

ACOUSTICAL LETTER

The effect of linearly moving sound image on perceived self-motion with vestibular information

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1. Introduction

Better understanding of human multimodal information processes, including hearing, is crucial for developing new human-machine interfaces and virtual-reality systems. Self-motion perception is a well-known multimodal perceptual process that incorporates visual, postural, and somatic information. Among these types of information, visual information strongly influences self-motion perception. A typical example of this phenomenon is "vection" [1]. Human beings sometimes perceive self-motion using only visual information; we may have an illusory feeling that our stationary train is moving when we see a train departing on the next track.

In this study, we specifically address the effect of auditory information on self-motion perception. Not only visual information but also auditory information includes rich spatial information. It is therefore likely that auditory information influences self-motion perception. Actually, this has already been shown in a few studies [2–6]. However, auditory information is rarely the only sensory information available during self-motion perception; we must usually address vestibular information simultaneously. For this reason, it is important to investigate the relationship between auditory information and vestibular sensation, but this point has been examined in few studies.

In this study, the effect of auditory information on self-motion perception with vestibular sensation was investigated. The vestibular system has two different sensing organs to sense rotations and translations: semicircular canals detect rotational movements; otoliths detect linear translations. In this study, we mainly examine the relationship between auditory information and information on linear acceleration obtained by otoliths. We examine whether self-motion perception is influenced by auditory information in conflict with vestibular sensation. Using these results, the relationship between auditory information and self-motion perception was analyzed.

2. Experimental method

The experiment was performed in an anechoic room of the Research Institute of Electrical Communication, Tohoku University. Six male and three female adults with normal hearing acuity participated in the experiment. They were given no information on the aims of this experiment. Moreover, they wore eye masks during the session. Consequently, they received no visual cues during the experiment. Figure 1 shows the experimental equipment. A swinglike device was installed in the anechoic room to provide vestibular information (Fig. 2). At the beginning of each trial, the experimenter pulled the device a distance of 25 cm and then released it. A laser-beam pointer was installed at the edge of the swing, and the swing was slowly pulled until the beam pointed to a mark on the floor to specify the amplitude. Table 1 shows the moving characteristics of the swing. A virtual sound image moving laterally 1.5 m in front of the listener was used as a source of auditory information. This sound image was produced by a virtual auditory display system and was presented via headphones (STAX SR-202 Basic). This system continuously changes the head related transfer functions (HRTFs) convolved depending on the listener's head motion and the sound image movement [7]. The HRTFs for this auditory display were all individualized on the basis of the measurement of the listener's own HRTFs before the experiment. The source signal of the virtual sound image was low-pass noise with a cutoff frequency of 1500 Hz. The sound pressure level was adjusted to 70 dB (A-weighted equivalent continuous sound pressure level). The stimuli had a duration of 20 s.

The listener sat on the chair fixed on the swing, which moved back and forth during the experiment. The motion of the virtual sound image was perpendicular to that of the swing. One of the following four types of virtual sound image was generated during a session:

(1) Sound image moving to the right during the listener's forward motion and to the left during the listener's backward motion (condition: R-F).
(2) Sound image moving antiphase to the R-F condition (condition: L-F).
(3) Sound image fixed on a point 1.5 m from the center of the listener's head (condition: F-F).
(4) No sound image presented (condition: None).

Figure 3 shows these conditions schematically. The paired-comparison method was used. Two of the four conditions were selected randomly. The stimuli for the selected conditions were presented as a pair. Each pairing condition was presented ten times. Listeners were asked in which of the two

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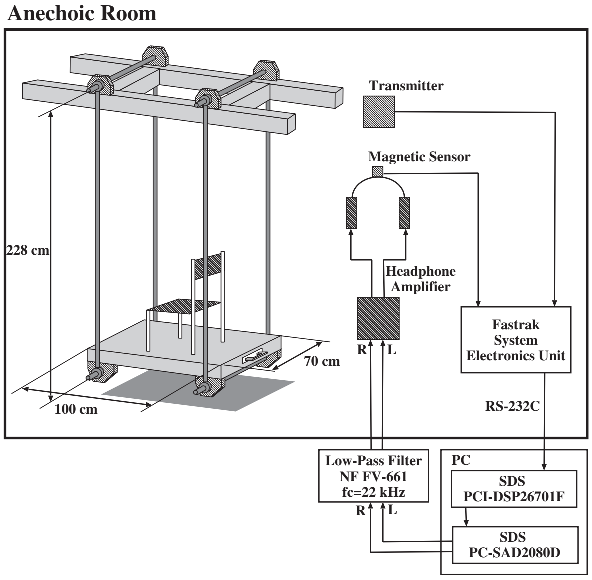

Fig. 1 Experimental setup.

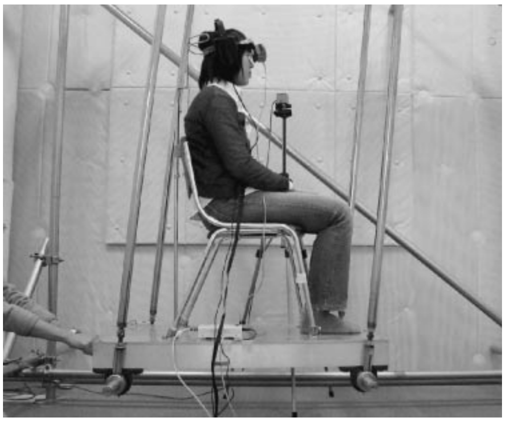

Fig. 2 Photograph of swinglike device.

Table 1 Oscillation parameter of the swinglike apparatus. This parameter was obtained when the equipment was pulled 25 cm and released.

Cycle(s)	Q ($=\tau$/cycle)	Time constant of attenuation τ
2.91	75.9	221

conditions they perceived more leftward self-motion when they were moving forward.

3. Results

Table 2 shows the psychological scale values for each listener. These values were calculated on the basis of Thurstone's case V [8] for each listener. Thurstone's law of comparative judgment is a general mathematical representation of a discriminal process. This law defines a psychological scale or continuum as the particular linear spacing of the confused stimuli, which yields a normal distribution of the

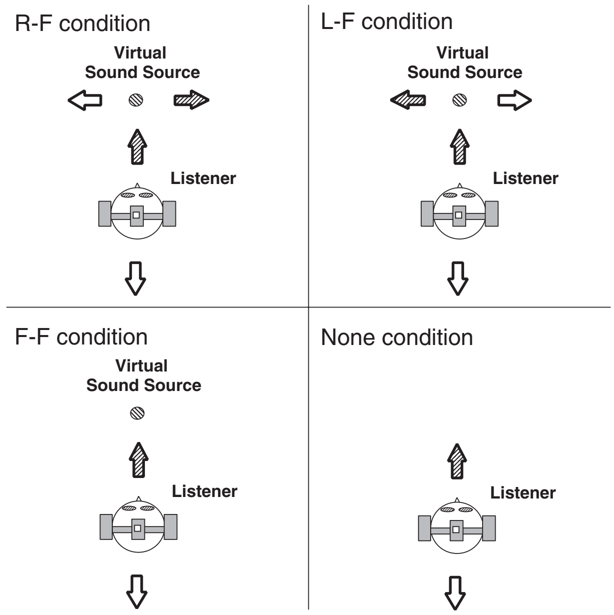

Fig. 3 Relation between presented sound image and listeners' self-motion perception.

Table 2 Psychological scale values of all listeners.

	Conditions			
	R-F	L-F	F-F	None
lis.AY	−1.16	0.89	0.39	−0.11
lis.AN	0.00	0.37	−0.18	−0.19
lis.MH	−1.08	1.08	−0.20	0.20
lis.SK	−0.31	0.31	0.12	−0.12
lis.SS	−0.37	0.66	0.00	−0.30
lis.NK	−0.12	0.32	−0.08	−0.12
lis.HW	−0.81	0.89	−0.09	0.02
lis.TK	0.00	0.06	0.12	−0.18
lis.AK	−0.70	0.69	0.07	−0.07

discriminal processes for each of the stimuli. Each psychological scale value for two compared stimuli is calculated from the discriminal difference, which is the scale difference between the discriminal processes of two specimens. This law has been considered under five cases involving different assumptions and degrees of simplification for practical use. Case V is the simplest formulation of the law. It involves the assumptions that there is no correlation between the discriminal deviations of the same judgment and that all the discriminal dispersions are equal. In this case, the calculated psychological scale gives positive values when listeners perceive greater leftward self-motion than that under the other conditions.

Table 2 shows that almost all listeners perceived larger leftward self-motion in the L-F condition than in the other conditions, while the smallest psychological scale value was obtained in the R-F condition. These calculated scale values were analyzed statistically by one-way repeated-measure ANOVA to elucidate the psychological scale values. In this analysis, the condition was treated as the within-subject variable and the listener was treated as the repeated measure.

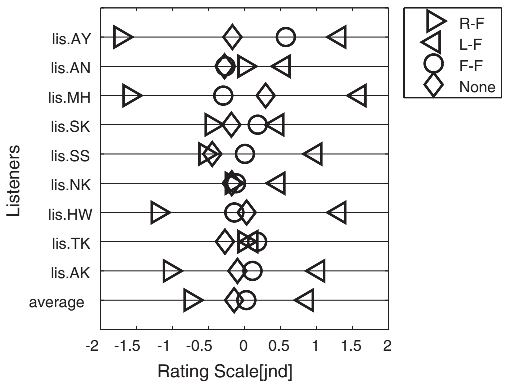

Fig. 4 JND scale values for each of the experimental stimuli.

Results show that the effect of conditions was statistically significant ($p < .01$).

The results of a multiple comparison based on pairwise comparisons using Tukey's honestly significant differences (HSD) test show that the value for the L-F condition was significantly larger than those for the other conditions ($p < .05$). Moreover, the value of the F-F condition was significantly larger than that of the R-F condition ($p < .05$). In contrast, the differences between the None and F-F conditions and between the None and R-F conditions were not significant.

To convert these psychological scale values into JND (just noticeable difference) values, these values were divided by the z-score corresponding to the 75% point on the cumulative normal distribution. By using the calculated JND values, we analyzed whether listeners noticed the difference of the conditions under which the virtual sound image was presented. Figure 4 shows the calculated JND values; almost all listeners noticed the difference between the L-F and R-F conditions, whereas they did not notice the difference between the F-F and None conditions.

4. Discussion

The results of this experiment show that auditory information provided by linearly moving sound image influenced vestibular sensation. However, the effect of auditory information on vestibular sensation differed from that of visual information in the following aspects. In the results of this experiment, a statistically significant effect was observed. That is, perceived self-motion was affected by the direction of the moving sound image. In this experiment, the direction of perceived self-motion was modified toward the moving sound image when the direction of the sound image was perpendicular to that of self-motion. A similar experiment using visual information demonstrated that the direction of perceived self-motion is modified away from moving visual images [9]. In other words, participants feel as if they follow the motion of the sound image, whereas they feel as if they are moving away from the visual images. This may mean that the moving sound image was perceived as a target while the visual images were considered as part of the environment. A possible explanation of this contrast may be that sound images are typically elicited from specific events, while visual images do not necessarily signify the occurrence of events. Clarification of the process behind this constrast is an interesting future problem.

This contrast suggests that visual information and auditory information might be complementary when humans perceive self-motion. Moreover, it also suggests that auditory and visual information might play complementary roles in spatial perception. Further studies should be carried out to consider this more in detail.

5. Conclusion

To clarify the relationship between auditory information and self-motion perception, we examined whether auditory information as well as visual information influenced vestibular sensation. The results suggest that the direction of a moving sound image influences the direction of the vestibular sensation. The direction of perceived self-motion appears to be modified toward the moving sound image, while the direction of perceived self-motion is usually modified away from the moving visual images. This suggests that visual information and auditory information might be complementary when we perceive self-motion. This knowledge is expected to be useful for developing new human-machine interfaces or virtual-reality systems.

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