position of a sound source was shifted. This implies that self-motion perception itself affects the displacement of the perceived sound potion. An earlier report described that such displacement was observed even when vestibular stimulation was not presented [5]. These results suggest that a certain link exists between self-motion perception and auditory space representation.

Results obtained in Exp. 1 and 2 indicated that the sound position aligned with the subjective coronal plane was displaced backward relative to the observers' physical coronal plane both in active and passive motion conditions. This tendency was observed even when participants were walking during experiment. However, in active motion conditinos, participants might not feel that they were moving actively and naturally. They were only able to control the amount of acceleration by stepping down on the pedal. Moreover, the participant's gait was extremely slow. Therefore, observed tendency might be changed by providing another active motion. The effect of the difference between the active motions should be investigated in future research.

However, the direction of the displacement obtained in this study was opposite to the direction of participants' movement. In the previous study [4, 5], the observed SCP was shifted in the direction of self-motion. A similar difference has been reported related to "audiogyral illusion [9–12]." Some studies examining the influence of rotary acceleration on auditory localization revealed that the perceived position of a sound source shifted in the opposite direction of acceleration [9–12]. In contrast, other studies showed that the sound source shifted in the direction of acceleration [13, 14]. The difference between these studies is expected to result from the strength of perceived self-motion. Earlier studies used a strong and long-lasting stimulus to vestibular afferents, whereas the latter did not. As described previously, the wheelchair seat back was removed for this study. Moreover, participants had to concentrate on reproducing the movement they had experienced in both active conditions. Because these movements were controlled by the participants, the presented vestibular information was varied among the trials as shown in Figs. 2 and 5. Therefore, participants' subjective self-motion might be decreased or inconsistent compared with results found in our previous studies [4, 5], although the strength of self-motion perception was not measured in the current study. However, there might be another reasons why such inconsistency was observed. A detailed investigation to confirm them shall be undertaken in future research.

5. Conclusion

We investigated the effects of linear acceleration on the auditory space representation. Results showed that the sound position aligned with the subjective coronal plane was displaced backward as compared with that in the no motion condition. These results imply a certain link between auditory space perception and self-motion perception. Moreover, this displacement was observed both in active and passive motion conditions. This result suggests that self-motion itself affects the perceived auditory space despite the intention of the movement.

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