ELSEVIER
Available online at www.sciencedirect.com
SCIENCE DIRECT®
Vision Research 45 (2005) 397–402
Vision Research
www.elsevier.com/locate/visres

Rapid Communication

Self-motion perception from expanding and contracting optical flows overlapped with binocular disparity

Hiroyuki Ito *, Ikuko Shibata

Department of Visual Communication Design, Kyushu University, 4-9-1 Shiobaru, Minami-ku, Fukuoka-shi 815-8540, Japan

Received 8 October 2002; received in revised form 13 September 2004

Abstract

Expanding and contracting patterns were presented on different disparity planes to investigate the role of stereo depth in vection. Experiment 1 tested the effect of stereo depth on inducing vection with expanding and contracting flows on different disparity planes. Subjects reported whether they felt forward or backward self-motion. The results clearly showed the dominance of the background flow in determining one's self-motion direction. Experiment 2 tested the effect of stereo depth on a vection direction using two expanding flows. The center of each expansion was displaced to either horizontal side. The subjects judged in which direction they were going when they felt vection. The results demonstrated that the subjects felt their heading biased toward the direction of the center of the farther expansion while feeling vection. The heading perception from the expanding flow was determined only by the background flow, not by 2-D integration of the retinal motion. The result demonstrates the importance of background flow produced by stereo depth in determining one's self-motion from an expanding/contracting motion.

1. Introduction

Some studies have demonstrated that a background (perceptually farther) optical flow determines vection (Ito & Takano, 2004; Kitazaki & Sato, 2003; Ohmi & Howard, 1988; Ohmi, Howard, & Landolt, 1987). Ohmi and Howard (1988) presented an expanding flow pattern and stationary random dots on different disparity planes to test the depth-order effect on inducing forward linear vection. The results showed that the foreground (perceptually closer) dots did not suppress vection induced by the background expanding flow. On the other hand, the opposite depth combination reduced the vection duration to half, not to zero. They attributed the incomplete vection suppression to a possible natural scene situation, that is, an image of a very far object expands slightly during one's forward movement. That is, a combination of an expanding foreground and a stationary background can be interpreted as representing one's forward self-motion without a contradiction.

As for circular vection, Ohmi et al. (1987) and Howard and Heckmann (1989) showed that background flow determined the vection direction when two opposing rotational flows were presented. However, it is possible that the two opposing flows are a cooperative (not competitive) combination for inducing vection because the foreground flow could also induce an "inverted vection" in the same direction as itself (Ito & Fujimoto, 2003; Nakamura & Shimojo, 1999, 2000, 2003). The "inverted vection" may be caused by misregistration of an eye movement in a direction opposite to the foreground flow (Nakamura & Shimojo, 2000). If expanding and contracting flows are presented instead of rotational flow, the effect of "inverted vection" can be removed as the expanding and contracting flow could not be caused by eye-movements.

The purpose of the present paper is to confirm and generalize the above noted background dominance

* Corresponding author. Tel./fax: +81 92 553 4496.
E-mail address: ito@design.kyushu-u.ac.jp (H. Ito).

0042-6989/$ - see front matter
doi:10.1016/j.visres.2004.11.009

in inducing vection using a purely competitive combination of flows. We presented expanding and contracting flows that could induce forward or backward linear vection. In Experiment 1, we superimposed these flows, varying their phenomenal depth. We used a disparity cue to indicate near–far relationship of the flows because it could determine the depth order without ambiguity and was suitable for quantitative manipulation of the phenomenal depth. We predicted that the perceived self-motion direction would be determined by the background flow although the two flows always suggested an opposing self-motion. Experiment 2 tested the effect of stereo depth when two expanding flows overlapped, varying their disparity. The center of each expansion was positioned to left or right of the fixation. If the background flow dominates vection, the perceived heading should be biased toward the center of the background flow.

2. Experiment 1

2.1. Method

Subjects. The second author and three naïve volunteers participated in the experiment. All of the subjects had normal or corrected-to-normal vision.

Apparatus and stimuli. The stimulus patterns were generated by a computer (SHARP X68000) and displayed on a video projector (Electrohome Electronics, DRAPAR). The size of the screen was 138 cm (horizontal) × 104 cm (vertical), subtending 75° (horizontally) and 60° (vertically) from a viewing distance of 90 cm. A black cloth covered the left, right and upper sides of the subjects. The display for each eye was treated as a 256 (vertical) × 512 (horizontal) dot matrix. The resolution was not so high, but the quality of the motion display was enough to compel the subjects to feel self-motion. The dot positions were renewed at 55 Hz, creating an impression of motion, while the images on the screen were refreshed at 110 Hz presenting each eye image alternately. The subjects wore LCD shutter goggles (CrystalEyes2) to achieve stereoscopic viewing. The number of dots in each flow pattern was 400 for all of the conditions, i.e., when expanding and contracting flows were overlapped, there were 800 dots on the screen for each eye. The dot luminance measured through the goggles was 7.0 cd/m^2 and background luminance was 0.01 cd/m^2. The dot diameters were 8.8′. The dot size on the screen was constant although each flow represented an optical motion arising when an observer moved forward or backward through an endless tunnel. Bright dots were attached to the inner surface (Ito, 1996).

The flows were first simulated on the zero-disparity plane as a 2-D expanding or contracting motion display. Therefore, the dots creating each flow pattern had the same disparity and it did not change over time. When they were presented to the subjects, a disparity was added to one of the two overlapping flows. The section of the simulated tunnel was a square (276 cm × 276 cm). The simulated observer's speed was 1.4 m/s. As the farther surface beyond 4 m along the line of sight was not displayed, there were no dots around the fixation cross at the center of the screen. The dots in an expanding (contracting) flow appeared (disappeared) around the fixation and disappeared (appeared) at the screen edge. The two flows were combined as follows (Fig. 1);

Expansion-zero-disparity conditions: the expanding flow was presented on the zero-disparity plane with the fixation cross. The contracting flow was presented with an added disparity of 0′, 8.8′, 26.3′ or 44′ in a crossed or uncrossed direction without other changes in the retinal flow. The zero-disparity plane had a relative disparity of 52.2′ in an uncrossed direction from the real screen surface. Thus, the screen frame func-

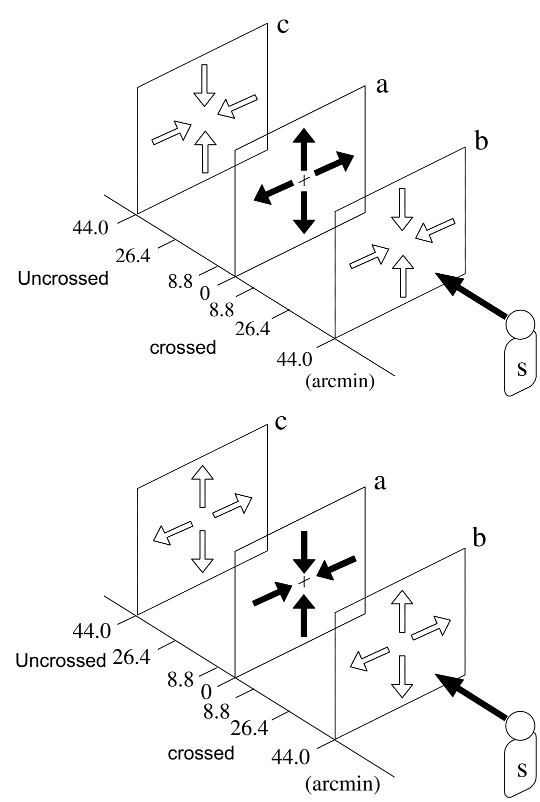

Fig. 1. Schematic illustrations of the stimuli used in Experiment 1. The upper panel shows the stimulus under *expansion-zero-disparity* conditions. An expanding flow pattern was presented on the same disparity plane with that of the fixation cross (a). A superimposed contracting flow pattern varied in seven steps of disparity. (b) or (c) indicates the condition under which a contracting pattern was presented on a plane with 44.0′ uncrossed or crossed disparity, respectively. The lower panel shows the stimulus under *contraction-zero-disparity* conditions. Under this condition, the expansion and contraction were switched.

tioned as a window through which subjects could see outside.

Contraction-zero-disparity conditions: the stimulus configuration was essentially the same as *Expansion-zero-disparity conditions*. The contracting flow was presented without disparity and the expanding flow varied in added disparity.

Each flow was also presented solely (expansion-only or contraction-only conditions) as a control. Our displays included some conflicts noted above, i.e., constant dot size and disparity over time against the simulated forward or backward motion. Palmisano (1996) demonstrated that sufficient forward vection arises from a display with constant dot size and disparity, but that cues-consistent displays increase vection. Our control displays also induced vection in sufficient strength against the cue conflicts, as noted later.

2.2. Procedure

The subjects were seated with their head positioned on a chinrest. During each trial, the subject fixated on the center cross, i.e., the center of the expansion or contraction. After a beep sound, the moving dots appeared on the screen. The subjects pushed the left (right) button of a mouse while feeling backward (forward) vection. When they perceived no vection or could not tell the self-motion direction, they released both buttons. The button was sampled at 27.5 times/s. The exposure duration for each trial was 60 s. There was a 2-min (at least) interval between the trials. There were 13 conditions: two zero-disparity-flow conditions (i.e., expansion-zero-disparity or contraction-zero-disparity) × seven disparities (from uncrossed to crossed) conditions minus one because the two of the possible displays were identical when the flow had zero disparity. After some practice trials, each subject performed ten trials under each of the 15 conditions presented in a random order.

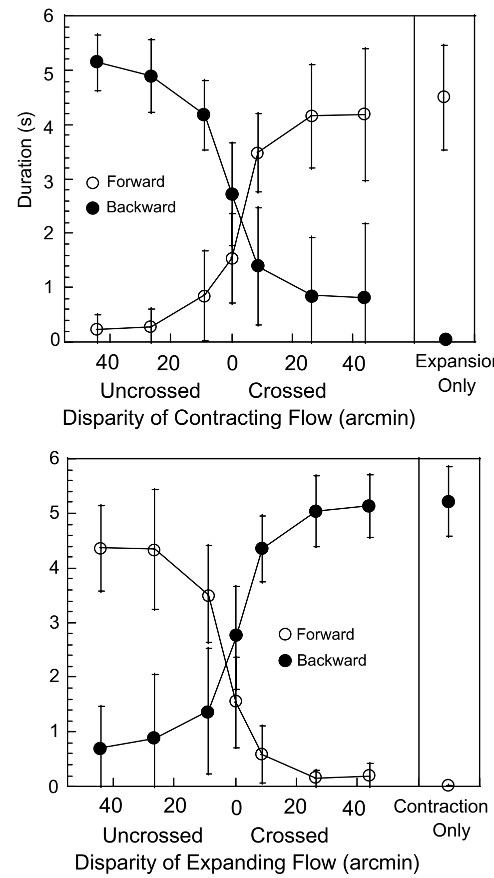

Fig. 2. Averaged vection durations as a function of superimposed flow disparity. The upper (lower) panel shows the data from *expansion-zero-disparity* (*contraction-zero-disparity*) conditions. When the contracting pattern was presented with a crossed (uncrossed) disparity under *expansion-zero-disparity* conditions, the forward (backward) vection was mainly reported. When the expanding pattern was presented with a crossed (uncrossed) disparity under *contraction-zero-disparity* conditions, the backward (forward) vection was mainly reported. Each data point represents a vection duration averaged across the four subjects and vertical bars represent the SDs.

2.3. Results and discussion

Fig. 2 shows the vection durations averaged across the four subjects as a function of flow disparity. The results under expansion-only and contraction-only conditions show that each display had sufficient motion strength and quality to induce vection. The results from *expansion-zero-disparity conditions* (*contraction-zero-disparity conditions*) show that when the contracting (expanding) flow was overlaid with uncrossed disparity, backward (forward) vection dominated and when overlaid with crossed disparity, forward (backward) vection dominated. When both flows were presented with zero disparity, the duration of backward vection was longer than that of the forward vection. This may reflect the relative strength of the two types of vection as also seen under the expansion-only and contraction-only conditions. Under this condition, the vection direction sometimes reversed as reported in Ito and Fujimoto (2003). This may reflect the reversals of the perceived depth order of the two flows. When the order was explicitly indicated by binocular disparity, such reversals were rare. Although attention may have played some role there, the effect of disparity seems stronger (Kitazaki & Sato, 2003). In our displays, an 8.8′ crossed or uncrossed disparity seems effective in determining one's self-motion direction. Under *expansion-zero-disparity* (*contraction-zero-disparity*) conditions, when the disparity of the contracting (expanding) flow was 26.4′ or 44.0′ in a crossed direction, the duration of forward (backward) vection was almost the same as that under expansion-only (contraction-only) conditions. In other words, an overlapped flow with a crossed disparity of more than 26.4′ had no effect on the vection direction.

These results clearly demonstrate that the stereoscopically farther flow determines the perceived self-motion direction while feeling vection under expanding–contracting opposing motion conditions, which are purely competitive in inducing vection.

3. Experiment 2

3.1. Method

The two authors and two naïve volunteers, having normal or corrected-to-normal vision, participated. The apparatus was the same as in Experiment 1. As shown in Fig. 3, the stimulus displays consisted of two expanding flows separated in stereo depth. Each flow simulated forward motion as in Experiment 1. After the flow patterns were simulated on the zero-disparity plane, each pattern was presented with a horizontal shift. The center of each expansion was 16.7° left or right of the fixation cross. There were seven disparity conditions as shown in Fig. 3, i.e., three left-farther, the same disparity, and three right-farther conditions. The subjects kept pushing the left (right) button when feeling as if moving in the left-forward (right-forward) direction. When they felt they were moving in a center-forward direction, they pushed both buttons. When they did not feel vection or their feelings were ambiguous, they released both buttons. After each trial, they judged the subjective strength of vection with a 6-point scale (0–5). Each subject performed 10 trials under each condition, presented in a random order.

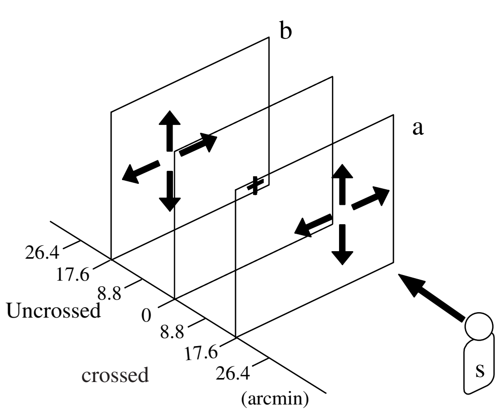

Fig. 3. Schematic illustrations of the stimuli used in Experiment 2. Two expanding flow patterns the centers of which were positioned to the left or right of the fixation were presented on the same or different disparity planes. A combination of flow pattern disparity varied in seven steps. When the left pattern had an uncrossed disparity, the right pattern had the same amount of crossed disparity, and vice versa. (a) or (b) indicates a condition under which the expanding patterns were presented on planes with 17.6′ crossed or uncrossed disparity, respectively.

3.2. Results and discussion

Fig. 4 shows the results. It is obvious that left-farther (right-farther) conditions mainly caused left-forward (right-forward) vection, demonstrating background dominance in forward vection. The center-forward vection was rarely reported under all of the conditions. The perceived heading was determined only by the direction suggested by the background flow without compromise between the two possible vection directions. Since the displays were essentially the same on the retina under all of the conditions, the stereo depth determined the heading. Computational models to extract a heading from the expanding optical flow may need to incorporate depth-order information.

When the two flows were on the same disparity plane, the duration of vection was shorter and the rating of the vection strength was lower. The conflict between the two possible self-motion directions may have suppressed vection without compromise to induce center-forward vection. There was a little dominance of right-forward vection under this condition. This may be an artifact caused by the stereo graphic system. As each eye image was presented alternately (first left, then right), horizontal motion of the dots may have produced a pseudo disparity. The flow expanding from the right (left) produced a leftward (rightward) dot motion around the fixation. As a flow expanding from the right seemed farther in the central visual field, right-forward vection may have dominated.

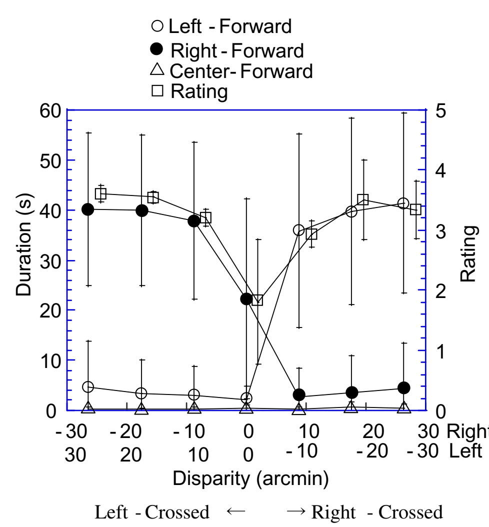

Fig. 4. Averaged vection durations as a function of flow disparity. Each filled (open) circle represents a right-forward (left-forward) vection duration averaged across the four subjects and the vertical bars indicate their SDs. When right (left) expansion was presented with an uncrossed disparity, i.e. negative numbers on the horizontal axis, right-forward (left-forward) vection was mainly perceived. Center-forward vection, represented by open triangles in the figure, was rarely perceived through all of the conditions. Open rectangles represent the averaged ratings of vection strength.

4. General discussion

In the two experiments, the stereoscopically farther flow determined the perceived direction of self-motion. The background dominance in vection may not be a flow-type-specific phenomenon. The effects of other depth cues also should be tested.

On the other hand, binocular disparity seems to produce a phenomenological difference between crossed and uncrossed disparity surfaces, even in a stationary display. Akerstrom and Todd (1988) pointed out that in stereoscopic transparency the space between dots is seen as filled-in in uncrossed disparities, giving rise to the perception of an opaque surface, but no filling-in is evident between dots in crossed disparities, where a transparent surface is seen. Our display included random dots on different disparity planes, which may have produced the qualitative difference between the foreground and background flows. It is worth testing how the opacity, isolated from depth-order perception, involves self-motion perception as the visual system might neglect transparent objects.

Our displays included discrepancy in information for self-motion directions between the two flows. Complete dominance of one flow in self-motion perception is an example of perceptual bistability. The visual system seems to detect the inconsistency and select one flow, not allowing a compromise-like vector summation of the two possible self-motion directions. Ito and Fujimoto (2003) also demonstrated that when vertical and circular flows were simply overlaid on a screen, only one induced vection at a given time. However, when there is a phenomenal depth separation between two flows, the farther flow seems to dominate vection.

What is the significance of selective analyzing of the farther flow in the natural environment? As it is rare that the motion of a distant object produces a flow with a considerable speed over a large region on the retina, a farther flow probably reflects the observer's self-motion or eye movement. Contrary, ignoring the closer flow may remove motion noise caused by movement of the body or falling snow. Fajen and Kim (2002) actually showed that perceived heading was unaffected by the existence of moving objects. Warren and Saunders (1995) also showed that a large moving object does not affect perceived heading unless it covers the focus of the outflow. The selection of the farther flow and no vector summation between near and far flows may contribute to the extraction of the self-motion components and may exclude the object-motion components.

On the other hand, Andersen and Saidpour (2002) demonstrated the role of pooling the local nonrigid motion of dots in heading judgment. Pooling (or summation) of inconsistent local motion vectors occurred to detect a global flow component in their display while two global flows with inconsistency were detected without local motion pooling in the present displays. It is still an open question what conditions integrate local motion components into a global flow and what conditions exclude some motion components from a global flow suggesting self-motion direction. The effects of disparity separation and a stimulus structure (a 3-D cloud or planes) would be involved there.

Finally, although we used the word "heading", it is not obvious whether or not the vection task in our experiments and the "heading" task in the literature engage the same mechanisms. Vection occurs after a certain period of stimulus presentation, while the "heading" tasks are performed with a brief presentation, e.g., shorter than 1 s (Crowell & Banks, 1993; Warren & Kurtz, 1992), which is clearly shorter than vection latency. Grigo and Lappe (1988) tested the accuracy of heading judgments using a flow simulating an observer's forward motion with eye rotation. The result was that the performance reduced according to the increase of stimulus duration from 0.4 to 3.2 s. This suggests that an initial impression of heading produced within several hundreds milliseconds is not the same as that while feeling vection produced after several seconds. A detailed research comparing vection directions and perceived heading should be conducted with the same kind of stimuli. This will combine (or differentiate) "vection direction" and perceived "heading."

Acknowledgement

This study was supported in part by Grant-in-Aid for the 21st Century COE Program entitled "Design of artificial environments on the basis of human sensitivity", Kyushu University, Japan.

References

Akerstrom, R. A., & Todd, J. T. (1988). The perception of stereoscopic transparency. *Perception & Psychophysics, 44*, 421–432.

Andersen, G. J., & Saidpour, A. (2002). Necessity of spatial pooling for the perception of heading in nonrigid environments. *Journal of Experimental Psychology: Human Perception and Performance, 28*, 1192–1201.

Crowell, J. A., & Banks, M. S. (1993). Perceiving heading with different retinal regions and types of optic flow. *Perception & Psychophysics, 53*, 325–337.

Fajen, B. R., & Kim, N. (2002). Perceiving curvilinear heading in the presence of moving objects. *Journal of Experimental Psychology: Human Perception and Performance, 28*, 1100–1119.

Grigo, A., & Lappe, M. (1988). An analysis of heading towards a wall. In L. R. Harris & M. Jenkin (Eds.), *Vision and action* (pp. 215–230). Cambridge, UK: Cambridge University Press.

Howard, I. P., & Heckmann, T. (1989). Circular vection as a function of the relative sizes, distances and positions of two competing visual displays. *Perception, 18*, 657–667.

Ito, H. (1996). The perception of an opening from expanding motion. *Perception & Psychophysics, 58*, 81–87.

Ito, H., & Fujimoto, C. (2003). Compound self-motion perception induced by two kinds of optical motion. *Perception & Psychophysics, 65*, 874–887.

Ito, H., & Takano, H. (2004). Controlling visually induced self-motion perception: Effect of overlapping dynamic visual noise. *The Journal of Physiological Anthropology and Applied Human Sciences, 23*, 307–311.

Kitazaki, M., & Sato, T. (2003). Attentional modulation of self-motion perception. *Perception, 32*, 475–484.

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

Nakamura, S., & Shimojo, S. (2000). A slowly moving foreground can capture an observer's self-motion—a report of a new motion illusion: Inverted vection. *Vision Research, 40*, 2915–2923.

Nakamura, S., & Shimojo, S. (2003). Sustained deviation of gaze direction can affect "inverted vection" induced by the foreground motion. *Vision Research, 43*, 745–749.

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.

Palmisano, S. (1996). Perceiving self-motion in depth: The role of stereoscopic motion and changing-size cues. *Perception & Psychophysics, 58*, 1168–1176.

Warren, W. H., & Kurtz, K. J. (1992). The role of central and peripheral vision in perceiving the direction of self-motion. *Perception & Psychophysics, 51*, 443–454.

Warren, W. H., Jr., & Saunders, J. A. (1995). Perceiving heading in the presence of moving objects. *Perception, 24*, 315–331.