The effects of linearly moving sound images on self-motion perception

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1. Introduction

To develop new man-machine interfaces and new communication systems, clarification of human multi-modal information processing has become a crucial, challenging and interesting topic. Self-motion perception is well known as a multi-modal information process influenced by visual, postural, and somatic information. However, we do not always use all of these kinds of information to perceive self-motion. With even only visual information, we often perceive self-motion, e.g., we may have an illusory feeling that our train is moving when we see a train departing on the next track. This phenomenon is called "vection." This suggests that visual information highly influences self-motion perception. Visual information can provide rich and accurate spatial information and this may be the reason why self-motion perception is highly influenced by such information. However, not only visual information but also auditory information can provide certain spatial information, and it is likely that auditory information may influence self-motion perception. In the past, Lackner [1] generated rotating sound field by using six loudspeakers and reported that subjects perceived rotating self-motion under this condition. Nara *et al.* [2] used similar equipments and reported that the amount of head sway was increased by rotating sound images. These studies show that vection is evoked also by auditory information. However, there seems to be no research on auditory vection with linearly moving sound images.

In this study, we investigated whether or not self-motion could be perceived based only on auditory information of linear motion. We generated linearly moving sound images by using eight loudspeakers and assessed the acoustically induced self-motion. Moreover, as an objective measure, we measured the sway of the center of gravity due to body movement.

2. Experimental procedure

A psychophysical experiment was performed in an anechoic room of the Research Institute of Electrical Communication, Tohoku University. Five young male and two young female adult subjects with normal hearing acuity participated the experiment. They were not given any information about experimental equipment. Moreover they were wearing eye masks during the experiment so they could not get any visual cues about this experiment. Figure 1 schematically shows the experimental set-up. Eight loudspeakers (Diatone DS-7) were set around a subject who was standing on a force plate (NEC EB1101). Subjects were standing upright on a force plate and looking ahead during the experiment. Pink noise was used as the source signal. One of four kinds of moving sound images was generated:

(1) movement from front to back (Condition: Front),
(2) from back to front (Condition: Back),
(3) from left to right (Condition: Left), and
(4) from right to left (Condition: Right).

For example, to generate sound images of movement from front to back, two uncorrelated pink noises were first presented from SP3 and SP7, respectively, at the beginning of a trial, and two moving images were generated by using SP3 and SP4 for one image and SP7 and SP6 for the other. In this condition, we assumed that subjects perceived two synthetic moving sounds separately. One was moving from front to back at the subjects' right side and compounded by using SP3, SP4, and SP5. The other was moving from front to back at the subjects' left side and compounded by using SP7, SP6, and SP5. The envelope of the pink noise presented by a loudspeaker was determined by a preliminary experiment to realize a smooth motion. The speed of moving sound images was set at 13.3 cm/s and 6.7 cm/s. For purposes of reference, two more condition were also examined. One was without any sound stimuli and the other was with a fixed sound image. These conditions are called "NoSound" condition and "Fixed" condition, respectively. The A-weighted sound pressure level of the stimulus was adjusted to be 80 dB at the position of the subject. When sound images were moving away from the subject, sound pressure level was decreased in conformity with inverse square row. The duration of each trial was 30 s and two trials were performed for each condition for each subject.

Subjects were instructed not to move during the experiment and to rate the magnitude of their perceived self-motion with a scale from "0" to "4." Here, "0" means that there was no perceived self-motion, and "4" means that the subjects felt as if they were moving at corresponding speeds, while the sound images were perceived as being stationary. Subjects were also asked to identify the direction of the self-motion if it was perceived.

The sway of the center of gravity was measured by using a force plate. The force plate output the coordinates of the

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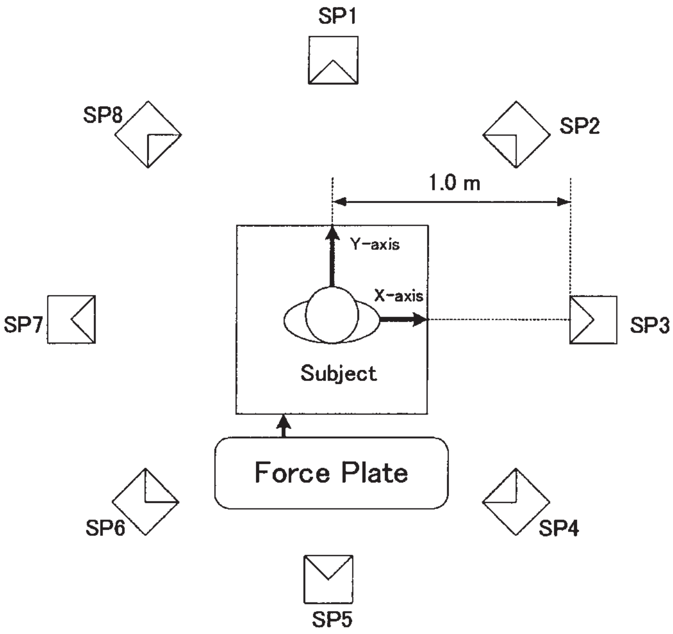

Fig. 1 Experimental set-up.

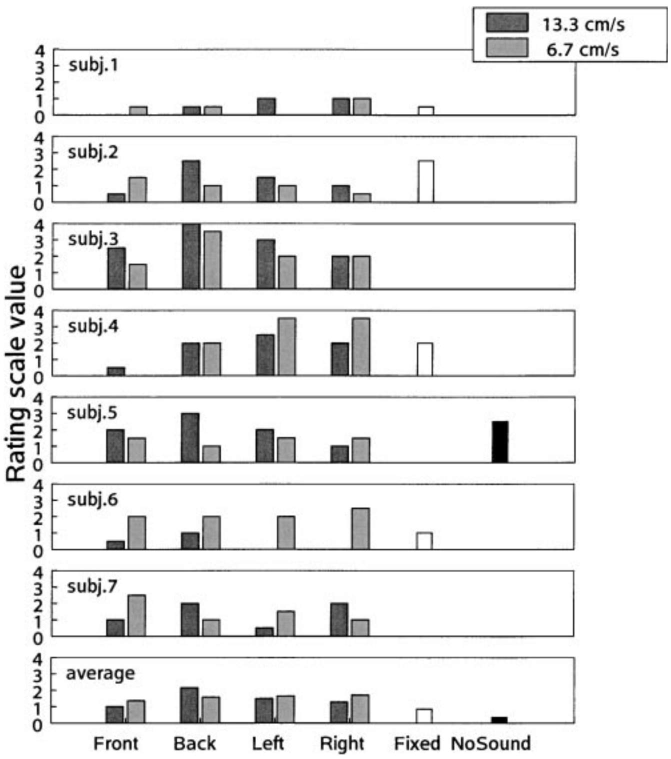

Fig. 2 Subjective magnitude of perceived self-motion. The score was the average for directions.

center of gravity during the experiment. The data was stored at a sampling rate of 100 Hz and the amount of the sway along *x*-*y* axis was calculated.

3. Results

Figure 2 shows the subjective magnitude of perceived self-motion. All subjects except for Subj. 1 perceived some self-motion when the moving sound images were presented. In contrast, except for Subj. 5, they did not perceive any self-motion in the "NoSound" condition.

Table 1 shows the relationship between the direction of moving sound images and the direction of perceived self-motion. The gray cells in the table indicate that the direction opposite to that of moving sound images is involved in the perceived direction.

Figures 3 and 4 show standard deviations (SDs) of body sway, i.e., the sway of the center of gravity due to body movement. The results show no significant difference between conditions.

4. Discussion

These results seem to show that illusory linear motion was induced by the linearly moving sound images.

The results in Table 1 show that the direction of the perceived self-motion was generally opposite to the direction of the moving sound images. Moreover, when there was no sound or only fixed sound images, most subjects answered that they could not perceive any self-motion. This could mean that the perceived self-motion was influenced by the auditory information which was provided. Therefore, χ^2 tests were performed to examine whether the frequencies at which the subjects perceived self-motion were significantly influenced by the moving sound images. Results showed that the subjects reported the occurrence of self-motion more frequently for

Table 1 Relationship between the direction of moving sound images and the direction of perceived self-motion. Values are the total frequency for all subjects.

	Subjects' Responses										
Condition of Sound: Speed	Front	Forward left	Left	Backward left	Back	Backward right	Right	Forward right	Counter-clockwise	Clockwise	None
Front:13.3	3	2			1	1	1	1			5
Front:6.7	6	1		1	1		1		1		3
Left:13.3			7	1					2		4
Left:6.7		1	6				1		3	1	2
Back:13.3		1		3	6	1					3
Back:6.7	1		1		9						3
Right:13.3		1					5	2		2	4
Right:6.7			1	1		2	2	3		3	2
Fixed	2				2		1		1		8
NoSound	1						1				12

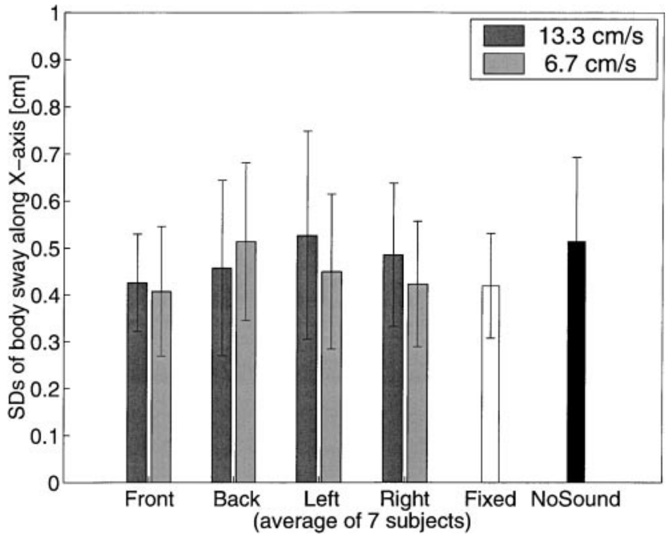

Fig. 3 Average SDs of body sway (x-axis).

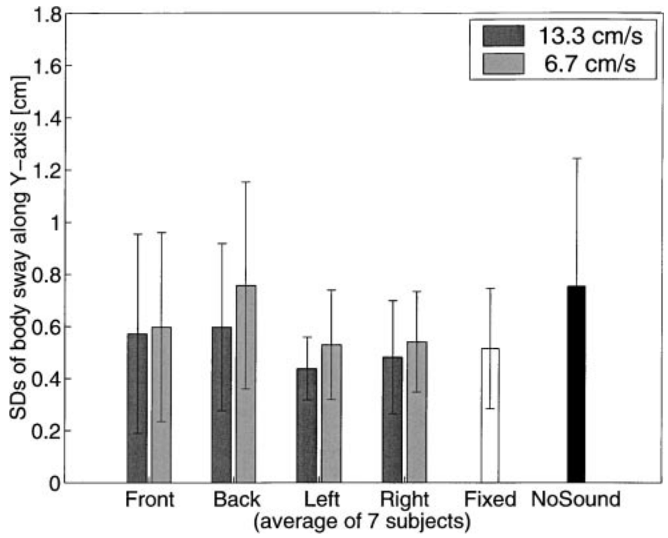

Fig. 4 Average SDs of body sway (y-axis).

some directions (gray cells in Table 1) than for others with the moving sound images for all directions (Front-back: $\chi^2(9) = 31.00$, $p < .01$, Left-Right: $\chi^2(9) = 68.00$, $p < .01$, Back-Front: $\chi^2(9) = 86.18$, $p < .01$, Right-Left: $\chi^2(9) = 26.18$, $p < .01$).

In Fig. 2, the subjective magnitude of perceived self-motion induced by sound images moving from back to front seems not to be equal to that induced by sound images moving from front to back. To analyze this phenomenon more in detail, we calculated the inner product between the direction of moving sound images and the direction of perceived self-motion shown in Fig. 2 and examined the results on the magnitude of perceived self-motion considering the direction with a two-way repeated-measure ANOVA. In this analysis, the direction and the speed of moving sound images were treated as between-subject variables and subject was treated as the repeated measure. As a result, the subjective magnitude of self-motion induced by sound images moving from back to front was larger on the average than that induced by sound images moving from front to back ($F(1,6) = 6.46$, $p < .05$).

In the visual domain, similar but opposite asymmetry is observed. That is, in visual vection, larger self-motion is usually perceived when a stimulus moves from front to back than when it moves from back to front [3]. This phenomenon in the visual domain is often related to the fact that the visual system is more sensitive to centrifugal movement than to centripetal movement [3]. Because of the law of perspective, this characteristic may consequently mean that the visual system is more sensitive to movement from front to back than that from back to front. The present results suggest that the auditory system may be more sensitive to a motion from back to front than that from front to back. It is interesting that visual information and auditory information might be complementary, in a sense, when we perceive self-motion. Moreover, this also suggests that auditory and visual information might play complementary rôles in spatial perception.

The body sway shown in Figs. 3 and 4 show no significant difference between conditions. Considering that significant effects are observed in visual vection, this may mean that auditory vection is smaller than visual vection under the present experimental condition.

5. Conclusion

Self-motion induced by moving sound images was investigated by a psychophysical experiment in this study. Moreover, the sway of the center of gravity induced by body movement was also analyzed as an objective measure. Results showed that auditory information could also induce linear self-motion perception and that the direction of the self-motion was influenced by the direction of the motion of sound images. Moreover, asymmetry between the subjective magnitude of forward self-motion and that of backward self-motion was observed. This asymmetry observed in auditory vection is opposite that observed in visual vection. This suggests that auditory and visual information may play complementary rôles in spatial perception.

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