Relationship between vection and motion perception in depth

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Abstract

This study examined the effects of cues to motion in depth – namely, stereoscopic (i.e., changing-disparity cues and interocular velocity differences) and changing-size cues on forward and backward vection. We conducted four experiments in which participants viewed expanding or contracting optical flows with the addition of either or both cues. In Experiment 1, participants reported vection by pressing a button whenever they felt it. After each trial, they also rated the magnitude of the vection (from 0 to 100). In Experiments 2 and 3, the participants rated the perceived velocity and motion-in-depth impression of the flows relative to standard stimuli, respectively. In Experiment 4, the participants rated the perceived depth and distance of the display. We observed enhancements in vection, motion-in-depth impression, and perceived depth and distance when either or both types of cues indicated motion-in-depth, as compared to those when the cues did not (Experiments 1, 3, and 4). The perceived velocity changed with cue conditions only for the high velocity condition (Experiment 2). Correlational analyses showed that the vection can be best explained by the motion-in-depth impression. This was partially supported by the multiple regression analyses. These results indicate that the enhancement of vection caused by cues is related to the impression of motion-in-depth rather than the perceived velocity and perceived three-dimensionality.

Keywords Vection · Cues to motion in depth · Depth perception

Introduction

When observers view a moving visual stimulus that occupies a large part of their visual field, they often perceive illusory self-motion in the direction opposite that of the stimulus motion. This phenomenon is called “vection.” Various attributes of vection-inducing stimuli and visual conditions have been reported to affect the magnitude and direction of vection. For example, vection magnitude appears to increase with stimulus velocity (Brandt, Dichgans, & Koenig, 1973; Nakamura & Shimojo, 1999; Seya, Shinoda, & Nakaura, 2015a; Seya, Tsuji, & Shinoda, 2014) and size (Berthoz, Pavard, & Young, 1975; Brandt et al., 1973; Telford & Frost, 1993).

One factor affecting vection is stereoscopic information. Although most vection studies have assumed that vection-

inducing stimuli provided to a single eye is sufficient to perceive self-motion, recent studies have indicated the importance of stereoscopic information provided by two eyes in vection (Allison, Ash, Palmisano, 2014; Palmisano, 1996, 2002; Palmisano, Summersby, Davies, & Kim, 2016). Various depth and motion-in-depth cues are provided by two eyes. For example, due to the horizontal separation of the right and left eyes, images of objects surrounding observers fall on different retinal positions, which is known as binocular positional disparities. Binocular disparity is well known to contribute to depth perception. During self-motion in depth, the disparity changes over time according to the distance from an observer and, as a result, the changing-disparity serves as a cue to an object’s motion-in-depth.

According to Palmisano et al. (2016), there are at least three ways that stereoscopic information might contribute either directly or indirectly to vection (see also Allison et al., 2014; Palmisano, 2002). First, stereoscopic information might indirectly enhance vection by improving the perception of the three-dimensional scene layout used to scale perceived velocity based on optical flow. During locomotion, objects around an observer produce various types of monocular cues about the three-dimensional scene layout such as relative size, changing-size, and motion perspective information (i.e., gradient of optical velocity). Research has suggested that motion

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perspective information in optical flow played the most important role in perceiving spatial layout (e.g., Braunstein & Andersen, 1981; Gibson, 1950, 1966) and self-motion (e.g., Gibson, 1950, 1966). Motion perspective information is effective for the perception of self-motion, but is non-optimal when observers travel through non-rigid and/or non-planar environments, because there are several ambiguities in processing optical flows. For example, it is not clear whether the optical flow results from a large motion in a large environment or a small motion in a small environment. Stereoscopic information regarding spatial layout may solve this ambiguity, resulting in an accurate perception of the speed of self-motion.

Second, stereoscopic information might directly improve vection by providing additional purely binocular motion information regarding either motion-in-depth or self-motion-in-depth (Palmisano, 1996, 2002; Palmisano et al., 2016). During self-motion-in-depth, objects surrounding an observer produce not only changing-disparity cues but also retinal images moving at different velocities in the two eyes, i.e., interocular velocity differences. Both of these cues, which are available in stereoscopic information, are well known to generate compelling perceptions of an object's motion-in-depth (e.g., Brooks, 2002; Fernandez & Farell, 2005; Norcia & Tyler, 1984; Sakano, Allison, & Howard, 2012; Shioiri, Saisho, & Yaguchi, 2000). It is thus likely that additional motion-in-depth information provided by either or both of these stereoscopic cues might contribute to self-motion perception.

Finally, stereoscopic information might indirectly improve vection by facilitating perception of environmental rigidity. When we view the rigid movements of all objects around us, our perceptual system will easily interpret that the retinal motions result from self-motion, because the relationship between the rigid movements of the objects' retinal images in the visual field and self-motion is quite natural. Several studies have reported that the more rigid visual motions are perceived, the stronger vection is perceived (e.g., Nakamura, 2010; Seno, Nakamura, Ito, & Sunaga, 2010b). Research has also reported that binocular and/or monocular depth cues play an important role in visual parsing of optical flow to disambiguate whether the components of retinal motion result from self-motion or object motion (e.g., Rushton & Warren, 2005; Warren & Rushton, 2009). Allison et al. (2014) argued that consistent stereoscopic information might enhance self-motion through a stable, rigid environment, although the relationship between the perceived rigidity and stereoscopic information is still not clear. It should be noted that several studies have reported inconsistent results regarding the effects of rigidity on vection (Palmisano, Allison, & Howard, 2006; Palmisano, Kim & Freeman, 2012; Palmisano et al., 2016).

Many studies have examined the advantages of stereoscopic information for vection-in-depth by manipulating stereoscopic cues (i.e., changing-disparity cues and interocular velocity differences) of optical flows. Palmisano (1996) reported the enhancement of vection by adding consistent stereoscopic

cues to the optical flows as compared with that induced by non-stereoscopic flows viewed monocularly or binocularly. In his study, various monocular cues regarding depth order (such as relative size and motion) were available even in the non-stereoscopic monocular or binocular conditions. Based on the findings, it was argued that the stereoscopic cues provided additional motion-in-depth information, resulting in the enhancement of vection. In a subsequent study, Palmisano (2002) investigated whether vection speed is affected by the consistency of information defined by binocular (changing-disparity cues and interocular velocity differences) and monocular (changing size and motion perspective information) cues. He considered that the binocular cues could be used to calculate the self-motion speed in two ways: (1) by directly providing information regarding the speed of self-motion in depth and (2) by improving the depth perception of the environment. He found that the faster speed of vection could only be attained when the information provided by the binocular cues was consistent with that provided by the monocular cues, compared to when these cues offered conflicting information. In his experiment, the perceived depth and distance of the displays were also measured. The results indicated that changes in the perceived depth and distance of the display cannot account for enhanced vection by cues. This suggests that the stereoscopic cues directly provide information on the speed of self-motion in depth.

Several studies have also reported the effects of stereoscopic cues with no motion-in-depth information on vection, and suggested that stereoscopic information can contribute to vection in multiple ways. Allison et al. (2014) examined the stereoscopic advantages for vertical vection. In their study, participants viewed the vertical translation of large stereoscopic surfaces defined by binocular disparities. They found that binocular viewing of the stimuli induced stronger vection as compared with vection induced by monocular viewing. They also separately manipulated the effects of monocular and binocular (cyclopean feature) motion signals on vection using dots with a short lifetime. They found that the cyclopean feature motions defined by such dots (monocular motion signals were available but weak) enhanced the vertical vection. Palmisano et al. (2016) reported different effects of stereoscopic information on vection induced by radial, circular, and spiral flows. They assumed that if the three-dimensional layout was essential for perceiving self-motion, then stereoscopic circular flow would improve vection as compared with non-stereoscopic circular flow even though binocular and monocular cues in that flow did not include motion-in-depth information. In a series of experiments, they found stereoscopic advantages for vection induced by radial and spiral flows. The stereoscopic circular flow enhanced vection only when monocular motion signals were weak by using dots with a short lifetime. It should be noted that they measured various types of perceptions (i.e., perceived depth, perceived rigidity,

perceived speed of flows, and adaptations to flows) and reported little support for the notion that stereoscopic advantages (when monocular motion signals were strong) can be explained by the perceived depth, rigidity, and flow speed.

Considering the aforementioned literature, we further examined the effects of stereoscopic information on forward and backward vection. As motion perspective information plays an important role in inducing forward (or backward) vection by using expanding (or contracting) stimuli (Andersen & Braunstein, 1985), this information was added to all inducing stimuli in the present study. There were two primary aims of this study. First, we wanted to extend the previous findings by systematically manipulating stereoscopic and changing-size cues. Research has indicated that motion-in-depth information plays an important role in vection-in-depth (Palmisano, 1996, 2002; Palmisano et al., 2016). However, to our knowledge, only a few studies have examined the effects of changing-size-based information of motion-in-depth on vection, and the results have been mixed. For example, Telford and Frost (1993) reported no enhancement of vection by the addition of changing-size cues. Palmisano (1996) reported that changing-size cues improved vection but this advantage for vection could be eliminated with increasing stimulus density. However, using denser and larger flows, Palmisano and Chan (2004) reported enhancement of vection by the changing-size cues. Second, we wanted to examine the effects of the cues to motion-in-depth on other perceptions such as the perceived velocity and motion-in-depth impression, i.e., the compellingness of the motion-in-depth. The cues to motion-in-depth could directly affect the perceived velocity and/or the motion-in-depth impression of the stimulus. Palmisano et al. (2016) measured the perceived velocity and reported that the stereoscopic advantages for vection cannot be explained by the perceived velocity alone. Conversely, the relationship between the vection and motion-in-depth impression is still unclear. Regan and Beverley (1979) and Regan, Beverley, and Cynader (1979) reported that object motion-in-depth provided by stereoscopic cues could be nulled by changing-size cues (or vice-versa). This suggests that the motion-in-depth information indicated by these types of cues converges at the same motion-in-depth stage. As such, it can be expected that the addition of changing-size or stereoscopic cues can systematically enhance vection as well as the impression of motion-in-depth.

We conducted four experiments. In Experiment 1, we measured the effect of the addition of either or both changing-size and stereoscopic cues on forward or backward vection induced by expanding and contracting optical flows. There were four cue conditions: changing-size, stereoscopic, full (i.e., both cues), and control. Motion perspective information was available in all conditions. Either or both dot size and stereoscopic information indicated no motion-in-depth in all conditions except for the full condition. In Experiments 2 and 3,

participants were asked to rate the perceived velocity and compellingness of the motion-in-depth impression, respectively, for the stimulus motion relative to those of standard stimuli. In Experiment 4, participants were asked to rate the perceived three-dimensionality of the display, i.e., the perceived depth and distance, as reported in previous studies (e.g., Palmisano, 2002).

Experiment 1

Method

Participants

Twenty-four individuals participated in the experiment (21 men and three women; mean age = 21.7 years; range = 21–25 years). The participants had no knowledge as to the purpose of the study and had normal or corrected-to-normal vision. The participants gave written informed consent before their participation. The experimental protocol was approved by the ethics committee of Ritsumeikan University. The tenets of the Declaration of Helsinki were followed.

Apparatus and stimuli

The apparatus and stimuli used in the present study were similar to those used in our previous studies (Seya et al., 2014; Seya, Yamaguchi & Shinoda, 2015b). A personal computer (Apple Mac Pro Early 2009) was used to control the experiment and generate stimuli that were rear-projected onto a screen with a 3D projector (Vivitek D795WT); 1,280 × 800 pixels resolution and 120 Hz refresh rate. The size of the screen area was 95 cm × 95 cm, subtending 72.3° × 72.3°. The participants viewed stimuli binocularly with 3D shutter goggles from a viewing distance of 65 cm. The experimental program was written using MATLAB with the Psychophysics Toolbox extension (Brainard, 1997; Pelli, 1997). The participants' responses were recorded using a numeric keypad at a sampling rate of 60 Hz.

Figure 1 illustrates the stimulus display used in this experiment. In the experiment, a space spreading in depth was simulated (Fig. 1a) using 1,000 dots (i.e., spheres) presented on a black background. The depth of the space was 10 m and the diameter was 40 m. The luminance of dots when measured through the goggles was approximately 7.55 cd/m² and 4.51 cd/m² on the central and 30° peripheral screen, respectively. The background luminance was approximately 0.15 cd/m² and 0.05 cd/m² on the central and 30° peripheral screen, respectively. To avoid the perception that participants sense that the dots will hit their face, the position of each dot was selected in such a way that each dot was simulated to move at least 10 cm away from the observer's line of sight. The position of

Fig. 1 Illustration of (a) simulated space and (b) stimulus displays

each dot was refreshed at a rate of 60 Hz, and each dot was simulated to move in depth (either approaching or receding) by manipulating the uncrossed screen disparity defined by the distances of the dot and screen from the observer. The maximum uncrossed screen disparity was 5.35° . When the dots moved into the space between the screen and observer, the crossed screen disparity was added to them, although most dots disappeared from the screen before moving into that space. If the dot moved on a path 10 cm away from the observer's line of sight, the maximum crossed screen disparity was 14.45° (corresponding to approximately 18.3 cm from the observer). The dots disappeared when they reached the edge of the space, and reappeared at the opposite side. The size of the dots changed depending on their simulated distance from the observer. The simulated dot size was 4 cm in diameter. The velocity of the dot motion was 2.5, 5.0, or 10.0 km/h. In the control and stereoscopic conditions, the dot size was 0.46° , which corresponded to the size of dots 5 m from the observer (the middle of the space), and did not change with the simulated distance from the observer. In the control and changing-size conditions, no disparity was added to any of the dots (indicating that the dots were always 65 cm in front of the observer). This is similar to the methodology used by Palmisano (1996).

A square frame in white (with a luminance of 3.75 cd/m^2 measured through the goggles) surrounded the screen area ($72.3^\circ \times 72.3^\circ$) in which the stimuli were presented (see Fig. 1b). No disparity was added to the frame. This frame served as a window through which the observer could see outside. A $1 \text{ cm} \times 1 \text{ cm}$ red fixation stimulus was presented at the center of the display (with a luminance of 0.38 cd/m^2 on the center of the screen measured through the goggles). In the stereoscopic

and full conditions, uncrossed screen disparity corresponding to a distance of 5 m was added to the fixation stimulus. In the control and changing-size cue conditions, no disparity was added to the fixation stimulus.

Procedure

The experiment was conducted in a dark booth. Participants sat comfortably on a chair with their head upright. No apparatus was used to support their head position. In other words, participants maintained their posture and head position during the experiment by themselves. After 3 min of adaptation to the dark booth, the participants performed several practice trials of the task until they were familiar with it, after which the experimental session began. Each trial started with the presentation of the fixation stimulus. After a key was pressed by the experimenter, a stationary random-dot pattern was presented for 5 s, after which it started to move. Sixty seconds after the onset of the dot motion, stationary dots were presented for 5 s, and then the dots and fixation stimulus disappeared. The participants' task was to maintain fixation on the fixation stimulus, and to indicate whether they had felt vection by pressing and holding one of two buttons on the keypad according to whether the vection was forward or backward. After each trial, the participants were asked to rate the average vection (i.e., the degree of saturation of vection sensation; Allison, Howard, & Zacher, 1999) from 0 to 100 during the moving inducing stimulus presentation. The instructions were as follows: "Please keep your fixation on the fixation stimulus during the presentation of the moving dots, and press and hold a corresponding button if you feel forward or backward self-motion. If self-motion perception ceases, please release the button." The participants were also instructed on how to choose the vection magnitude in a similar way to that in previous studies (e.g., Seya et al., 2015a), as follows: "A value of 0 would indicate no vection and only an inducing stimulus appears to move. In contrast, a value of 100 would indicate that you perceive yourself as moving through a stationary environment. A value of 50 would indicate that dots appear to be moving in one direction, and that you also perceive self-motion in the opposite direction at the same speed." In all trials, the key press data (taken from the keypad) and vection magnitude were recorded.

During the main experimental session, there were two blocks of 36 trials: three trials for each cue condition (control, changing-size, stereoscopic, and full conditions), inducing stimulus velocities (2.5, 5.0, and 10.0 km/h), and inducing stimulus direction (approaching and receding). In each block, the order of the conditions was randomized across participants. After the first block, the participants were given a 20-min break. The participants were also given rest periods whenever requested.

Data analysis

Using the key press data during the experimental session, we calculated the vection-onset latency from the onset of the inducing stimulus motion to the participant first pressing of the button on the keypad. We also calculated the duration that participants felt the vection. In trials where no vection was reported and vection onset was not detected, we assigned a value of 60 s to the latency, which was equal to the whole duration of the stimulation, and 0 s to the duration; this practice has been used in previous studies (e.g., Seya et al., 2014).

Results

Vection-onset latency

Figure 2 shows the mean vection-onset latency for each cue condition as a function of stimulus velocity. Positive values on the horizontal axis mean that the dots were approaching, and negative values mean that the dots were receding. As shown in the figure, the latency was longer in the control condition than in the other conditions. There was no difference between the changing-size and stereoscopic conditions. It should be noted that the effects of cues tended to be saturated at ± 10 km/h. The latency also decreased with increasing stimulus velocity.

A 4 (cue: control, changing size, stereoscopic, and full) $\times$ 2 (direction: approaching and receding) $\times$ 3 (velocity: 2.5, 5.0, 10.0 km/h) ANOVA revealed significant main effects of cue [$F(3, 69) = 12.91, p < .0001, \eta_p^2 = .3595$] and velocity [$F(2, 46) = 22.02, p < .0001, \eta_p^2 = .4891$]. There was a significant cue $\times$ velocity interaction [$F(6, 138) = 5.78, p < .0001, \eta_p^2 = .2008$]. Neither the other main effect (direction) nor the other interactions were significant.

A subsequent analysis showed significant simple main effects of cue at 2.5 km/h [$F(3, 207) = 19.07, p < .0001, \eta_p^2 = .2165$] and 5.0 km/h [$F(3, 207) = 10.61, p < .0001, \eta_p^2 = .1332$]. Multiple comparisons using Tukey's HSD showed a

significantly longer latency in the control condition than in the other conditions at those velocity conditions (all $ps < .05$). There were significant simple main effects of velocity in all cue conditions [control, $F(2, 184) = 37.55, p < .0001, \eta_p^2 = .2898$; changing-size, $F(2, 184) = 10.90, p < .0001, \eta_p^2 = .1059$; stereoscopic, $F(2, 184) = 6.54, p = .0018, \eta_p^2 = .0664$; full, $F(2, 184) = 5.77, p = .0037, \eta_p^2 = .0590$].

Duration

Figure 3 shows the mean duration for each cue condition as a function of stimulus velocity. As shown in the figure, a pattern of results opposite to that of the latency results was observed. A 4 $\times$ 2 $\times$ 3 ANOVA revealed significant main effects of cue [$F(3, 69) = 16.84, p < .0001, \eta_p^2 = .4227$] and velocity [$F(2, 46) = 22.83, p < .0001, \eta_p^2 = .4982$]. There was a significant cue $\times$ velocity interaction [$F(6, 138) = 4.33, p = .0005, \eta_p^2 = .1583$]. We found no other significant effects.

A subsequent analysis showed a significant simple main effect of cue at all velocities [2.5 km/h, $F(3, 207) = 20.84, p < .0001, \eta_p^2 = .2320$; 5.0 km/h, $F(3, 207) = 14.34, p < .0001, \eta_p^2 = .1721$; 10.0 km/h, $F(3, 207) = 5.56, p = .0011, \eta_p^2 = .0746$]. Multiple comparisons showed that at 2.5 km/h, the duration was significantly shorter in the control condition than in all of the other conditions (all $ps < .05$). The duration was also significantly shorter in the changing-size cue condition than in the full cue condition ($p < .05$). At 5 km/h, the duration was significantly shorter in the control condition than in all of the other conditions (all $ps < .05$). At 10 km/h, the only significant difference was between the control and full conditions, with a significantly shorter duration in the control condition than in the full condition ($p < .05$). There were also significant simple main effects of velocity in all the cue conditions [control, $F(2, 184) = 32.19, p < .0001, \eta_p^2 = .2592$; changing-size, $F(2, 184) = 17.92, p < .0001, \eta_p^2 = .1630$; stereoscopic, $F(2, 184) = 8.59, p = .0003, \eta_p^2 = .0854$; full, $F(2, 184) = 9.417, p = .0001, \eta_p^2 = .0929$].

Fig. 2 Mean vection-onset latency for each cue condition as a function of stimulus velocity. The vertical bars indicate the standard errors of the mean

Fig. 3 Mean duration for each cue condition as a function of stimulus velocity. The vertical bars indicate the standard errors of the mean

Vection magnitude

Figure 4 shows the mean vection magnitude for each cue condition as a function of stimulus velocity. As indicated in the figure, the pattern of results was similar to that for the duration except that there was no saturation at ± 10 km/h. A $4 \times 2 \times 3$ ANOVA revealed significant main effects of cue [$F(3, 69) = 29.80, p < .0001, \eta_p^2 = .5644$] and velocity [$F(2, 46) = 23.50, p < .0001, \eta_p^2 = .5054$]. There was a significant cue $\times$ direction interaction [$F(3, 69) = 2.98, p = .0374, \eta_p^2 = .1146$]. Neither the other main effect (direction) nor the other interactions were significant.

A subsequent analysis showed a significant simple main effect of cue in both directions [approaching, $F(3, 138) = 18.75, p < .0001, \eta_p^2 = .2896$; receding, $F(3, 138) = 31.65, p < .0001, \eta_p^2 = .4076$]. Multiple comparisons showed significant differences between all pairs of cue conditions (all p s $< .05$) except for the difference between the changing-size and stereoscopic conditions. No simple main effect of direction was found in any cue conditions.

Discussion

Experiment 1 examined the effects of motion-in-depth information provided by stereoscopic cues and changing-size cues on forward and backward vections. Regarding the effect of the stereoscopic cues, a larger magnitude of vection in the stereoscopic condition was observed compared with the control condition. In addition, the vection magnitude was also larger in the full condition than in the changing-size condition (in which the stereoscopic cues did not indicate useful motion-in-depth information). These results were partially supported by the latency and duration of vection. It should be noted that the latency and duration showed a tendency to saturate at ± 10 km/h, possibly due to ceiling and floor effects. Taken together, the present results support the previous findings of stereoscopic advantages for vection induced by radial flows (Palmisano,

1996, 2002; Palmisano et al., 2016). Two types of motion-in-depth cues were available in the stereoscopic and full conditions: changing-disparity and interocular velocity differences. Therefore, motion-in-depth information provided by these cues would have enhanced the vection (Palmisano, 1996, 2002; Palmisano et al., 2016). It should be noted that we measured the saturation of vection and found more saturated vection with the cues, while Palmisano (2002) measured the vection speed. This suggests that binocular cues contribute not only to the speed of vection but also to the saturation of vection.

The results showed stronger vection for the changing-size condition than in the control condition. In addition, vection was also stronger in the full condition than in the stereoscopic condition (in which the changing-size cues did not indicate useful motion-in-depth information). These results indicate changing-size-based advantages for vection, irrespective of the availability of stereoscopic information regarding motion-in-depth. As mentioned in the *Introduction*, the effects of changing-size cues on vection are still controversial: Palmisano and Chan (2004) reported that vection was improved by the addition of changing-size, while other investigators indicated that changing-size cues had limited (Palmisano, 1996) or no effect (Telford & Frost, 1993). The present study adds to the positive evidence for the enhancing effects of changing-size cues in the literature.

Palmisano (2002) argued that the binocular information regarding the three-dimensional layout of the environment can improve vection, particularly when the monocular depth cues (e.g., relative size and motion cues) are limited. This argument would be in agreement with the findings that cyclopean-feature motion without motion-in-depth can enhance vection when monocular motion signals are weak (Palmisano et al., 2016). All of the displays used in the present study contained motion perspective information, but not changing-size (and relative size) cues in the stereoscopic condition (cf. Palmisano, 2002). It is still possible that the enhancement of vection in the stereoscopic condition reflected the increases in the perceived three-dimensionality of the display provided by the binocular cues. Note that Palmisano et al. (2016) used radial flows in which changing-size (and relative size) cues did not indicate motion-in-depth or three-dimensional layout and reported that the perceived depth did not explain the stereoscopic enhancement of vection. Nonetheless, the effects of perceived depth and distance were further examined in Experiment 4.

The present results also showed stronger vection with increasing stimulus velocity, consistent with previous findings (e.g., Palmisano, 1996, 2002; Seya et al., 2014, 2015a, 2015b). However, we found no effects of direction. Previous research has reported that contracting flows produce stronger vection than expanding flows (e.g., Bubka, Bonato, & Palmisano, 2008; Seno, Ito, Sunaga, & Nakamura, 2010a). It

Fig. 4 Mean vection magnitude for each cue condition as a function of stimulus velocity. The vertical bars indicate the standard errors of the mean

should be noted, however, that there are mixed results on this directional asymmetry. Other investigators reported stronger vection by expanding flows than by contracting flows (e.g., Reinhardt-Rutland, 1982, 1983) or no asymmetry (e.g., Palmisano, Pinninger, Ash, & Steele, 2009). The present results support the latter finding.

Experiment 2: Perceived velocity effects

Method

Participants

Sixteen participants took part in this experiment (14 men and two women; mean age = 21.8 years; range = 21–25 years). All of them had participated in Experiment 1.

Apparatus and stimuli

The apparatus and stimuli used in this experiment were identical to those of Experiment 1 with the exception that two types of stimuli were used: a standard and a test stimulus. The standard stimulus was either an expanding or a contracting flow in which both changing-size and stereoscopic cues did not indicate motion-in-depth (as for the flows used in the control condition of Experiment 1). The velocity of the standard stimuli was set at ± 5 km/h. The test stimuli were the flows used in Experiment 1.

Procedure

The procedure was identical to that used in Experiment 1 with the following exceptions. First, a standard stimulus was presented before the presentation of the test stimulus in every trial. After the key was pressed by the experimenter, a stationary standard stimulus was presented for 5 s, which subsequently started to move. Twenty seconds after the onset of the dot motion, stationary dots were presented for 5 s. The display was then replaced with a stationary test stimulus. The stimulus persisted for 5 s, then moved for 20 s, followed by the presentation of stationary dots for 5 s. We used a relatively short duration of test stimulus presentation to reduce the difficulty in discriminating vection (self-motion) and perceived stimulus velocities. The direction of the standard stimulus motion was the same as the test stimulus.

Second, the participants were asked to rate the perceived velocity of the inducing test stimulus motion relative to the standard stimulus after each trial. The instructions were as follows: “Two types of moving dots will be sequentially presented in a trial. The first one is a standard stimulus and the second one is a test stimulus. Your task is to rate the perceived velocity of moving dots of the test stimulus relative to that of

the moving dots of the standard stimulus. Please keep your fixation on the fixation stimulus throughout the trial, and memorize the perceived velocity of the first stimulus in each trial. Please rate the perceived velocity of the dots by combining both the three-dimensional and two-dimensional velocities. A value of 0 would indicate that the dots did not appear to move at all. A value of 100 would indicate that you perceived the dots as moving at the same velocity as the standard stimulus.”

There were 72 trials in total, with three trials for each combination of the four types of cues, two directions, and three velocities.

Results and discussion

Figure 5 shows the mean ratings of the perceived velocity for each cue condition as a function of stimulus velocity. As seen in the figure, the ratings of the perceived velocity increased with cues for ± 10 km/h. A $4 \times 2 \times 3$ ANOVA revealed no significant main effects of cue. There were significant main effects of velocity [$F(2, 30) = 94.61, p < .0001, \eta_p^2 = .8632$] and direction [$F(1, 15) = 5.39, p = .0347, \eta_p^2 = .2645$]. There were significant interactions of cue $\times$ velocity [$F(6, 90) = 3.33, p = .0053, \eta_p^2 = .1815$] and direction $\times$ velocity [$F(2, 30) = 4.40, p = .0211, \eta_p^2 = .2267$]. The other interactions were not significant.

A subsequent analysis of the cue $\times$ velocity interaction only showed a significant simple main effect of cue at 10 km/h [$F(3, 135) = 6.29, p = .0005, \eta_p^2 = .1226$]. Multiple comparisons showed significantly higher ratings of the perceived velocity in the changing-size and full conditions than in the control condition (all $ps < .05$). There was a significant simple main effect of velocity in all cue conditions [control, $F(2, 120) = 58.71, p < .0001, \eta_p^2 = .4946$; changing-size, $F(2, 120) = 78.74, p < .0001, \eta_p^2 = .5675$; stereoscopic, $F(2, 120) =$

Fig. 5 Mean ratings of the perceived velocity of the stimulus motion for each cue condition as a function of stimulus velocity. The vertical bars indicate the standard errors of the mean

78.74, $p < .0001$, $\eta_p^2 = .5675$; full, $F(2, 120) = 95.42$, $p < .0001$, $\eta_p^2 = .6139$].

A subsequent analysis of the direction $\times$ velocity interaction showed a significant simple main effect of direction at 10 km/h [$F(1, 45) = 13.41$, $p = .0007$, $\eta_p^2 = .2296$], with a significantly higher perceived velocity in the receding flow than in the approaching flow. There was a significant simple main effect of velocity in both directions [approaching, $F(2, 60) = 86.06$, $p < .0001$, $\eta_p^2 = .7415$; receding, $F(2, 60) = 97.55$, $p < .0001$, $\eta_p^2 = .7648$].

In order to further examine the relationship between the perceived velocity and vection, a correlation analysis was performed using 24 mean values (i.e., 4 cue conditions $\times$ 2 direction conditions $\times$ 3 velocity conditions) of the perceived velocity and vection (obtained in Experiment 1) for each participant. The overall α level of .05 was preserved by a Bonferroni correction. Table 1 shows the correlation coefficient for each participant. In seven or fewer of the 16 participants, the perceived velocity was significantly correlated with latency, duration, and magnitude.

In summary, although the motion-in-depth cues affected the perceived velocity of the stimulus motion, the effect was limited to the high velocity condition, i.e., ± 10 km/h. This was not consistent with the results of Experiment 1, as there was an enhancement of vection by motion-in-depth cues, irrespective of the stimulus velocity. In addition, we found no correlations between the perceived velocity and vection in most participants. These results suggest that the enhancement of vection with the addition of the cues cannot be explained by the

perceived velocity of the stimulus motion, which is in agreement with the previous finding (Palmisano et al., 2016).

In the present experiment, the standard stimulus was identical to the test stimulus in the control condition at ± 5 km/h. The ratings were approximately 100 to the test stimuli at ± 5 km/h in all cue conditions. This not only suggests that the participants were able to accurately estimate the velocity of the simulated stimulus motion (irrespective of whether either or both types of cues indicated motion-in-depth), but they also support the findings of small effects of motion-in-depth cues on the perceived velocity mentioned above.

The small effects of motion-in-depth cues on the perceived velocity may be explained by motion perspective information. The optical flows used in all the conditions had this information. If we assume that the motion perspective information may have indicated reliable velocity information, the participants may not have needed to combine additional information provided by the cues. It is also possible that the effects of the cues on the perceived velocity may have been much smaller than those of the stimulus velocity (i.e., 2.5, 5.0, and 10.0 km/h). Consequently, the changes in the perceived velocity due to the cues may have been concealed.

Experiment 3: Perceived motion-in-depth effects

Method

Participants

Twenty participants took part in this experiment (17 men and three women; mean age = 22.0 years; range = 21–25 years). All of them participated in Experiment 1.

Apparatus and stimuli

The apparatus and stimuli used in this experiment were identical to those of Experiment 2 except that the standard stimulus was an expanding or a contracting flow with motion-in-depth information by changing-size and stereoscopic cues (similar to the flows used in the full condition of Experiment 1). The velocity of the standard stimulus was set at ± 5 km/h.

Procedure

The procedure was identical to that used in Experiment 2 except that the participants' task was to rate the perceived strength of the motion-in-depth impression (i.e., how compelling the motion-in-depth was) for the test stimulus relative to that for the standard stimulus after each trial. The instructions were as follows: "Two types of moving dots will be sequentially presented in a trial. The first one is a standard stimulus,

Table 1 Correlation coefficients between the vection (Experiment 1) and perceived velocity calculated from each participant

Participant	Latency	Duration	Magnitude
1	-0.233	0.271	0.099
2	-0.416	0.290	0.240
3	-0.702*	0.665*	0.799*
4	-0.203	0.582*	0.617*
5	-0.442	0.364	0.549
6	-0.553	0.186	0.093
7	-0.738*	0.744*	0.462
8	-0.457	0.455	-0.180
9	-0.469	0.508	0.765*
10	-0.741*	0.721*	0.727*
11	-0.110	0.108	0.191
12	-0.861*	0.649*	0.639*
13	-0.592*	0.683*	0.668*
14	-0.319	0.245	0.014
15	-0.384	0.384	0.495
16	-0.488	0.655*	0.678*

Note. * $p < .05/16$. $df = 22$

and the second one is a test stimulus. Your task is to rate the compellingness of the motion-in-depth for the second stimulus relative to that of the first stimulus. Please keep your fixation on the fixation stimulus throughout the stimulus presentation, and memorize the motion-in-depth impression for the first stimulus in each trial. A value of 0 would indicate no motion-in-depth impression and, thus, you perceived dots as two-dimensionally expanding or contracting on the screen. A value of 100 would indicate that you perceived dots as moving in depth at the same level with that perceived for the standard stimulus.” The participants were also told not to rate the perceived velocity of the stimulus motion orvection.

There were 72 trials in all, with three trials for each combination of the four types of cues, two directions, and three velocities.

Results

Figure 6 shows the mean ratings of the motion-in-depth impression for each cue condition as a function of stimulus velocity. As shown in the figure, the ratings increased when either or both cues were added. A $4 \times 2 \times 3$ ANOVA revealed significant main effects of cue [$F(3, 57) = 72.02, p < .0001, \eta_p^2 = .7913$] and velocity [$F(2, 38) = 21.08, p < .0001, \eta_p^2 = .5259$]. There was a significant cue $\times$ direction $\times$ velocity interaction [$F(6, 114) = 2.25, p < .0433, \eta_p^2 = .1059$]. Neither of the other main effect (direction) or other interactions were significant.

Subsequent analyses of the three-way interaction revealed a significant simple-simple main effect of cue at all velocities in both the approaching [2.5 km/h, $F(3, 342) = 51.13, p < .0001, \eta_p^2 = .3096$; 5.0 km/h, $F(3, 342) = 43.94, p < .0001, \eta_p^2 = .2782$; 10.0 km/h, $F(3, 342) = 48.55, p < .0001, \eta_p^2 = .2987$] and receding directions [2.5 km/h, $F(3, 342) = 46.49, p < .0001, \eta_p^2 = .2897$; 5.0 km/h, $F(3, 342) = 57.86, p < .0001, \eta_p^2 = .3367$; 10.0 km/h, $F(3, 342) = 66.60, p < .0001, \eta_p^2 = .3688$]. Multiple comparisons showed significant differences between all pairs of cue conditions (all $ps < .05$) except for the

Fig. 6 Mean ratings of the impression of stimulus motion-in-depth for each cue condition as a function of stimulus velocity. The vertical bars indicate the standard errors of the mean

difference between the changing-size and stereoscopic conditions. There were also significant simple-simple main effects of velocity in all cue conditions in both the approaching [control, $F(2, 304) = 11.15, p < .0001, \eta_p^2 = .0683$; changing-size, $F(2, 304) = 10.86, p < .0001, \eta_p^2 = .0667$; stereoscopic, $F(2, 304) = 9.19, p = .0001, \eta_p^2 = .0570$; full, $F(2, 304) = 9.73, p = .0001, \eta_p^2 = .0601$] and receding directions [control, $F(2, 304) = 4.11, p = .0173, \eta_p^2 = .0264$; changing-size, $F(2, 304) = 15.04, p < .0001, \eta_p^2 = .0900$; stereoscopic, $F(2, 304) = 18.87, p < .0001, \eta_p^2 = .1104$; full, $F(2, 304) = 14.53, p < .0001, \eta_p^2 = .0872$]. There were also significant simple-simple main effects of direction in the control condition at 5.0 km/h [$F(1, 228) = 7.01, p = .0087, \eta_p^2 = .0298$] and 10.0 km/h [$F(1, 228) = 7.86, p = .0055, \eta_p^2 = .0333$] and in the stereoscopic condition at 2.5 km/h [$F(1, 228) = 5.91, p = .0158, \eta_p^2 = .0253$], which showed significantly higher ratings in the approaching flow than in the receding one.

Table 2 shows the results of the correlation coefficients calculated from each participant. There were significant correlations with the latency, duration, and magnitude for 9, 11, and 11 of the 20 participants, respectively.

Discussion

The impression for the motion-in-depth was accentuated when either or both cues indicated motion-in-depth consistent with a

Table 2 Correlation coefficients betweenvection (Experiment 1) and motion-in-depth impression calculated for each participant

Participant	Latency	Duration	Magnitude
1	-0.747 *	0.744 *	0.806 *
2	-0.676 *	0.800 *	0.818 *
3	-0.644 *	0.599 *	0.336
4	-0.210	0.313	0.172
5	-0.246	0.388	0.913 *
6	-0.482	0.681 *	0.871 *
7	0.201	-0.208	-0.065
8	-0.460	0.463	0.479
9	-0.691 *	0.671 *	0.511
10	-0.340	0.362	0.335
11	-0.881 *	0.886 *	0.798 *
12	-0.354	0.737 *	0.879 *
13	-0.375	0.574	0.705 *
14	-0.686 *	0.813 *	0.942 *
15	-0.660 *	0.681 *	0.827 *
16	-0.706 *	0.741 *	0.740 *
17	-0.293	0.293	0.387
18	-0.483	0.336	0.570
19	-0.680 *	0.669 *	0.754 *
20	-0.241	0.156	0.275

Note. * $p < .05/20$. $df = 22$

simulated distance from an observer. The ratings of the motion-in-depth impression were higher in the full condition than in the changing-size and stereoscopic conditions. These results coincide with the vection results of Experiment 1, and indicate that the motion-in-depth impression can account for the vection enhancement based on cues. Our correlation analyses showed significant correlations between the duration of vection and motion-in-depth impression and between the vection magnitude and motion-in-depth impression in more than half the participants, supporting this view. Note that the test stimulus was identical to the standard stimulus in the full condition at ± 5 km/h. The results showed values of almost 100 at ± 5 km/h, indicating that the participants' ratings with standard stimuli were consistent, and the participants sufficiently understood the task.

The present results for the compelling impression of motion-in-depth in the changing-size condition support not only the notion that changing-size and stereoscopic cues both contribute to motion-in-depth (e.g., Regan & Beverley, 1979; Regan et al., 1979), but also the possibility that the cues directly provide information on self-motion in depth as discussed in Experiment 1.

Experiment 4: Perceived depth and distance effects

Method

Participants

Seventeen participants took part in this experiment (14 men and three women; mean age = 21.9 years; range = 21–23 years). All of them participated in Experiment 1.

Apparatus and stimuli

The apparatus and stimuli used in this experiment were identical to those of Experiment 3.

Procedure

The procedure was identical to that of Experiment 3 except that the participants were asked to rate the perceived depth or maximum extent of the display after each trial. The instructions of the perceived depth task were as follows (see also, Palmisano, 2002): “Two types of moving dots will be sequentially presented in a trial. The first one is a standard stimulus, and the second one is a test stimulus. Your task is to rate the perceived three-dimensionality, that is how far apart the dots are separated from each other for the test stimulus relative to that of the standard stimulus. Please keep your fixation on the fixation stimulus throughout the stimulus presentation, and

memorize the perceived three-dimensionality for the standard stimulus in each trial. A value of 0 would indicate that all the dots appeared to be at the same distance. A value of 100 would indicate that the dots appeared to be distributed in 3D space at the same level as that of the standard stimulus.” The instructions of the perceived maximum extent task were as follows: “Two types of moving dots will be sequentially presented in a trial. The first one is a standard stimulus, and the second one is a test stimulus. Your task is to rate the perceived distance of the furthest dot of the test stimulus relative to that of the standard stimulus. Please keep your fixation on the fixation stimulus throughout the stimulus presentation, and memorize the perceived distance for the standard stimulus in each trial. A value of 0 would indicate all the dots appeared to be at the same distance as the screen. A value of 100 would indicate that the furthest dot appeared to be distant at the same level as that of the standard stimulus.”

There were 72 trials in total, with three trials for each combination of the four types of cues, two directions, and three velocities, for each task. Nine of the participants conducted the perceived depth task first, while the other participants completed the perceived maximum extent task first.

Results

Perceived depth

Figure 7 shows the mean ratings of the perceived depth of dots for each cue condition as a function of the stimulus velocity. As shown in the figure, the ratings increased when either or both cues indicated motion-in-depth. The ratings increased with increasing stimulus velocity in all but the full condition. A $4 \times 2 \times 3$ ANOVA revealed significant main effects of cue [$F(3, 48) = 59.44, p < .0001, \eta_p^2 = .7879$] and velocity [$F(2, 32) = 23.52, p < .0001, \eta_p^2 = .5951$]. There were significant

Fig. 7 Mean ratings of perceived depth of the dots for each cue condition as a function of stimulus velocity. The vertical bars indicate the standard errors of the mean

cue $\times$ velocity [$F(6, 96) = 4.58, p = .0004, \eta_p^2 = .2226$] and direction $\times$ velocity interactions [$F(2, 32) = 6.09, p = .0057, \eta_p^2 = .2758$]. Neither the other main effect nor the other interactions were significant.

A subsequent analysis of the cue $\times$ velocity interaction showed significant simple main effects of cue at 2.5 km/h [$F(3, 144) = 59.92, p < .0001, \eta_p^2 = .5552$], 5.0 km/h [$F(3, 144) = 50.58, p < .0001, \eta_p^2 = .5131$], and 10.0 km/h [$F(3, 144) = 45.59, p < .0001, \eta_p^2 = .4871$]. There were significant differences between all the pairs (all $ps < .05$) except for between the changing-size and stereoscopic conditions at all the velocities. There were significant simple main effects of velocity in the control [$F(2, 128) = 13.58, p < .0001, \eta_p^2 = .1750$], changing-size [$F(2, 128) = 25.83, p < .0001, \eta_p^2 = .2875$], and stereoscopic conditions [$F(2, 128) = 4.56, p = .0122, \eta_p^2 = .0665$]. A subsequent analysis of direction $\times$ velocity interaction showed significant simple main effects of direction at 2.5 km/h [$F(1, 48) = 4.36, p = .0422, \eta_p^2 = .0832$], with higher ratings for the approaching flows compared with the receding ones. There were also significant simple main effects of velocity in both directions [approaching, $F(2, 64) = 12.05, p < .0001, \eta_p^2 = .2736$; receding, $F(2, 64) = 29.18, p < .0001, \eta_p^2 = .4769$].

Perceived distance

Figure 8 shows the mean ratings of the perceived distance of the furthest dot for each cue condition as a function of stimulus velocity. As shown in the figure, the ratings increased when either or both cues were added. A $4 \times 2 \times 3$ ANOVA revealed significant main effects of cue [$F(3, 48) = 68.12, p < .0001, \eta_p^2 = .8098$] and velocity [$F(2, 32) = 8.12, p = .0014, \eta_p^2 = .3365$]. There was a significant cue $\times$ direction interaction [$F(3, 48) = 3.05, p = .0373, \eta_p^2 = .1602$]. Neither the other main effect nor the other interactions were significant.

Fig. 8 Mean ratings of the perceived distance of the furthest dot for each cue condition as a function of stimulus velocity. The vertical bars indicate standard errors of the mean

A subsequent analysis of cue $\times$ direction interaction showed significant simple main effects of cue in both directions [approaching, $F(3, 96) = 59.92, p < .0001, \eta_p^2 = .6519$; receding, $F(3, 96) = 69.57, p < .0001, \eta_p^2 = .6850$]. There were significant differences between all the pairs (all $ps < .05$) except for between the changing-size and stereoscopic conditions in both directions. There was also a significant simple main effect of direction in the changing-size condition [$F(1, 64) = 8.96, p = .0039, \eta_p^2 = .1228$], which showed higher ratings for the receding flows than for the approaching ones.

Correlation and multiple regression analyses

Table 3 shows the results of the correlation analysis. The results were similar to those in Experiment 3. The perceived depth and distance were significantly correlated with latency, duration, and magnitude in seven or fewer of 17 participants.

Thirteen participants (participants 1–13 in Tables 1, 2, and 3) participated in all the experiments. By employing 52 data from those participants, i.e., for 13 participants $\times$ 4 cue conditions (the data were averaged across the other conditions), we conducted stepwise multiple regression analyses. The results showed that the magnitude ofvection was best predicted by the motion-in-depth impression alone [$F(1, 50) = 22.50, p < .0001, \text{adjusted } R^2 = 0.297$]. Conversely, the latency and duration ofvection were best predicted by the perceived depth alone [latency, F

Table 3 Correlation coefficients between thevection (Experiment 1) and perceived three-dimensionality calculated from each participant

Participants	Latency		Duration		Magnitude	
	Depth	Distance	Depth	Distance	Depth	Distance
1	-0.698*	-0.755*	0.707*	0.740*	0.729*	0.749*
2	-0.632*	-0.564	0.813*	0.798*	0.813*	0.869*
3	-0.507	-0.279	0.478	0.309	0.254	0.117
4	-0.257	-0.227	0.277	0.309	0.132	0.151
5	-0.191	-0.348	0.407	0.475	0.882*	0.915*
6	-0.552	-0.552	0.561	0.759*	0.703*	0.820*
7	-0.103	-0.069	0.110	0.067	0.293	0.169
8	-0.454	-0.415	0.458	0.417	0.580	0.647*
9	-0.684*	-0.629*	0.680*	0.621*	0.532	0.491
10	-0.171	-0.124	0.191	0.153	0.132	0.132
11	-0.805*	-0.782*	0.810*	0.786*	0.729*	0.754*
12	-0.280	-0.132	0.727*	0.608*	0.830*	0.679*
13	-0.239	-0.038	0.337	0.211	0.439	0.304
14	-0.534	-0.562	0.568	0.520	0.697*	0.500
15	-0.520	-0.431	0.495	0.412	0.498	0.365
16	-0.197	-0.170	0.212	0.103	0.432	0.447
17	-0.491	-0.386	0.589*	0.498	0.577	0.492

Note. * $p < .05/17$. $df = 22$

(1, 50) = 7.67, $p = .0079$, adjusted $R^2 = 0.116$; duration, $F(1, 50) = 5.16$, $p = .0274$, adjusted $R^2 = 0.075$].

Discussion

The results showed that the tendencies of perceived depth and distance were similar to those of the vection in Experiment 1. However, the ratings of perceived depth did not vary with stimulus velocity in the full conditions. For the other cue conditions, the effects of stimulus velocity appear to be small, as compared with the vection measures obtained in Experiment 1. In addition, the ratings of perceived depth and distance tended to be lower (although not significantly) in the stereoscopic condition than in the changing-size condition. These results are not consistent with the results of Experiment 1. Note that the values were almost 100 for the test stimuli at ± 5 km/h in the full condition, identical to the standard stimulus, indicating that the participants' ratings with the standard stimulus were consistent and that the participants sufficiently understood the task.

Our correlation analyses showed significant correlations with each of the vection measures in seven or fewer of the 17 participants. This implies that the tendency of the vection results in Experiment 1 cannot be explained by the perceived depth or distance. Taken together, the present results suggest that binocular (changing-disparity cues and interocular velocity differences) and monocular cues (changing-size cues) did not improve vection by simply improving the perceived depth and distance, which is consistent with previous findings (e.g., Palmisano, 2002; Palmisano & Chan, 2004; Palmisano et al., 2016).

Multiple regression analyses showed inconsistent results among the vection measures: the motion-in-depth impression was the best predictor for the vection magnitude, suggesting that the motion-in-depth impression is related to vection more closely than the other perception measures. On the other hand, the perceived depth was the best predictor for the latency and duration of vection. It should be noted that the latency and duration of vection may have been subject to ceiling and floor effects as we mentioned in Experiment 1. Several studies have reported discrepancies between vection magnitude and latency (e.g., Allison et al., 2014; Palmisano et al., 2016).

General discussion

To examine the effects of stereoscopic cues and changing-size cues on forward and backward vection, we conducted four experiments. Experiment 1 revealed the systematic dependency of vection on cues, indicating that both the forward and the backward vection were enhanced in the changing-size, stereoscopic, and full conditions as compared to the vection in the control condition. Additionally, vection was also enhanced in

the full condition compared to the changing-size and stereoscopic conditions. Experiment 2 showed a clear enhancement in the perceived velocity with increasing stimulus velocity, a finding that was in agreement with the tendencies of the vection results in Experiment 1. However, the effect of the cues on the perceived velocity was small and appeared to be limited to only the 10 km/h velocity condition. Experiment 3 showed a clear enhancement in the compellingness of the motion-in-depth impression for the changing-size, stereoscopic, and full conditions. The results also showed higher ratings for the motion-in-depth impression in the full condition than in the changing-size and stereoscopic conditions. Experiment 4 showed an enhancement of the perceived depth and distance. However, the tendencies of the results were different from that of vection: on average, the perceived depth and distance was higher (although not significantly) for the changing-size condition than in the stereoscopic condition. The findings of the correlation analyses suggested that motion-in-depth impressions better accounted for the vection results than perceptions of velocity and three-dimensionality. This was partially supported by the multiple regression analyses showing that the vection magnitude was best predicted by the motion-in-depth impression. These results suggest that the motion-in-depth impression is more closely related to the stereoscopic advantages and changing-size based advantages for vection. As we mentioned in the *Introduction*, only a few studies have measured vection by systematically manipulating both cues to motion-in-depth provided by the stereoscopic (e.g., Palmisano, 1996, 2002; Palmisano et al., 2016) and changing-size cues (Palmisano, 1996; Palmisano & Chan, 2004; Telford & Frost, 1993). In addition, research examining the relationships between vection and other perceptions are limited in the context of the effects of motion-in-depth cues on vection (e.g., Palmisano, 2002; Palmisano et al., 2016). Therefore the present study is the first to systematically examine the effects of both types of cues on vection, including comparisons with other perceptions, i.e., perceived velocity, motion-in-depth of stimulus, and perceived three-dimensionality.

In the stereoscopic and full conditions, two types of binocular cues were available: changing-disparity cues and interocular velocity differences. From the present study, it is not clear which of these types of cues is more important for the stereoscopic advantages of vection. However, the stereoscopic advantages in the present study may have reflected the effects of changing-disparity cues more strongly than those of interocular velocity differences, particularly during the later part of the stimulus presentation. Sakano et al. (2012) demonstrated adaptation for motion-in-depth provided by interocular velocity differences alone, while no adaptation was found for motion-in-depth provided by changing-disparity cues alone. Palmisano et al. (2016) demonstrated weak stereoscopic advantages for vection induced by radial flows (as compared

with that induced by spiral flows) due to adaptation to the flows. Note that the participants of the present study viewed the stimuli for longer durations (i.e., 60 s in Experiment 1) than that reported by Palmisano et al. (2016) (i.e., 30 s). Taken together, it is likely that the contribution of the interocular velocity differences to vection may have been weak due to the adaptation to the stimuli in the present study.

The present study did not exclude the possibility of the use of binocular (and monocular) information about spatial layout. In fact, our results showed correlations between vection measures and the perceived three-dimensionality in some of the participants. This finding partially supports the recent notion that stereoscopic information can contribute to vection in multiple ways (Allison et al., 2014; Palmisano et al., 2016). On the other hand, Ott, Pohl, Halfmann, Hardiess, and Mallot (2016) reported that stereoscopic information about spatial layout of the environments did not disambiguate the confusion between the narrowing (or widening) environments and self-motion acceleration (or deceleration), suggesting that earlier visual processing for self-motion might ignore both parallaxic and stereoscopic information about the spatial layout of the environments. However, their findings also leave open the possibility of cue combination at a later stage of visual processing. Further studies are needed to explore the role of binocular (and monocular) information about spatial layout in vection.

One may argue that other factors contributed to the present results. For example, it is conceivable that the present results reflected attentional resources. Seno, Ito, and Sunaga (2011) showed that vection weakened as attentional resources allocated to the inducing stimuli dwindled. If the addition of cues helped the participants allocate more of their attentional resources towards the stimuli, this could account for the differences in vection due to the cue conditions. However, in the present study, the participants were asked to pay attention (allocate resources) fully to the stimuli while maintaining their fixation on the fixation stimulus, irrespective of the cue conditions. Therefore, it is unlikely that the participants changed the amount of resources to the stimuli depending on the stimulus display.

Two points are noteworthy concerning the methodologies used in the present study. First, in order to simulate natural and wide scenes viewed in daily life situations, we used a relatively large range of disparities and short viewing distance. However, due to the limitation inherent to the stereoscopic presentations (e.g., Howard, Fukuda, & Allison, 2013), the stereoscopic flows of the present study would be perceived to be less natural and three-dimensional than we expected. In the stereoscopic and full conditions, the participants focused on the fixation stimulus on the screen (at a distance of 65 cm) while their eyes moved in response to disparities (corresponding to an object at a distance of 5 m). This accommodation-vergence mismatch is well known to reduce depth and/or distance perception (e.g., Hoffman, Girshick, Akeley, & Banks,

2008; Watt, Akeley, Ernst, & Banks, 2005). Palmisano (1996) realized the potential effects of accommodation-vergence mismatch on vection and reduced these by using a long viewing distance (1.5 m) (see also Palmisano, 2002; Palmisano et al., 2016). However, it should be noted that Palmisano (1996) reported a clear enhancement of vection by stereoscopic flow even when a short viewing distance was employed (50 cm), although this finding could be confounded by the differences in the viewing conditions: binocular or monocular viewing. In addition, the present study showed clear enhancement in the three-dimensionality of the display (Experiment 4) and vection (Experiment 1) by the cues. Taken together, the accommodation-vergence mismatch does not refute the present findings, although a long viewing distance would have been better.

Second, we did not use disparity at the center of the simulated space (5 m) for the dots and fixation stimulus in the changing-size condition (and control condition). Therefore, the disparity as well as accommodation and the lack of changing-vergence and stereoscopic cues (i.e., changing-disparities and interocular velocity differences) always indicated that the display was flat, near, and consequently small. As a result, the reduced three-dimensionality from these factors may have weakened the motion-in-depth perception and vection. Furthermore, reduced three-dimensionality may also have weakened the monocular motion-in-depth. From the present study, we were unable to determine the degree to which these factors weakened perceived three-dimensionality, motion-in-depth perception, and vection. However, the present results showed a clear enhancement of these by the cues. It should be noted that there would be still disparities in the changing-size condition, because the participants viewed the same image by two eyes from the short viewing distance (cf. Palmisano, 1996).

In conclusion, the present study supports the notion that motion-in-depth information provided by changing-size and stereoscopic cues enhances vection (Palmisano, 1996, 2002; Palmisano et al. 2016). The present results also indicate that, although these two types of cues improve the perceived depth and distance, the enhancement of vection caused by cues to motion-in-depth is related to motion-in-depth impression rather than the perceived velocity and three-dimensionality.

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References

- Allison, R. S., Ash, A., & Palmisano, S. (2014). Binocular contributions to linear vertical vection. *Journal of Vision*, **14** (12): 5, 1–23.
- Allison, R. S., Howard, I. P., & Zacher, J. E. (1999). Effect of field size, head motion, and rotational velocity on roll vection and illusory self-tilt in a tumbling room. *Perception*, **28**, 299–306.

- Andersen, G. J., & Braunstein, M. L. (1985). Induced self-motion in central vision. *Journal of Experimental Psychology: Human Perception & Performance*, **11**, 122–132.
- Berthoz, A., Pavard, B., & Young, L.R. (1975). Perception of linear horizontal self-motion induced by peripheral vision (linearvection) basic characteristics and visual-vestibular interactions. *Experimental Brain Research*, **23**, 471–489.
- Brainard, D. H. (1997). The psychophysics toolbox. *Spatial Vision*, **10**, 433–436.
- 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.
- Braunstein, M. L., & Andersen, G. J. (1981). Velocity gradients and relative depth perception. *Perception & Psychophysics*, **29**, 145–155.
- Brooks, K. R. (2002). Interocular velocity difference contributes to stereomotion speed perception. *Journal of Vision*, **2**, 218–231.
- Bubka, A., Bonato, F., & Palmisano, S. (2008). Expanding and contracting optic-flow patterns and vection. *Perception*, **37**, 704–711.
- Fernandez, J. M., & Farell, B. (2005). Seeing motion in depth using interocular velocity differences. *Vision Research*, **45**, 2786–2798.
- Gibson, J. J. (1950). *The perception of the visual world*. Boston, MA: Houghton Mifflin.
- Gibson, J. J. (1966). *The sense considered as perceptual systems*. Boston, MA: Houghton Mifflin.
- Hoffman, D. M., Girshick, A. R., Akeley, K., & Banks, M. S. (2008). Vergence-accommodation conflicts hinder visual performance and cause visual fatigue. *Journal of Vision*, **8** (3): 33, 1–30.
- Howard, I. P., Fukuda, K., & Allison, R. S. (2013). The dichoptoscope: An instrument for investigating cues to motion in depth. *Journal of Vision*, **13** (14): 1, 1–11.
- Nakamura, S. (2010). Additional oscillation can facilitate visually induced self-motion perception: The effects of its coherence and amplitude gradient. *Perception*, **39**, 320–329.
- Nakamura, S., & Shimojo, S. (1999). Critical role of foreground stimuli in perceiving visually induced self-motion (vection). *Perception*, **28**, 893–902.
- Norcia, A. M., & Tyler, C. W. (1984). Temporal frequency limits for stereoscopic apparent motion processes. *Vision Research*, **24**, 395–401.
- Ott, F., Pohl, L., Halfmann, M., Hardiess, G., & Mallot, H. A. (2016). The perception of ego-motion change in environments with varying depth: Interaction of stereo and optic flow. *Journal of Vision*, **16** (9): 4, 1–15.
- Palmisano, S. (1996). Perceiving self-motion in depth: The role of stereoscopic motion and changing-size cues. *Perception and Psychophysics*, **58**, 1168–1176.
- Palmisano, S. (2002). Consistent stereoscopic information increases the perceived speed of vection in depth. *Perception*, **31**, 463–480.
- Palmisano, S., Allison, R. S., & Howard, I. P. (2006). Illusory scene distortion occurs during perceived self-rotation in roll. *Vision Research*, **46**, 4048–4058.
- Palmisano, S., & Chan, A. Y. C. (2004). Jitter and size effects on vection are immune to experimental instructions and demands. *Perception*, **33**, 987–1000.
- Palmisano, S., Kim, J., & Freeman, T. C. A. (2012). Horizontal fixation point oscillation and simulated viewpoint oscillation both increase vection in depth. *Journal of Vision*, **12** (12):15, 1–14.
- Palmisano, S., Pinniger, G. J., Ash, A., & Steele, J. R. (2009). Effects of simulated viewpoint jitter on visually induced postural sway. *Perception*, **38**, 442–453.
- Palmisano, S., Summersby, S., Davies, R. G., & Kim, J. (2016). Stereoscopic advantages for vection induced by radial, circular, and spiral optic flows. *Journal of Vision*, **16** (14): 7, 1–19.
- Pelli, D. G. (1997). The videotoolbox software for visual psychophysics: Transforming numbers into movies. *Spatial Vision*, **10**, 437–442.
- Regan, D., & Beverley, K. I. (1979). Binocular and monocular stimuli for motion in depth: Changing-disparity and changing-size feed the same motion-in-depth stage. *Vision Research*, **19**, 1331–1342.
- Regan, D., Beverley, K. I., & Cynader, M. (1979). Stereoscopic subsystems for position in depth and for motion in depth. *Proceedings of the Royal Society of London B*, **204**, 485–501.
- Reinhardt-Rutland, A. H. (1982). Asymmetry in forward and backward vection. *Perceptual and Motor Skills*, **54**, 870.
- Reinhardt-Rutland, A. H. (1983). Induced movement-in-depth: Relative location of static stimulus and direction asymmetry. *Perceptual and Motor Skills*, **57**, 255–258.
- Rushton, S. K., & Warren, P. A. (2005). Moving observers, relative retinal motion and the detection of object movement. *Current Biology*, **15**, R542–R543.
- Sakano, Y., Allison, R. S., Howard, I. P. (2012). Motion aftereffect in depth based on binocular information. *Journal of Vision*, **12** (1): 11, 1–15.
- Seno, T., Ito, H., & Sunaga, S. (2011). Attentional load inhibits vection. *Attention, Perception, & Psychophysics*, **73**, 1467–1476.
- Seno, T., Ito, H., Sunaga, S., & Nakamura, S. (2010a). Temporonasal motion projected on the nasal retina underlies expansion-contraction asymmetry in vection. *Vision Research*, **50**, 1131–1139.
- Seno, T., Nakamura, S., Ito, H., & Sunaga, S. (2010b). Static visual components without depth modulation alter the strength of vection. *Vision Research*, **50**, 1972–1981.
- Seya, Y., Shinoda, H., & Nakaura, Y. (2015a). Up-down asymmetry in vertical vection. *Vision Research*, **117**, 16–24.
- Seya, Y., Tsuji, T., & Shinoda, H. (2014). Effect of depth order on linear vection with optical flows. *i-Perception*, **5**, 630–640.
- Seya, Y., Yamaguchi, M., & Shinoda, H. (2015b). Single stimulus color can modulate vection. *Frontiers in Psychology*, **6**/406, 1–12.
- Shioiri, S., Saisho, H., & Yaguchi, H. (2000). Motion in depth based on inter-ocular velocity differences. *Vision Research*, **40**, 2565–2572.
- Telford, L., & Frost, B. J. (1993). Factors affecting the onset and magnitude of linear vection. *Perception and Psychophysics*, **53**, 682–692.
- Warren, P. A., & Rushton, S. K. (2009). Perception of scene-relative object movement: Optic flow parsing and the contribution of monocular depth cues. *Vision Research*, **49**, 1406–1419.
- Watt S. J., Akeley, K., Ernst, M. O., & Banks, M. S. (2005). Focus cues affect perceived depth. *Journal of Vision*, **5**, 834–862.