Nakamura & Shimojo (2000) *Vision Research*, **40**, 2915-2923

A slowly moving foreground can capture an observer's self-motion - a report of a new motion illusion: inverted vection

Shinji Nakamura[a,*] and Shinsuke Shimojo[b,c]

[a] Future Project Division, Toyota Motor Corporation
1200, Mishuku, Susono, Shizuoka, 410-1193 Japan
[b] Computation & Neural Systems, Division of Biology,
California Institute of Technology,
139-74 Pasadena CA 91125 USA
[c] NTT Comunication Science Laboratories, Kanagawa, Japan

* Corresponding author. Fax: +81-559-97-7884.
E-mail address: snakamur@square.mk.toyota.co.jp

Abstract

We investigated interactions between foreground and background stimuli during visually induced perception of self-motion (vection) by using a stimulus composed of orthogonally moving random-dot patterns. The results indicated that, when the foreground moves with a slower speed, a self-motion sensation with a component in the same direction as the foreground is induced. We named this novel component of self-motion perception "inverted vection." The robustness of inverted vection was confirmed using various measures of self-motion sensation and under different stimulus conditions. The mechanism underlying inverted vection is discussed with regard to potentially relevant factors, such as relative motion between the foreground and background, and the interaction between the mis-registration of eye-movement information and self-motion perception.

Key Words: vection, self-motion, depth, foreground

1. Introduction

It is widely known that uniform motion of a visual stimulus which occupies a large area of an observer's visual field can induce illusory motion perception of the observer's own body in the direction opposite to that of the visual motion (Fisher & Kornmuller, 1930; Brandt, Dichgans & Koenig, 1973). This perceptual phenomenon is called vection and is recognized as evidence for the strong effect of visual information on proprioceptive perception (see Warren [1995] for a review). When an observer moves in a natural environment, retinal images of external scenes move in the direction opposite to the observer's motion. Such retinal image motion is consistent with the visual stimulus which induces vection. Thus, vection is likely to reflect the learning through experience of the natural relationship between self-motion and consequent retinal image motion (Gibson, 1979).

Many studies have emphasized the fact that the most distant stimulus in the visual field, or background, governed the occurrence of vection (Brandt, Wist & Dichgans, 1975; Delmore & Martin, 1986; Ohmi, Howard & Landolt, 1987; Ohmi & Howard, 1988; Howard & Heckman, 1989; Heckman & Howard, 1991; Telford, Spratley & Frost, 1992). In our everyday visual circumstances, a fast retinal image motion of a distant object would not be caused by the object's motion in the external world, but would most likely reflect the observer's self-motion. Thus we can depend on such a background as a reliable frame of reference for perceiving self-motion, and this might be why vection is dominated by the background stimulus. Since, for the reasons above, most of the vection studies have concentrated on an analysis of the effects of the background on vection, the possible effects of the foreground have been ignored. However, some recent studies have indicated that the foreground stimulus can also play a role in an observer's perception of self-motion (Howard & Howard, 1994; Nakamura & Shimojo, 1999).

In this study, we attempted to investigate interactions between the foreground and the background inducers during illusory self-motion. We were especially interested in analyzing the effects of the foreground motion on self-motion perception. We used a stimulus composed of two random-dot patterns which overlapped one another but had different binocular disparities and were set to move orthogonally.

2. Experiment 1

2.1. Methods

2.1.1. Stimulus and Apparatus

Stimuli were two overlapping random-dot patterns, which were set to move orthogonally with particular speeds. One was made the foreground stimulus, by giving it a binocularly crossed disparity of 36 minarc. The other was made the background stimulus by giving it an uncrossed disparity of 27 minarc. These disparities corresponded to the foreground being 15 cm nearer and the background being 15 cm farther than the screen. We used stimuli composed of either a vertically moving foreground and a horizontally moving background, or a horizontally moving foreground and a vertically moving background. A fixation cross, whose size was 1 deg in height and 1 deg in width, and whose luminance was 14.8 cd/m^2, was also presented in the center of the screen with zero-disparity relative to the screen. Fig.1 illustrates the stimulus schematically. 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 stimuli were generated by a graphics workstation (Silicon Graphics IRIS320VGX) and projected to a screen whose size was 115 cm high and 200 cm wide by a 3D video projection system (Sony Tektronix 4190).

2.1.2. Procedure

Subjects were four adult volunteers (three males and one female, ages ranged from 25 to 36) and all had corrected-to-normal vision and previous experience of vection observations, yet were naive for the purpose of the investigation. In a dark room, subjects sat upright in a comfortable chair in front of the screen without any head constraints, and observed the stimulus with their eyes fixed on the fixation cross at a viewing distance of 100 cm. Subjects wore goggles with polarized filters for the stereoscopic observations. The edges of the goggles limited the subjects' visual fields to 60 vertical deg and 90 horizontal deg, and subjects could not see anything (such as edges of the screen, or the wall and floor of the room) except for the stimulus.

While the visual stimulus composed of an orthogonally moving foreground and background might induce self-motion sensation in oblique directions, subjects were instructed to attend to the component of self-motion sensation parallel to the foreground, ignoring the self-motion orthogonal to it, because we are mostly interested in analyzing the effect of the foreground stimulus on self-motion perception. Thus, subjects reported horizontal self-motion in the condition where the foreground moved horizontally, and vertical self-motion with vertical foreground motion. If there were no foreground effects, observer's self-motion perception would be determined solely by the background motion, and induced only in the direction parallel to the background (orthogonal to the foreground), without any components parallel to the foreground motion. On the other hand, if the effect of the foreground became stronger, a greater self-motion component parallel to the foreground motion would be perceived. Because self-motion sensation in the diagonal direction could be decomposed to the horizontal and vertical components easily, all subjects could execute the above task after adequate training observations (it took about ten minutes) without special efforts.

As indices of the strength of self-motion sensation, we measured duration and estimated magnitude of self-motion. Subjects held a button in each hand, and were instructed to press the button corresponding to the direction of self-motion whenever they perceived any self-motion parallel to the foreground motion. After the end of the stimulus presentation, which lasted for 120 sec, subjects were requested to estimate the strength of either the vertical or horizontal component of the self-motion sensation induced in the direction parallel to the foreground motion. Before the experimental session, subjects had undergone ten training trials using a standard stimulus. The standard stimulus consisted of a single random-dot pattern which had the same stimulus attributes as either of the patterns used in the experimental trials except that it had zero binocular disparity. The standard stimulus was set to move right or upward at a constant speed of 50 deg/sec. In the experimental trials, subjects estimated the strength of the vertical or horizontal components of the self-motion sensation which were parallel to the foreground stimulus, on a scale from 0 (no vertical or horizontal self-motion was perceived) to 100 (the vertical or horizontal self-motion component was as strong as that with the vertical or horizontal standard stimulus, respectively) or beyond.

2.1.3. Stimulus conditions

The speed of the foreground stimulus was manipulated as an independent variable and had ten levels (±20, ±10, ±.0, ±2.5, ±1.25 deg/sec. "+" means right or upward motions and "-" means left or downward motions), whereas the background stimulus always moved at a constant velocity of +25 deg/sec. Motion direction was also varied. In the horizontal-foreground condition, the foreground stimulus moved horizontally while the background motion was vertical, and vice versa in the vertical-foreground condition. There were 20 different conditions (ten foreground speeds for two different directions), and trials for each stimulus condition were repeated five times in a random order. Thus all together, 100 trials were obtained from each of the subjects.

We executed an additional control experiment in order to examine the effects of the foreground stimulus presented by itself. A single random-dot pattern which was identical to the foreground stimulus used in the experimental condition was presented on the screen by itself. Stimulus motion was set vertically or horizontally at ten different speeds (±20, ±10, ±.0, ±2.5, ±1.25 deg/sec). No background stimulus was presented. A fixation cross was presented in the center of the screen with zero-disparity relative to the screen. Thus the binocular disparity of the foreground was kept identical to the experimental condition. The same four subjects took part in this control experiment.

2.2. Results

Durations and strength estimates of self-motion were averaged across the subjects. In the data-analysis, positive values were assigned to right or upward self-motion sensation and negative values to left or downward self-motion sensation. Fig. 2 shows the mean durations (a) and strength estimates (b) of the self-motion parallel to the foreground motion as a function of the foreground speed under different motion direction conditions. The strength of the self-motion sensation varied non-linearly with the motion speed of the foreground stimulus. When the speed of the foreground was slow (approximately below 5.0 deg/sec), strong self-motion in the same direction as the foreground motion was perceived, while there was no obvious self-motion sensation parallel to the foreground with faster motion. These results were common to both the horizontal and vertical-foreground conditions and both indices of self-motion (duration and strength estimation). A two-way analysis of variance indicated significant main effects of foreground speed, both for duration ($F_{9,27}$=17.11, p<.01) and estimation ($F_{9,27}$=21.68, p<.01). But there was neither a significant main effect of motion direction, i.e. horizontal vs. vertical foreground, (Duration: $F_{1,3}$<1; Estimation: $F_{1,3}$=1.11, n.s.), nor an interaction between these effects (Duration: $_{9,27}$<1; Estimation: $F_{9,27}$=1.63, n.s.).

The results of the control experiment were also plotted in fig. 2. In the control experiment, durations and strength estimates of the self-motion sensation varied linearly with the speed of the stimulus motion. The faster motion induced stronger self-motion sensation in the direction opposite to the pattern motion, in the case where there was no background stimulus.

2.3. Discussion

The results of this experiment indicated that when the foreground stimulus moved slowly in front of the orthogonally moving background, self-motion with components in the same direction as the foreground motion was perceived Thus, a slowly moving foreground can "capture" the self-motion perception of the observer, or induce self-motion perception in the same direction as the foreground motion itself, when there is a fast, orthogonal inducer in the background. In the previous studies of vection, it has been maintained that self-motion sensation was always induced in the direction opposite to the inducer's motion and understood in terms of the natural relationships between self-motion and retinal image motion of external scenes in the real world (Gibson, 1979). In contrast, our experiment indicated that self-motion sensation would be induced in the same direction as the inducer's motion, or in an inverted direction compared to the above mentioned standard vection, in an artificial stimulus configuration which contains orthogonally moving foreground and background patterns. We would like to refer to this newly discovered perceptual phenomenon as "inverted vection."

The result of the control experiment indicated that a foreground stimulus presented by itself induces standard vection in the opposite direction, not inverted vection. Thus, inverted vection requires stimulus situation where the foreground is presented in front of a moving background. The results also indicated that there is a difference in speed-efficacy between the two types of vection; inverted vection is induced only by the slower foreground motion and attenuated as the speed of the foreground motion increases, whereas standard vection becomes stronger as the foreground pattern increases its speed. The latter is consistent with previous studies which indicated that the perceived speed of standard vection is increased with the motion speed of the inducing pattern up to 120 deg/sec (e.g., Brandt et al., 1973). This discrepancy between the two types of vection in terms of speed dependency makes it unlikely that the inverted vection is merely a variation of the standard vection caused by the induced or biased direction of background motion under the influence of the foreground motion. However, we will consider this possibility once again in the General Discussion.

The result of this experiment indicated that a slowly moving foreground presented in front of an orthogonally moving background can induce inverted vection. However, there was a methodological problem: the subjects' task was not straightforward, in that they had to attend only to the self-motion component parallel to, and ignore the component orthogonal to, the motion of the foreground stimulus. In the next experiment, inverted vection was examined with a more direct and objective measure.

3. Experiment 2

In this experiment, the strength of inverted vection was analyzed by measuring the perceived direction of self-motion. When the background moves vertically and the foreground moves horizontally, as in the case of the present experiment, the angle of the self-motion direction measured against vertical would indicate the strength of the self-motion component parallel to the foreground motion. When inverted vection is induced more strongly, the self-motion angle would become greater. Thus, we can obtain the magnitude of inverted vection by analyzing the self-motion direction and calculating the tangent of the self-motion angle (if vertical component of self-motion sensation induced by the background is assumed to be constant).

This measure has an other advantage in that the task is much less demanding and natural.

3.1. Methods

The stimulus and apparatus used in this experiment were almost the same as in experiment 1. The four adult volunteers who participated in experiment 1, took part in this experiment.

Subjects held a joystick which was attached to the graphics computer via a 16-bit A/D converter board (VME Microsystems VMIVME3118). The subjects' task was to indicate the perceived direction of their self-motion by using the joystick. The subjects pushed the joystick foward to indicate upward motion, left to indicate leftward motion, and so on. The subjects were allowed to indicate oblique self-motion by pushing the joystick in diagonal ways. The joystick system allowed analog measurment of the response with angular resolution less than one degree.

At the end of each trial, the subject estimated the strength of the self-motion component parallel to the foreground using the same scale as in experiment 1.

Data obtained from the joystick system was stored at a sampling rate of 60 Hz, and the angle of perceived self-motion direction, measured against vertical, was calculated for each sampling period. Then, the angles obtained within a trial were averaged. We also measured the durations of self-motion having components parallel to the foreground by counting the total time when the joystick system registered any self-motion having a horizontal component.

3.1.1. Stimulus Condition

The background stimulus always moved upward at a constant speed of 25 deg/sec, and thus it can be assumed that the vertical component of self-motion sensation induced by this background did not vary between the conditions. The foreground stimulus was set to move from left to right at four different speeds (2.5, 5.0, 7.5 and 15.0 deg/sec).

3.2.Results and discussion

Fig. 3 compares the three indices of self-motion; (a) duration, (b) estimated strength and (c) self-motion direction. Tangent of the angle in pannel (c) refers to the tangent of the self-motion angle which would indicate the magnitude of the horizontal component of vection. The tangent of the self-motion angle showes qualitative agreement with the measures employed in experiment 1, i.e. duration or strength estimate. In the condition where the foreground moved at 5.0 deg/sec, all measures indicated that subjects perceived strong self-motion in the same direction as the foreground motion. Additionally, the strength of inverted vection was reduced as the speed of the foreground was increased or decreased from 5.0 deg/sec, and there was only weak inverted vection in the condition with the fastest foreground motion (15.0 deg/sec). These results were consistent with the results of experiment 1. One-way analysis of variance indicated that there was a significant main effect of foreground speed in all self-motion indices (duration: $F_{3,9}$=23.78, p<.01; estimation: $F_{3,9}$=21.97, p<.01; self-motion direction: $F_{3,9}$=18.91, p<.01).

With more refined measures, we duplicated the inverted vection which was found in experiment 1, and also confirmed that slower foreground motion is the optimal stimulus for this effect. Pearson's coefficients of correlation between indices were remarkably high (.89 between direction and duration, .88 between direction and strength estimate and .86 between duration and strength estimate), suggesting robustness of the inverted vection effect and reliability of the measures.

4. Experiment 3

Howard and Heckman (1989) reported that, when a moving foreground and a stable background were presented simultaneously, self-motion perception was induced in the same direction as the foreground motion. They interpreted this phenomenon as follows: the foreground motion induced apparent motion of the stable background in the opposite direction, and the perceived motion of the background in turn induced the self-motion perception in the opposite direction to the apparent motion, i.e., in the same direction as the foreground motion ("contrast-motion vection"). In the stimulus setting in our experiment, foreground motion could bias the perceived direction of the background motion towards the opposite direction to the foreground motion, as a result of the vector summation of the original actual motion of the background and the induced component of it caused by the foreground (Loomis & Nakayama, 1973; Post & Chaderjian, 1988). Such a biased direction of the background motion could then induce a self-motion sensation with a component which is apparently in the same direction as the foreground motion. Thus, we could not tell whether foreground motion could directly induce the inverted self-motion perception, or whether it merely affects the direction of self-motion indirectly, by biasing the perceived direction of the background motion.

We analyzed inverted vection induced by a stimulus composed of a vertically striped background which moved horizontally and a vertically moving random-dot foreground, in order to examine the effects of the relative motion between these patterns on inverted vection[1]. Vertical stripes have no luminance gradient along the direction in which the foreground random-dots were moving. As a consequence, very little vertical motion of the vertically striped background would be induced by the vertically moving foreground dots. This is expected because the observer in general cannot disambiguate the motion component parallel to the orientation of the stripes (the aperture problem; Wallach, 1935), and tends to perceive the stripes moving in the direction of its terminator's motion, even in the condition where an orthogonally moving dot-pattern is presented simultaneously (Shiffrar, Li and Lorenceau, 1995). Thus, we could assume that the effect of the foreground motion on the perceived direction of the background motion is much weaker in this case, as compared to the condition where the background consists of a random-dot pattern. Just to see if this had been indeed the case or not, we executed experiment 3-1 in which observers were asked to judge perceived directions of the background motion. In experiment 3-2, we compared inverted vection experienced in the condition with a vertically striped background to that with a random-dot background.

4.1. Experiment 3-1

4.1.1 Methods

The background pattern was either a vertically-striped pattern or a random-dot pattern which moved horizontally from left to right at a constant speed of 25 deg/sec. In the striped background, luminance was 7.8 cd/m^2 for the brighter stripes and 1.2 cd/m^2 for the darker stripes (contrast = .73). Each stripe had a width of 7.5 deg. The stimulus configurations of the random-dot background, the foreground pattern and the fixation cross were identical as in the previous experiments. The foreground moved upward either at a faster (25 deg/sec) or a slower (5deg/sec) speed.

Three naive observers who did not participate in the previous experiments were asked to judge the perceived direction of the background motion. The observers indicated the direction of the background motion by the joystick system with similar procedure as the one used in experiment 2. The joystick system stored the angles during each experimental trial which lasted for 120 sec at a sampling rate of 60 Hz. Then, the angles obtained within a trial were averaged, and bias of the angle caused by the foreground motion was calculated in terms of the difference in direction between the observer's indication of the perceived background motion and the real background motion (positive values were assigned to biases against the foreground motion, and negative values were assigned to opposite biases).

4.1.2 Results & discussion

In the striped-background condition, the effect of foreground motion was almost negligible, and the background was almost always perceived to move in a horizontal direction with little vertical components. On the other hand, in the dotted-background condition, motion direction of the background was considerably biased in the direction opposite to the foreground motion. Fig. 4 shows mean biased angle of the background motion as a function of foreground speed for each background type. A two-way analysis of variance indicated significant main effects of background-type ($F_{1,2}$=55.49, p<.05) and foreground-speed ($F_{1,2}$=21.56, p<.05). Interaction between these factors were also significant ($F_{1,2}$=50.17, p<.05).

The result of this experiment verified our assumption and indicated that vertically moving foreground cannot induce vertical motion component on vertically stripped background. Therefore, if inverted vection is a result of the apparent shift of the motion direction of the background induced by the foreground motion, the strength of inverted vection should be significantly reduced in the striped background condition. Experiment 3-2 will directly test this prediction.

4.2. Experiment 3-2

4.2.1 Methods

The stimulus conditions were set to be identical to experiment 3-1. Four subjects participated in experiments 1 and 2 observed the stimulus and reported inverted vection in the condition with vertically stripped or random-dotted background. The foreground stimulus consisted of a random-dot pattern which moved upward with faster (25 deg/sec) or slower (5 deg/sec) speed. In experiment 1, it was found that the foreground speed of 5 deg/sec was optimal for inducing inverted vection, whereas a foreground moving at 25 deg/sec could not induce self-motion.

The procedure in measuring inverted vection was the same as that in experiment 1. Duration and estimated magnitude of self-motion parallel to the foreground motion were measured as indices of inverted vection.

4.2.2. Results and discussion

Fig. 5 shows averaged duration (a) and estimated strength (b) of inverted vection as a function of foreground speed for each background condition. In the condition where the foreground stimulus moved faster, there was no obvious self-motion parallel to the foreground. On the other hand, a slowly moving foreground could induce self-motion sensation effectively in the same direction as its own motion. Furthermore, there was no difference in the strength of the inverted vection between the striped and dotted background with slower foreground motion. Two-way analysis of variance revealed that only a main effect of foreground speed was significant (Duration: $F_{1,3}$=42.19, p<.01; Estimation: $F_{1,3}$=56.6, p<.01), while neither a significant main effect of background types (Duration: $F_{1,3}$<1.0; Estimation: $F_{1,3}$<1.0) nor an interaction (Duration: $F_{1,3}$<1.0; Estimation: $F_{1,3}$=1.67, n.s.) was obtained.

The results of experiment 3-2 indicated that the visual stimulus composed of a vertically moving random-dot foreground and a vertically striped background can induce inverted vection with the same strength as the stimulus with a random-dot background, whereas experiment 3-1 suggested that there was a substantial difference in the effects of the foreground on perceived motion of the background between these two background conditions. If an observer's self-motion perception is determined only by the perceived motion of the background, there must have been much weaker inverted vection in the striped background condition in comparison with the dotted background. Thus, the apparent shift of the motion direction of the background induced by the foreground motion cannot fully explain the inverted self-motion perception revealed in this study. We attribute it to more direct effect by the foreground motion, as we will discuss in the General Discussion.

5. General Discussion

5.1. Possible hypotheses about the effects of the foreground

In this study, we analyzed vection induced by orthogonally moving foreground and background patterns, in order to investigate interactions between these two stimuli in perceiving self-motion perception. When the foreground moves slowly in front of a fast orthogonal background, self-motion with a component in the same direction as the foreground motion is perceived. It suggests that the foreground stimulus, which had been assumed to be irrelevant to vection, can critically affect self-motion perception, while the background inducer remains a primary determiner of self-motion perception, which is consistent with the some recent studies (Howard and Howard, 1994; Nakamura & Shimojo, 1999). Indeed, when there is no background, the inverted vection in the same direction as the foreground inducer is not observed. Nonetheless, the finding of reversaled vection induced by orthogonal front/back inducers is new, and requires an account. In this section, we consider possible hypotheses about the effect of the foreground motion on self-motion perception.

5.1.1. "Vector summation" hypothesis

In the condition where there are orthogonally moving foreground and background inducers, as in the case of our experiments, one might expect that self-motion sensation is determined by vector summation of the self-motion components which are induced separately by each of the inducers. Thus, in the condition where the foreground moves rightward and the background moves upward, for example, the foreground induces leftward and the background induces downward self-motion components, and oblique self-motion down to the left can be perceived as a result of vector summation of these. Alternatively, one might assume that the orthogonal motions of foreground and background inducers are vector summed first, and this combined motion in the oblique direction (up to the right in the above-mentioned case) induces self-motion perception in the opposite direction (down to the left). The predictions based on these variations of the vector summation hypothesis are identical, and inconsistent with the current results. Our results indicated that self-motion is induced down to the right: that is, a component of self-motion is in the same direction as the foreground motion (inverted vection). The effects of the foreground stimulus on self-motion perception should be explained otherwise.

5.1.2. "Motion-contrast" hypothesis

As mentioned earlier, Howard & Heckman (1989) argued that foreground motion affected perceived motion of the background via induced motion or motion contrast, and then, the biased motion of the background induces self-motion in the direction which is opposite to the biased background motion. There can be a self-motion component in the same direction as the foreground motion in this case. In this motion contrast account, the foreground motion can affect self-motion only indirectly via affecting perception of the background motion. Although the motion-contrast hypothesis can be a possible alternative for accounting for inverted vection, the results of experiment 3-1, i.e. the foreground motion had a significant effect on the perceived direction of the dotted background, but very little effect on that of the striped, and of experiment 3-

2, i.e. the inverted vection observed in the striped background condition was nonetheless as strong as that in the dotted background condition, all together suggested that biased motion perception of the background cannot fully explain the effects of the foreground on self-motion perception. The result of experiment 3-1 also revealed that motion of the foreground can bias perceived direction of the background if it is composed of random-dots, but the amount of the bias is greater with the faster foreground than with the slower one. To be consistent with the motion contrast account, inverted vection must have been stronger in the faster foreground condition. This prediction is inconsistent with our result which indicated that inverted vection is induced only by the slower foreground. Thus, the motion contrast is unlikely to be a primary factor causing inverted vection.

5.1.3. "Eye-movement" hypothesis

We would like to propose yet another alternative in which we assume that mis-registered information about eye-movement plays a role in perceiving self-motion. Post and his colleagues (e.g., Post, Shupert & Leibowitz, 1984) suggested that observation of a translating pattern with stable fixation would evoke mis-registration of eye-movement information in the opposite direction, due to a suppression of optkinetic nystagmus which could be potentially induced if there were no fixation. In our experimental situation as well, the foreground motion could cause mis-registration of eye-movement information as if the eyes rotated in the orbit in the opposite direction to the foreground motion. A series of investigations about heading judgment (e.g., Royden, Banks & Crowell, 1992; Banks, Ehrlich, Backus & Crowell, 1996) have indicated that, when observers translate forward with their eyes rotating, they utilize information about eye-movement in order to correctly perceive self-motion direction. In a situation where the eye-movement information is not available, an erroneous perception occurs with the heading biased in the direction of the eye-movement (Reagan & Beverly, 1982). Likewise in our experiments, the eye-movement information mis-registered by the foreground motion may affect self-motion perception: the perceived direction of the self-motion originally induced by the background motion may be biased in the opposite direction to the mis-registered eye-movement, i.e, in the same direction as the foreground inducer.

We assumed that the effect of the foreground motion on self-motion is a modifying one, biasing the direction of self-motion that is primarily determined by the background motion. (In this regard, our eye-movement account is compatible with Howard & Heckman's motion-contrast account.) The result in the control condition of experiment 1, i.e. that the foreground stimulus presented by itself induced self-motion perception in the opposite, not the same direction to the inducer's motion (standard vection), is also consistent with this notion of additional modification.

5.2. Why slower motion is optimal for inverted vection

We found that only slower foreground motion induces inverted vection. This might be related to the following facts. When two visual patterns which move in the same direction, but at different speeds, are presented simultaneously, the observer's eye follows the slower motion (Mestre & Masson, 1997). Moreover, according to Banks et al. (1996), it is only when the speed of eye-movements are slow enough that eye-movement information can be extracted from visual information. These findings indicate a stronger link between eye-movements and visual information at slower speeds. The extra-retinal components of the eye-movement information may become less reliable at a slower eye-movement speed, thus the visual information about eye-movment may have stronger effect on the motion perception. This interpretation is indeed consistent with the effect of the foreground speed on the inverted vection.

5.3. Comparison with similar phenomena

It would be worth noting that there are yet other perceptual phenomena which have phenomenological similarities to inverted vection. Duffy and Wurtz (1993) showed that, when a translating pattern was superimposed on an expanding pattern, the perceived location of the focus of expansion (FOE) in the expanding pattern shifted toward the motion direction of the translational motion. Royden and Hildreth (1996) argued that observers' heading judgments were systematically biased by the presentation of an object which moved independently in front of an optic flow field. They indicated that perceived heading was shifted toward the same direction as the moving object when the object crossed an observer's path. These two phenomena are similar to inverted vection in that the additional moving pattern biased the observer's self-motion perception in the same direction as the additional pattern, and opposite to the one expected as a result of vector summation of the two moving patterns. These phenomena might have similar underlying mechanisms with inverted vection. In particular, the account based on mis-registration of eye-movements may be applicable to them.

Recently, we reported that self-motion perception is strongly suppressed by a foreground which moves slowly in the same direction as the background (Nakamura & Shimojo, 1999). We can explain this result, based on our new knowledge about the inverted vection. In the condition where the foreground moves slowly with the background, the foreground stimulus induces self-motion in the same direction (inverted vection), while the background motion induces self-motion opposite to the visual stimulus motion (standard vection). As a result of the cancellation between standard and inverted vections, a strong suppression of self-motion perception might be observed.

Acknowledgements

The authors would like to thank Dr. Johanna Weber for carefully reading our manuscript and correcting English expression. And we also thank two anonymous reviewers for many helpful suggestions.

References

Banks, M. S., Ehrlich, S. M., Backus, B. T. & Crowell, J. A. (1996). Estimating heading during real and simulated eye movements. Vision Research, 36 431-443.

Brandt, T., Dichgans, J. & Koenig, E. (1973). Differential effects of central versus peripheral vision on egocentric and exocentric motion perception. Experimental Brain Research, 16, 476-491.

Brandt, T., Wist, E. R. & Dichgans, J. (1975). Foreground and background in dynamic spatial orientation. Perception & Psychophysics, 17, 497-503.

Delmore, A. & Martin, C. (1986). Roles of retinal periphery and depth periphery in linear vection and visual control of standing in humans. Canadian Journal of Psychology, 40, 176-187.

Duffy, C. J. & Wurtz, R. H. (1993). An illusory transformation of optic flow fields. Vision Research, 33, 1481-1490.

Fischer, M. H. & Kornmüller, A. E. (1930). Optokinetic ausgelöste Bewegungswahrnehmungen und optokinetisher Nystagmus. Journal für Psychogie und Neurologie (Leipzig), 41, 273-308.

Gibson, J. J. (1979). The ecological approach to visual perception. (Boston, Massachusetts: Houghton-Mifflin)

Heckman, T. & Howard, I. P. (1991). Induced motion: Isolation and dissociation of egocentric and vection-entrained components. Perception, 20, 285-305.

Howard, I. P. & Heckman, T. (1989). Circular vection as a function of the relative sizes, distances, and positions of two competting visual displays. Perception,18, 657-665.

Howard, I. P. & Howard, A. (1994). Vection: the contributions of absolute and relative visual motion. Perception, 23, 745-751.

Loomis, J. M. & Nakayama, K. (1973). A velocity analogue of brightness contrast. Perception, 2, 425-428.

Mestre, D. R. & Masson, G. S. (1997). Ocular responses to motion parallax stimuli: the role of perceptual and attentional factors. Vision Research, 37, 1627-1641.

Nakamura, S & Shimojo, S. (1999). Critical role of foreground stimuli in perceiving visually induced self-motion (vection). Perception, 28, 893-902.

Ohmi, M,. & Howard, I. P. (1988). Effect of stationary objects on illusory forward self-motion induced by a looming display. Perception, 17, 5-12.

Ohmi, M., Howard, I. P. & Landolt, J. P. (1987). Circular vection as a function of foreground-background relationships. Perception, 16, 17-22.

Post, R. B. & Chaderjian, M. (1988). The sum of induced and real motion is not a straight path. Perception & Psychophysics, 43, 121-124.

Post, R. B., Shupert, C. L. & Leibowitz, H. W. (1984). Implications of OKN suppression by smooth pursuit for induced motion. Perception & Psychophysics, 36, 493-498.

Reagan, D. & Beverly, K. I. (1982). How do we avoid confounding the direction we are looking and the direction we are moving? Science, 215, 194-196.

Royden, C. S., Banks, M. S. & Crowell, J. A. (1992). The perception of heading during eye movements. Nature, 360, 583-585.

Royden, C. S. & Hildreth, E. C. (1996). Human heading judgment in the presence of moving objects. Perception & Psychophysics, 58, 836-856.

Shiffrar, M., Li, X. & Lorenceau, J. (1995) Motion integration across differing image features. Vision Research, 35 2137-2146.

Telford, L., Spratley, J. & Frost, B. J. (1992). Linear vection in the central visual field facilitated by kinetic depth cues. Perception, 21, 337-349.

Wallach, H. (1935). Uber visuell wahrgenommene Bewegungsrichtung. Psychologishe Forshung, 20, 214-380.

Warren, W. H. (1995). Self-Motion: Visual perception and visual control. In Epstein, W. & Rogers, S. (Eds), Perception of space and motion (pp.263-325). San Diego: Academic Press.

Footnote

1 We could also use a stimulus configuration with a background composed of a horizontally-striped pattern and a horizontally moving dotted foreground, that is a 90 deg-rotated version of the stimulus pattern which we actually employed. In this study, however, we used horizontal binocular disparity to produce the stimulus depth structure, and horizontal disparity could not be established with horizontal stripes. Thus we were forced to use the stimulus condition described in the text.