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# Critical role of foreground stimuli in perceiving visually induced self-motion (vection)

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**Abstract.** The effects of a foreground stimulus on vection (illusory perception of self-motion induced by a moving background stimulus) were examined in two experiments. The experiments reveal that the presentation of a foreground pattern with a moving background stimulus may affect vection. The foreground stimulus facilitated vection strength when it remained stationary or moved slowly in the opposite direction to that of the background stimulus. On the other hand, there was a strong inhibition of vection when the foreground stimulus moved slowly with, or quickly against, the background. These results suggest that foreground stimuli, as well as background stimuli, play an important role in perceiving self-motion.

## 1 Introduction

When a visual stimulus surrounding observers and occupying a large area of their visual fields moves uniformly, the observers experience a sensation of self-motion in the direction opposite to that of the visual stimulus. This perceptual phenomenon is called visually induced self-motion, or vection (Fischer and Kornmüller 1930), and is widely accepted as evidence for the effect of visual information on the perception of self-motion [see reviews by Howard (1982) and Warren (1995)]. When a person moves or rotates at a constant speed, there is no vestibular information because vestibular organs respond only to acceleration, and the retinal image of the whole visual scene moving opposite to the self-motion is the only indicator of sustained self-motion (Dichgans and Brandt 1978). Such retinal-image motion is consistent with the moving visual stimulus which induces vection. This may be why the perceptual system produces a self-motion sensation when it receives a large moving pattern as input.

Many studies of the visual stimulus parameters which affect the occurrence and strength of vection have indicated that the depth structure of the visual stimulus has a very strong effect on it (Brandt et al 1975; Delmore and Martin 1986; Ohmi et al 1987; Ohmi and Howard 1988; Howard and Heckman 1989; Heckman and Howard 1991; Telford et al 1992; Howard and Howard 1994). For example, Brandt et al (1975) indicated that stationary bars located behind a moving pattern weakened vection, but when the same stationary bars appeared in front of the moving display, they had no effect on vection. Ohmi et al (1987) and Howard and Heckman (1989) reported that when two different stimulus patterns moving in opposite directions were presented simultaneously, vection occurred in the direction opposite to, and therefore was consistent with, the moving pattern which appeared more distant. Thus, vection was dominated by the more distant visual stimulus.

In our daily visual circumstances, the part of the scene which is perceived as more distant, ie the background, hardly moves in real world and retinal-image motion of such a background would most likely reflect the observer's self-motion (Gibson 1979). Therefore, the perceptual system may depend on the background as a reliable frame of reference for self-motion perception. On the other hand, objects close to the observer, ie in the foreground, generally move independently of the observer's motion, and thus the perceptual system cannot use such objects as a reliable indicator of self-motion. This might be why background stimuli play a more dominant role in vection than foreground stimuli.

Does this indicate, however, that foreground stimuli have no effect on the perception of self-motion? Many vection studies have concentrated on the analysis of the effects of background stimuli, whereas the contributions of foreground stimuli have been ignored for years. Recently, Howard and Howard (1994) studied the effect of a foreground stimulus on vection by presenting a stationary object in front of a moving background pattern. Their study was noteworthy because most of the earlier studies did not present any stationary objects in the visual field of the observer, on the simple assumption that such a stationary object might weaken the perception of vection. Contrary to such speculations, Howard and Howard found that a stationary foreground object can shorten the latency and enhance the strength of the vection, especially with slower background motion. This result cannot be explained if the perceptual system uses only the most distant stimulus as the source of self-motion information. They interpreted this phenomenon in relation to the relative motion between foreground and background stimuli which exists only when a foreground stimulus is presented. Because it is widely known that relative motion between two objects is easier to detect than retinal-image motion of a single object, ie absolute motion (Johnson and Scobey 1982; Snowden 1992), it is plausible that such relative motion between foreground and background is more salient and can induce stronger vection than the absolute motion of background presented by itself.

Thus Howard and Howard indicated a facilitative effect of a stationary foreground stimulus on vection. However, the foreground stimulus used in their experiment was a pair of thin vertical bars, while the background stimulus was a moving random-dot pattern which occupied the entire visual field of the subjects. Since stimulus attributes were greatly different between these two stimuli, the perceptual potency of their foreground stimulus might have been much weaker than that of the background. Such a stimulus configuration does not seem to be suitable for examining the effects of foreground – background relationships. Furthermore, the facilitative effect of the foreground presentation has never been confirmed elsewhere. In this study, we systematically investigated the effects of a foreground stimulus which had the same stimulus attributes as the background on the strength of visually induced self-motion. In experiment 1, the effect of depth order (foreground – background) was analysed by using superimposed stationary and moving random-dot patterns which had identical stimulus attributes except for their motions and distances from the observer. In experiment 2, we addressed the question about the origin of the effect of the foreground stimulus by manipulating foreground speed independently of background speed, in order to test the idea that relative motion between foreground and background can facilitate vection.

## 2 Experiment 1

### 2.1 *Methods*

2.1.1 *Stimulus.* Stimuli used in this experiment had three components: a foreground pattern, a background pattern, and a fixation cross — all of which were presented on an otherwise blank screen at a 100 cm observation distance. Foreground and background patterns were random-dot patterns, one of which moved horizontally from left to right at a designated speed while the other remained stationary. Each dot had a luminance of 14.8 cd $m^{-2}$ and a diameter of 3.2 deg. Dot density was 0.02 dots $deg^{-2}$. Thus 16% of the pixels were illuminated in each stimulus pattern. The foreground pattern had horizontally crossed binocular disparity of 36 min of arc, and the background pattern was given uncrossed disparity of 27 min of arc. These disparities corresponded to the foreground pattern being 15 cm nearer and the background pattern being 15 cm farther than the screen. All the subjects reported the designated depth order, and our preliminary observations suggested that the amount of perceived depth roughly corresponded to this value. A fixation cross, 1.0 deg in height and 1.0 deg in width with a luminance of 14.8 cd $m^{-2}$ was presented in the centre of the screen with zero binocular disparity. It therefore always appeared in the plane of the screen. Figure 1 illustrates the subject's perception of the stimuli.

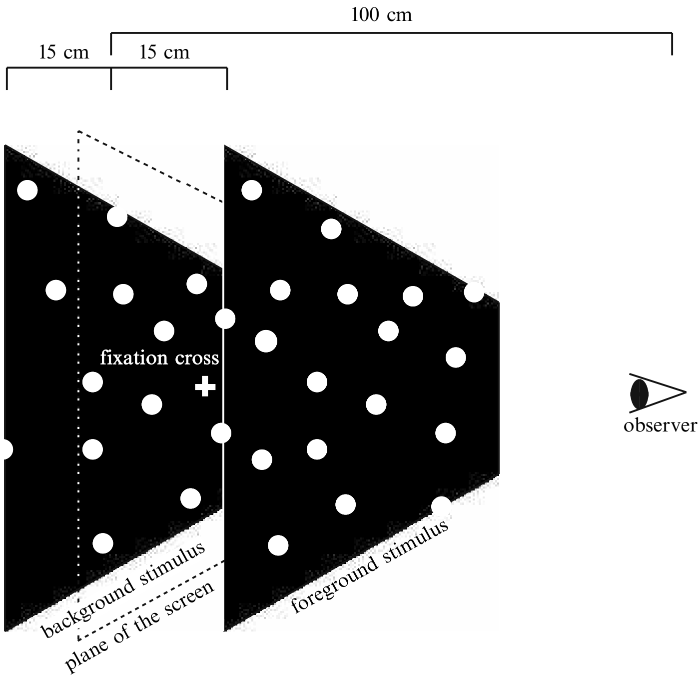


**Figure 1.** Schematic illustration of the perceived layout of the visual stimuli. The foreground and background patterns had horizontal binocular disparities which corresponded to the situation where the foreground was 15 cm in front of the plane of the screen and the background was 15 cm behind the plane of the screen (crossed disparity of 36 min of arc and uncrossed disparity of 24 min of arc, respectively). One of the patterns moved from left to right at a designated speed and the other was stationary. A fixation cross was presented in the plane of the screen. See text for more details.

2.1.2 *Apparatus.* The apparatus used in the experiment was improved from our previous studies (Nakamura and Shimojo 1998b). All stimuli were generated by a graphics workstation (Silicon Graphics IRIS320VGX), and projected onto a screen, 115 cm in height and 200 cm in width, by a video projector (Sony Tektronix 4190). Three-dimensional perception was accomplished by flickering orthogonal polarising filters on the projector and the subject's polarisation goggles. The refresh rate of the visual stimuli for each eye was 60 Hz, and subjects observed smoothly moving patterns with this refresh rate.

2.1.3 *Procedure.* Four naive adult volunteers (three males and one female, with ages ranged from 25 to 36 years), all having corrected-to-normal vision and previous experience of vection experiments, served as subjects. They had no knowledge about the aim of, and the predictions in, the experiment. In a dark room, subjects sat upright in a comfortable chair in front of the screen without any constraints on their heads, and observed the stimulus with their eyes fixed on the fixation cross at a viewing distance of 100 cm. Each subject's visual field was limited by the edges of the goggles for stereoscopic observations to 60 deg vertically and 90 deg horizontally, so that they could not observe anything else except for the stimulus, for example edges of the screen or the wall and floor of the room.

As indices of the strength of vection, both duration and estimated magnitude of vection were obtained in each trial. In our previous studies, we found that stronger vection tended to have a longer duration (Nakamura and Shimojo 1998a). Subjects were instructed to press a button when they experienced self-motion during the presentation of a moving stimulus which lasted 120 s. Before the experimental sessions, subjects performed training trials with the standard stimulus, consisting of a single random-dot pattern which had otherwise the same stimulus attributes as that used in the experimental conditions and set to move rightward at a constant speed of 50 deg $s^{-1}$, in order to establish the standard for the estimation of vection strength. Subjects estimated the strength of vection during experimental trials, on a scale from 0 (no vection) to 100 (vection with the same strength as in the control condition) or beyond, after each stimulus presentation.

2.1.4. *Stimulus conditions.* The depth order of the moving and stationary patterns was manipulated as an experimental variable. In the foreground-motion condition, the foreground pattern moved rightward while the background pattern remained still, and vice versa in the background-motion condition. In the control condition, there was only a single moving pattern which had zero disparity and was perceived in the plane of the screen.(1)

The speed of the stimulus motion was 25 or 50 deg $s^{-1}$. Each subject thus performed trials under 6 different conditions (3 types of the depth order $\times$ 2 different speeds). Trials for each stimulus condition were repeated 5 times in random order. Thus, altogether, 30 trials were obtained from each subject.

### 2.2 *Results and discussion*

Because similar results were obtained across the subjects, each measure of vection was averaged across subjects for each stimulus condition. Figure 2 shows mean durations and estimations under different stimulus conditions.

In the control condition, where the moving pattern was presented alone, faster movement of the stimulus induced stronger vection as indicated by longer durations and higher strength estimates. This result was consistent with those in previous studies which indicated that speed of vection increased with the speed of the inducing pattern, up to 120 deg $s^{-1}$ (eg Brandt et al 1973).

In the foreground-motion condition, only very weak vection was perceived as indicated by shorter durations and lower strength estimates, even in the faster-motion condition, and no subjects reported any self-motion with the slower motion. On the other hand, in the background-motion condition, quite strong vection was perceived as indicated by longer durations and higher strength estimates even with the slower motion. Furthermore, in comparison with the control, vection obtained in the background-motion condition was stronger than in the control condition with the slower motion, whereas there was no such difference with the faster motion.

Two-way analysis of variance (3 depth orders $\times$ 2 motion speeds) for each vection index indicated significant main effects of depth order (duration: $F_{2,6} = 27.09$, $p < 0.05$; estimations: $F_{2,6} = 37.63$, $p < 0.01$) and motion speed (duration: $F_{1,3} = 32.49$, $p < 0.05$; estimations: $F_{1,3} = 29.54$, $p < 0.05$). The interactions between

(1) In our pilot observation, it was shown that there was no difference in vection strength between the stimulus conditions where a single moving pattern was presented in the plane of the screen, 15 cm in front of it, or 15 cm behind it. Therefore the control condition which had a single moving pattern presented in the plane of the screen could serve to indicate the baseline strength of the vection in the case where a moving foreground or background stimulus was presented on its own, without the stationary pattern.

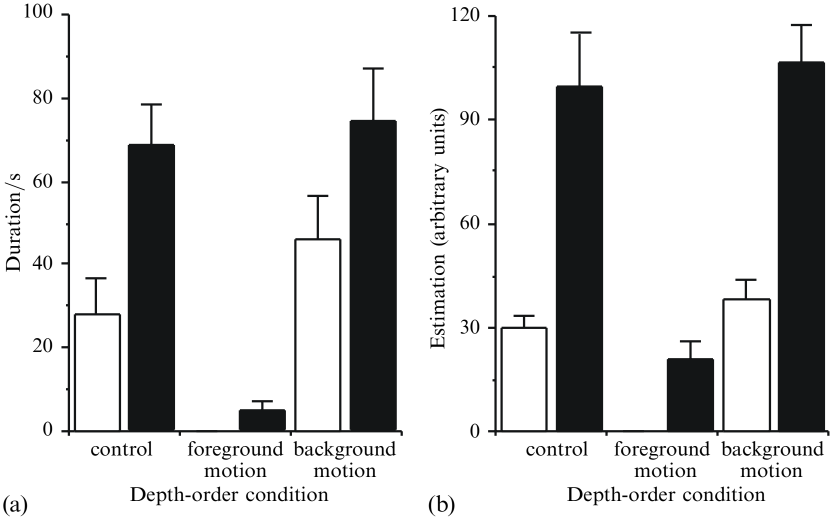


**Figure 2.** (a) Mean durations and (b) estimations of vection under different depth-order conditions. Black bars indicate faster motion (50 deg $s^{-1}$) of the stimulus pattern and white ones indicate slower motion (25 deg $s^{-1}$). Error bars indicate standard deviations.

these two factors were also significant (duration: $F_{2,6} = 40.71$, $p < 0.01$; estimations: $F_{2,6} = 18.19$, $p < 0.01$). Furthermore, a posteriori multiple comparisons of the differences between the depth-order condition for each motion speed were executed. Tukey tests ($\alpha = 0.05$ for all comparisons) revealed that durations and strength estimates were significantly different between the control and the foreground-motion condition, both with faster and with slower motion. And both indices in the background-motion condition were also significantly greater than in the control condition with slower motion, but such differences did not reach the significance level in the faster-motion condition.

The results of this experiment suggest that vection is effectively suppressed by a stationary background presented behind the moving foreground pattern. They support the idea that the most distant object serves as a frame of reference in perceiving self-motion, and that such a background governs vection, as indicated in the previous studies (eg Brandt et al 1975; Ohmi and Howard 1988; Telford et al 1992). When a stationary foreground was presented in front of a slowly moving background pattern, the strength of vection was significantly enhanced in comparison with that in the control condition where a single moving pattern was presented. This result confirmed the facilitative effect of the foreground presentation on vection which was originally reported by Howard and Howard (1994), although in our study, unlike in theirs, the foreground and the background stimuli were identical.

Is such a facilitative effect really due to the relative motion between the foreground and the background patterns as claimed by Howard and Howard? The next experiment was designed to examine the contributions of the relative motion by manipulating the speed of the foreground motion independently of the speed of the background motion. If the relative motion between the two stimuli plays a dominant role in the facilitative effects of the foreground, one can predict that vection would occur more strongly with faster motion of the foreground in an opposite direction to that of the background, owing to faster relative motion. Foreground motion in the same direction as background motion would reduce vection strength because of decreased relative motion, and when these two stimuli move at identical speeds in the same direction, no facilitation should be obtained because there is no relative motion.

## 3 Experiment 2

### 3.1 *Method*

Methods used in this experiment were the same as those used in experiment 1, except for the stimulus conditions in which foreground and background stimuli simultaneously moved in the same or opposite directions at a designated speed. Also, the treatment of data was modified in accordance with the change of the stimulus conditions, as described in the procedure section.

3.1.1 *Stimulus conditions.* The background stimulus was set to move from left to right at a faster (50 deg $s^{-1}$) or slower (25 deg $s^{-1}$) speed. The foreground stimulus moved at 11 different speeds, ±50, ±25, ±12.5, ±10, ±5, and 0 (stationary foreground) deg $s^{-1}$ ('+' means the foreground moved with the background, and '−' means it moved against the background). As in experiment 1, control conditions consisted of a single moving pattern, having zero disparity with respect to the screen and which moved from left to right at 50 or 25 deg $s^{-1}$. Consequently, there were 24 different conditions (11 foreground speeds × 2 background speeds plus 2 different control conditions). Each stimulus condition was repeated 5 times in a random order. Thus, altogether, 120 trials were obtained from each of the subjects.

3.1.2 *Procedure.* Subjects held a button in each hand, and were instructed to press the button corresponding to the direction of perceived self-motion when they experienced any vection: they pressed the right button for rightward vection and the left button for leftward vection. After the end of the stimulus presentation, subjects estimated the strength of vection on the same scale as in experiment 1, but this time with a sign ('+' for leftward and '−' for rightward vection).

### 3.2 *Results and discussion*

Subjects reported that, in certain conditions, leftward and rightward vections were perceived alternately within one trial. Thus, durations of leftward and rightward vection during each trial were obtained individually first, and then summarised with positive values for leftward vection (consistent with rightward background motion) and negative values for rightward vection (inconsistent with background motion). Durations and estimations of vection obtained in each experimental condition were expressed as a ratio to the measures in the control condition under each background speed. Thus, values greater than 1.0 indicate stronger vection and the values below 1.0 indicate weaker vection than that experienced in the control condition of each background-motion speed. Finally, the results were averaged across the subjects for each condition as in experiment 1. Figure 3 shows the mean standardised durations and estimations of vection as a function of foreground speed under each background-speed condition.

Duration and magnitude of vection varied nonlinearly with the foreground speed. When the foreground stimulus was still or moved slowly against the background, stronger vections were perceived, as indicated by longer durations and greater strength estimates than in the control condition. Especially, in the slower background condition, durations of vection became much longer. On the other hand, very weak vection was perceived (durations and estimations became close to 0) in conditions where the foreground stimulus moved with slower speeds in the same direction as the background stimulus. Further, only weak vection was perceived with the faster foreground motion against the background, while the faster foreground motion with the background induced vection as strong as in the control condition (both indices approached 1.0).

There was no difference between the faster-background and slower-background conditions.

Two-way analysis of variance (11 foreground speeds × 2 background speeds) indicated significant main effects of foreground speed for both indices (duration: $F_{10,30} = 23.54$,

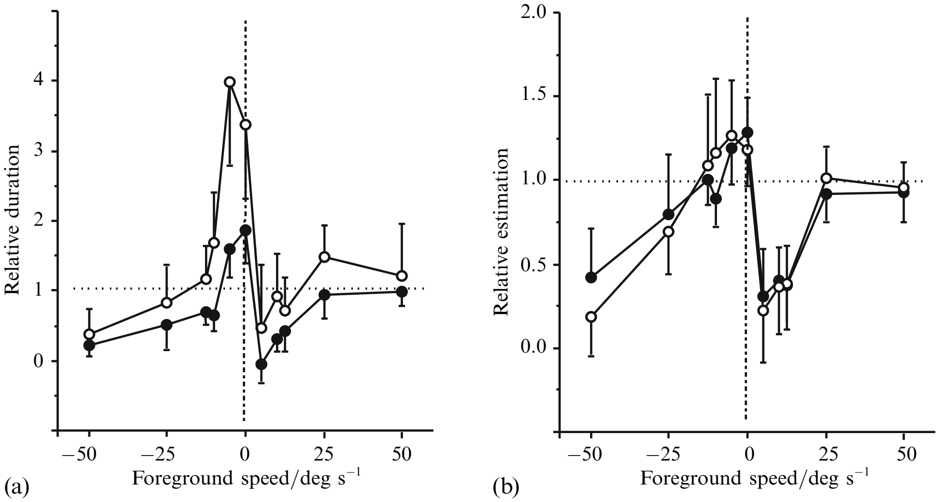


**Figure 3.** (a) Mean durations and (b) estimations of vection as a function of foreground motion speed at different background speeds. Data for each stimulus condition and index were standardised into the ratios to values obtained in the control condition for each background speed. Positive values indicate leftward vections which are consistent with the rightward background motion. Black circles indicate faster background motion (50 deg $s^{-1}$) and white circles indicate slower background motion (25 deg $s^{-1}$). Error bars shows standard deviations.

$p < 0.01$; estimation: $F_{10,30} = 15.79$, $p < 0.01$) . However, the main effects of the background speed were not significant (duration: $F_{1,3} = 2.37$, ns; estimation: $F_{1,3} = 1.21$, ns). Furthermore, the interaction of these two factors was significant for duration ($F_{10,30} = 15.41$, $p < 0.01$), but not for estimation ($F_{10,30} < 1$). Such a difference in the interaction between two indices might reflect the following result: when the foreground stimulus did not move or moved slowly against the background, the ratios of the durations to the control condition were considerably greater in the condition of slower background motion than in the faster one, whereas there was no such difference in estimations of strength.

In this experiment, we examined the effects of foreground motion speed on the strength of vection. To be consistent with the speculation of Howard and Howard (1994) that the relative motion between the foreground and the background stimulus could facilitate vection, vection strength was expected to vary linearly with the foreground speed, because the speed of relative motion increased with faster foreground motion against the background and decreased with foreground motion in the same direction as the background motion when the speed of background motion was fixed. However, the result of this experiment revealed more complex relationships between the speed of the foreground and vection strength, and did not support the above-mentioned simple hypothesis.

There is one more possible role of the foreground stimulus in vection. If the foreground stimulus does not serve as a reference for relative motion of the background, as suggested by Howard and Howard, it could still be used as a reference for the depth structure, indicating that the background is more distant. In this case, the facilitatory effect of the foreground stimulus might not vary with the foreground speed. This idea would seem plausible, because the background observed through the foreground, whether it was still or in motion, makes a stronger impression that the background was more distant than the background presented on its own, and such an impression might induce stronger vection. However, the result of this experiment indicated that the speed of the foreground motion affects the strength of vection, and is not consistent with this alternative hypothesis, either.

## 4 General discussion

We investigated the effect of the foreground stimulus on visually induced self-motion perception, using stimulus conditions where moving and stationary patterns (experiment 1) or two moving patterns with different speeds (experiment 2) were superimposed with different depths defined by binocular disparities.

### 4.1 *The effect of a moving foreground in front of a stationary background*

In experiment 1, we confirmed that the strength of vection is strongly suppressed by the presentation of a stationary background stimulus behind the moving foreground. Such a result is consistent with other vection studies, and supports the idea that the most distant object in the visual field is used as a reliable frame of reference in perceiving self-motion. Thus, background stimulus might be the primary determiner of self-motion perception. The moving foreground does not have enough strength to induce vection to overcome the strong inhibition produced by the stationary background.

### 4.2 *The effect of a stationary foreground in front of a moving background*

The results of experiment 1 also reveal that the presentation of a stationary foreground stimulus in front of a slowly moving background can facilitate the strength of vection relative to the control condition where the moving pattern is presented alone. Similarly, the results of experiment 2 in the condition where the foreground was motionless indicate that the strength of vection is enhanced relative to that in the control condition, as indicated by indices greater than 1.0, especially with the slower background movements. These results are consistent with those reported by Howard and Howard (1994).

With the faster background motion, however, there seemed to be decreased facilitatory effects of the stationary foreground stimulus. This result is also consistent with those of Howard and Howard, where they reported that facilitation of vection caused by a stationary foreground object was greater with a slower background motion than with a faster one. This might be because the vection-inducing potential of the faster-moving pattern was so strong, as indicated in the control condition with faster motion, that the strength of the vection induced by the faster background was already saturated at the maximum level, and additional enhancement by the foreground was impossible.

### 4.3 *The effect of relative motion between foreground and background*

In experiment 2 we investigated the effect of relative motion between the foreground and the background by manipulating the speed of the foreground independently of that of the background motion. The results suggest that vection is stronger when the foreground is stationary or moves slowly against the background than in the control condition. In such conditions, there were moderate relative motions between foreground and background. In the condition where the foreground moved faster in the same direction as the background, vection strength was almost the same as in the control condition. Thus, there was little effect of the foreground stimulus in such a condition. These results are consistent with the hypothesis that relative motion between foreground and background determines vection strength.

Contrary to the above, the other aspects of the results in experiment 2 did not agree with the relative-motion hypothesis. In the conditions where the foreground moved faster against the background, there was much greater relative motion between the two patterns, and thus there should have been stronger vection according to the relative-motion hypothesis. However, there was almost no vection in these large-relative-motion conditions. Furthermore, in the conditions where the foreground moved slowly with the background, the vection strengths were also very weak. In this slow-same-direction condition, there was still greater relative motion than in the conditions with the faster foreground motion in the same direction. Nevertheless, the strength of vection was greater with the faster foreground motion than with the slower one.

These results cannot be explained if the foreground stimulus affects the vection mechanism merely through being a reference for relative motion, with the strength of vection increasing with the speed of such relative motion. Thus, the results of the present experiments suggest that the foreground stimulus also plays an important role in perceiving self-motion, although the background stimulus primarily dominates the self-motion perception.

As to the stimulus configuration in experiment 2, it would be worth noting that when stimulus patterns move in parallel with different velocities, just as our stimulus patterns did, apparent depth between these patterns is perceived in accordance with motion parallax, by the geometrical relationship between the external depth structure and the observer's self-motion (Rogers and Graham 1979). In our experiments, the depth distance between the foreground and the background was defined explicitly by the binocular disparities, which were typically inconsistent with the one afforded by motion parallax. Thus, visual stimuli used in our experiment were artificial, ignoring the natural relationship between the depth and motion. This fact should be considered in evaluating the results obtained in the present experiments.

We must consider yet another potential factor: induced motion of the visual pattern. Howard and Heckman (1989) suggested that moving foreground induces apparent motion of a stable background, and then the perceived motion of the background would induce self-motion perception ('contrast-motion vection'). In our experiment, the foreground moving slowly in the same direction as the background might induce contrast-motion of the background, thus reducing the perceived speed of the background. Such a perceptually slowed down speed of the background would reduce the strength of vection. Similarly, foreground motion in the opposite direction to that of the background would increase the perceived speed of the background and thus induce stronger vection, as the results show. Perhaps all the three factors we have described here: relative motion, motion parallax, and induced motion, may all together have given rise to the overall pattern of our results.

Unfortunately, at present, there is no consistent explanation for the nonlinear effects of the foreground on self-motion perception. We propose to carry out experiments to investigate the effects of the foreground stimulus in more detail using various combinations of foreground and background motions.

### 4.4 *The indices of vection strength*

In this study, the duration and magnitude of vection strength were used as indices of the strength of vection, and they showed almost the same tendencies in the results of the two experiments with one exception described below. In experiment 2, the facilitation of vection with a stationary or slowly moving foreground in front of a slowly moving background in the same direction was more apparent in the duration measure than in the estimates of strength. Such a difference may be interpreted to mean that these two indices reflect different properties of the strength of vection, but it seems more likely that duration is merely more sensitive in detecting the facilitative effect of the foreground stimulus. Further comparisons must be done with other indices, such as the latency of the vection, or body sway which is strongly affected by perceived self-motion (Lee and Lishman 1975; Previc et al 1993).

### 4.5 *Concluding remarks*

In this study, the presentation and motion of a foreground stimulus turned out to have a remarkable effect on the vection perception. In particular, the foreground increases the strength of vection when it is static or moves slowly against the background. On the other hand, slow foreground motion with, or fast foreground motion against the background suppresses vection. These findings are surprising, considering that the foreground stimulus has been thought to be irrelevant to vection and, with few exceptions, ignored in vection studies.

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