A new spin on vection in depth

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Previous research has shown that adding lateral viewpoint changes to visual displays simulating self-motion in depth can increase the strength of linear vection. We performed experiments to determine whether these vection increases are caused by reduced adaptation to retinal motion, rather than increased motion parallax in the visual display. In Experiment 1, we added increasing amplitudes of sinusoidal angular viewpoint oscillation around the viewing axis (up to 94.2°/s) to radial flow simulating self-motion in depth. We found that angular viewpoint oscillation systematically reduced the onset latencies and increased the overall strength of vection in depth, compared with pure radial flow. In Experiment 2, we compared vection strength between radial flow displays with either added angular oscillation or continuous spiral rotation of equivalent peak velocity around the viewing axis (62.8°/s), and found that angular viewpoint oscillation generated the strongest vection. In Experiment 3, we found that pure radial flow with or without continuous spiral rotation produced radial motion aftereffects that lasted longer than that produced by radial flow with angular viewpoint oscillation. These findings support the view that the way viewpoint oscillation increases vection does not critically depend on motion parallax, but rather, on a changing pattern of retinal motion that serves to reduce visual adaptation and sustain sensitivity to optic flow.

Introduction

Optic flow is the physical pattern of optical motion that is normally generated when an observer moves relative to objects in the environment (Gibson, 1950). Optic flow provides a valuable source of information for visually guided behavior because it generates retinal motion that provides information about the speed and direction of self-motion. Previous research has demonstrated the capacity of the visual system to compute optic flow (e.g., Badcock & Khuu, 2001; Edwards & Badcock, 1993; Khuu & Badcock, 2002), and neural mechanisms have been identified in the visual cortex that selectively process the retinal motion it generates (e.g., Duffy & Wurtz, 1991). This retinal motion is sufficient to support the subjective sensation of self-motion; powerful illusions of self-motion can occur (e.g., linear vection) when stationary observers view radially expanding optic flow simulating self-motion in depth. Many studies have shown that linear vection in depth can be increased by adding simulated sinusoidal changes in translational (or linear) head position to this radial flow, despite the ensuing visual-vestibular conflicts (see Palmisano, Allison, Kim, & Bonato, 2011 for a review). These sinusoidal translations in horizontal or vertical viewpoint increase motion parallax—the perspective gradient in optic flow velocities that scales inversely with distance to the observer. It has been noted that motion parallax could increase vection by enhancing the perception of scene layout (Kim & Palmisano, 2010; Nakamura, 2010; Nawrot, 2003; Palmisano et al., 2011; Palmisano, Kim, & Freeman, 2012) or increasing the perceived speed of self-motion (Kim & Palmisano, 2008). However, a recent study found that vection increases can also occur when oscillatory horizontal angular viewpoint rotations are added to radial flow, which does not increase motion parallax (Kim, Palmisano, & Bonato, 2012). Here, we explore parameters of optic flow that may account for these increases in vection.

Palmisano, Gillam, and Blackburn (2000) showed that the strength of linear vection in depth can be increased by adding random horizontal or vertical changes in simulated head position (jitter) to radial flow. Vection was increased further by increasing the frequency (and in turn velocity) of viewpoint jitter. More recent studies have found similar vection increases when adding horizontal or vertical oscillation in linear viewpoint position that followed a smooth
The sinusoidal velocity function (Kim & Palmisano, 2008; Palmisano, Allison, & Pekin, 2008). These simulated changes in linear head position alter the optical projection of the scene toward the eye, and increase vection despite the inherent changes in velocity conflicting with the lack of vestibular signaling about head acceleration (c.f., Zacharias & Young, 1981).

More recent work has investigated potential properties of optic flow patterns that may account for viewpoint oscillation increasing vection (Palmisano et al., 2011; Palmisano et al., 2012). There are three main properties that could be implicated in these vection advantages: perceived display depth, perceived speed relative to path integration, and the retinal motion generated by optic flow.

Linear viewpoint oscillation could increase vection by increasing motion parallax to provide superior depth cues concerning self-motion. Previous research has shown that farther simulated fixation distances in displays with motion parallax increase the perceived dimensions of the scene in depth (Nawrot, 2003). Palmisano and Kim (2009) found that stable central fixation—consistent with long distance fixation—increased the strength of self-motion perception generated by oscillating radial optic flow. These increases in vection strength could be caused by an increase in perceived distance of self-motion traversed in depth, because increases in the perceived dimensions of the display in depth with far fixation may have increased the perceived distance of simulated self-motion. Contrary to this view, however, Palmisano and Chan (2004) found no consistent increase in perceived display depth when adding viewpoint jitter, suggesting that increases in vection during viewpoint oscillation do not depend on an increase in perceived display depth per se. Also, Nakamura (2010) found that vertical vection increased by adding horizontal viewpoint oscillation to 2D vertical optic flow, which lacked any perspective cues to depth. Based on the evidence to date, it would appear that increases in vection during viewpoint oscillation do not critically depend on perceived display depth.

Another explanation for linear viewpoint oscillation increasing vection is that the added display oscillation modulates the perceived path and speed of self-motion. Viewpoint oscillation added to radial optic flow preserves the simulated speed of forward translation, but increases the overall velocity of simulated translations along oblique heading directions. Oblique velocity vectors result from adding the velocity vector of horizontal translation to the velocity vector of self-motion in depth, and will reach higher velocity overall than the velocity of self-motion in depth. These oblique translations simulate curvilinear self-motion in depth, which could average out to be perceived as closer self-motion in depth (see Figure 1). The perceived speed of forward self-motion may increase if the oblique heading direction were perceptually underestimated to be closer in alignment with the average heading in depth. Indeed, Kim and Palmisano (2008) found that the strength of vection in depth correlated positively with increases in perceived display speed measured using the method of adjustment in a speed-matching task. A recent study (Kim et al., 2012) reasoned that if increases in perceived speed and vection strength are caused by the misperception of oblique heading trajectories, then combining radial flow with horizontal angular viewpoint oscillation—which does not alter the simulated path of self-motion—should not affect vection in depth. Surprisingly, angular viewpoint oscillation around the vertical axis still increased the perception of self-motion in depth, suggesting that vection increases during viewpoint oscillation do not critically depend on increasing motion parallax cues to depth. Previous researchers have shown that simulated angular viewpoint oscillations added to pure radial flow have been shown to influence the perceived path of heading in depth when there is a mismatch between retinal and eye-movement command signals (Royden, Banks, & Crowell, 1992). This illusory percept of heading in depth along a curvilinear pathway could influence the strength of vection in depth. This view is further supported by a recent finding that horizontal oscillation in gaze across a pure radial flow display—sufficient to generate illusory oblique self-motions—

Figure 1. Possible perceived path of self-motion when viewing radial flow. (A) Pure radial flow displays simulate self-motion along a constant axis in depth (gray arrow). (B) Curvilinear motion is simulated when lateral viewpoint translations are added to simulated motion in depth (gray path). However, the perceived path of self-motion may potentially be less oblique (red path).
increased the strength of vection in depth (Palmisano et al., 2012).

There is growing evidence to suggest that angular viewpoint oscillation effects on vection could depend on the pattern of peripheral retinal motion it generates. Consistent with this view, Palmisano and Kim (2009) showed that vection can be increased by instructing observers to regularly change their gaze around the focus of expansion by making saccades to briefly presented eccentric fixation targets. The changes in fixation may increase vection by varying the direction of visual motion across the fovea. Variation in the direction of retinal motion reduces adaptation to unidirectional motion, which should result in maintained sensitivity to retinal motion generated by optic flow. This maintained sensitivity to visual motion could contribute to observed increases in vection strength (Seno, Ito, & Sunaga, 2010; Seno, Palmisano, & Ito, 2011). In support of this explanation, Palmisano et al., (2012) found that vection strength obtained with linear viewpoint oscillation could not be explained by the duration of motion aftereffects (MAEs), a physiological measure of neural adaptation. However, they found that the duration of the MAE was partially reduced, which potentially accounted for vection increases obtained with horizontal fixation point oscillation. It is possible that angular viewpoint oscillation may increase vection through a similar adaptation-limiting mechanism as fixation point oscillation.

The following experiments were designed to determine whether viewpoint oscillation effects on vection depend on sustained sensitivity to visual motion. We used angular viewpoint oscillations to examine whether vection increases depend on displays that enhance sensitivity to visual motion by reducing adaptation to retinal motion, rather than by increasing motion parallax cues to depth and heading.

**Experiment 1**

In Experiment 1, we created displays that prevented the increases in motion parallax that are generated when linear viewpoint display oscillation is added to radial flow. To this end, we added oscillatory angular rotation around the z-axis to radial flow simulating self-motion in depth. This stimulus ensures stable fixation at the focus of expansion and allowed us to modulate changes in peripheral visual motion systematically. It also ensures that optic flow will simulate continuous self-motion along a straight pathway of heading in depth. We predicted that if adaptation to visual motion mediates viewpoint oscillation effects on vection, then the addition of alternating angular viewpoint oscillation should increase the strength (and reduce the onset latency) of linear vection in depth. This vection increase should occur because angular viewpoint oscillation will reduce the overall duration of unidirectional peripheral retinal motion (Figure 2). Here, we used 0.5Hz sinusoidal angular viewpoint oscillation, which systematically changes the direction of angular rotation each second.

**Method**

**Observers**

Eight adult observers with normal or corrected-to-normal vision participated in the present study. Aside from one expert observer, co-author SK, all observers were completely naïve to the purposes of the current experiment. All procedures adhered to an ethics protocol approved by the ethics committee at the University of New South Wales.

**Stimuli**

Radial flow simulating self-motion in depth was presented to the observers on a 21" Mitsubishi Diamond Pro 2070SB Monitor viewed from a distance of 50 cm (visual angle = 36.0°). This field of view is comparable to displays used previously in head free observers (Kim & Palmisano, 2008; Palmisano & Kim, 2009). Head movements were restricted in the current study relative to the display using a tabletop mounted headrest (HeadSpot, College of Optometry University of Houston). The radial flow was generated by simulating the smooth and continuous movement of a camera through a cloud of approximately 1,024 blue squares that loomed in depth to increase in size on the display with simulated proximity to the observer (0.08° to 0.8°). The blue squares had a luminance of 20cd/m² against an otherwise black background (0.5 cd/m²). Objects were distributed approximately uniformly in depth. The simulated distances varied between approximately 0.3 m to 3 m from the observer. As the camera passed beyond the square objects in the foreground, the squares re-spawned off in the distance at the start of the flow field around the focus of expansion.

We presented two main conditions of optic flow (linear and angular display oscillation), in addition to a control condition of pure radial flow that simulated self-motion in depth at an approximate rate of 2 m/s. Each of the oscillation conditions had three levels, which together with the pure radial flow control formed seven separate conditions. In the linear display oscillation condition, we added one of three amplitudes of 0.5 Hz sinusoidal movements of the simulated viewpoint along the horizontal axis to the simulation of
linear translation in depth. The combination of these two motion directions (horizontal and in depth) ensured that simulated oblique heading directions were to the left for one second and then to the right on the subsequent second. This condition simulated the translation of the observer along a curvilinear path in depth with peak oblique amplitudes of $\pm 9^\circ$. The addition of horizontal translations to display oscillation simulated the motion of the observer along a curvilinear path in depth. In the angular oscillation condition, we added one of three amplitudes of 0.5Hz sinusoidal viewpoint rotation around the $z$-axis in depth to radial flow ($\pm 10^\circ$, $\pm 20^\circ$, and $\pm 30^\circ$). The angular oscillation maintains the perceived path of self-motion along a straight trajectory in depth. It also has the benefit of allowing observers to easily fixate the focus of expansion. The amounts of angular oscillation were selected to create a range of global image motions that were approximately comparable to the visual motion generated by other levels of horizontal linear oscillation. The retinal motion ranged up to 94.2°/s, and could not be nulled by torsional ocular following responses (OFRs), which occur in response to the stimulus on the display. This is because these eye movements have small peak positional amplitudes and long latencies of approximately 90 ms (Sheliga, Fitzgibbon, & Miles, 2009). The alternating periods of clockwise and counterclockwise rotations added to radial optic flow ensured that the local directions of peripheral retinal motion varied systematically over time.

Presentations of radial flow conditions were fully randomized. There were two repeat presentations for each condition. Two blocks of trials were performed; either with or without a green fixation point (34cd/m²) presented at the centre of the display. Observers were instructed to hold their gaze near the centre of the display in the no-fixation condition. The order of fixation trials was counterbalanced across observers. We compared fixation conditions to determine whether any deviation in gaze away from the focus of expansion influenced vection. In linear viewpoint oscillation conditions, the absence of fixation generates horizontal ocular following responses (Kim & Palmisano, 2008), which can be suppressed with active fixation.

**Procedure**

Observers were seated in an otherwise completely dark room, and were instructed to maintain their fixation at the centre of the flow field at all times. They were instructed to fixate the green target presented at
the physical center of the display on trials when it was present. Observers pressed the spacebar on a keyboard to indicate vection onset. Following each 50 s presentation of radial flow, observers adjusted a horizontally aligned meter to indicate the overall strength of illusory self-motion they experienced. They were instructed to set the meter all the way to the right (a rating of 100) if they experienced self-motion that was indistinguishable from physical self-motion. They were instructed to set the meter all the way to the left (a rating of 0) if they experienced no self-motion (i.e., felt completely stationary). They were instructed to set the meter around the centre of the scale (a rating around 50) to reflect the strength of self-motion they experienced with pure radial flow on a single initial practice trial that was not recorded (the modulus).

Data analysis

Data were analyzed in R using a repeated-measures ANOVA, which tested for main effects of display type (three levels) and fixation (two levels). Vection strength and latency data were analyzed on these dimensions separately. Post-hoc repeated-measures t tests were used to test specific follow-up comparisons.

Results and discussion

Figure 3 plots means and standard errors of vection strength ratings as a function of increasing amplitude of linear and angular viewpoint oscillation. Hollow points at zero in each set of axes indicate the vection strength ratings for pure radial flow. A repeated-measures ANOVA found a significant main effect of display oscillation type (angular, linear, or none) on the strength of vection in depth, \( F(2, 14) = 21.28, p < 0.0001 \). There was no significant main effect of fixation on overall vection strength, \( F(1, 7) = 0.70, p = 0.43 \). There was no significant interaction effect between fixation and display oscillation condition on vection strength, \( F(2, 14) = 2.53, p = 0.115 \). Post-hoc repeated-measures t tests found that the vection strength obtained with angular oscillation was significantly greater overall compared with that obtained with pure radial flow (\( t_7 = 3.84, p < 0.05 \)).

Means and standard errors of vection onset latencies are plotted in Figure 4 as a function of increasing amplitude of linear and angular viewpoint oscillation. Hollow points at zero in each set of axes indicate the latency of vection onset for pure radial flow. A repeated-measures ANOVA found a significant main effect of display oscillation type on vection onset latency, \( F(2, 14) = 4.33, p < 0.05 \). There was no significant interaction effect between fixation and display oscillation condition on vection onset latency, \( F(2, 14) = 0.10, p = 0.77 \). There was no significant interaction effect between fixation and display oscillation conditions on vection onset, \( F(2, 14) = 0.97, p = 0.40 \).

The vection strength data show that angular viewpoint oscillation, and not just linear viewpoint oscillation, is sufficient to generate increases in vection strength. Linear viewpoint oscillation increases motion parallax cues that could account for some of the effects on vection strength and onset. However, angular viewpoint oscillation does not generate these motion parallax cues, but may improve vection strength by...
reducing visual motion adaptation. The regular change in the pattern of local eccentric retinal motions occurring over time would have disrupted the constant linear trajectories of radial flow. These discontinuities in unidirectional motion may have reduced the amount of adaptation to sustained radial motion, preserving retinal sensitivity to the radial flow pattern and superior vection strength.

Alternatively, it is possible the generation of torsional OFRs by angular display oscillation contributed to the vection increases we observed. We consider the potential role of eye movement command signals in the next experiment.

**Experiment 2**

One possible explanation for the results of Experiment 1 is that angular oscillation increases vection because it reduces adaptation to retinal motion. If this is true, then angular display rotation that does not oscillate—i.e., sustains constant local velocity—should reduce vection strength. This reduction should occur because the constant local motion across the retina should generate greater adaptation to visual motion, reducing vection strength. To test this prediction, we created vection displays similar to those of the previous experiment, but this time we presented radial flow with added continuous clockwise rotation (or anti-clockwise rotation) that did not alternate in direction. We expected this continuous spiral rotation to generate weaker vection in depth than would radial flow with angular oscillations that alternated in direction. Alternatively, it is possible that the generation of eye movement motor command signals contributed to the vection increases. If it is the generation of torsional eye movement per se that contributes to the vection increases, then both spiral and oscillation conditions should increase vection strength.

**Method**

**Observers**

Seven adult observers with normal or corrected to normal vision participated in the present study. Again, aside from one author (SK), the observers were completely naive to the design of the current experiment. All procedures adhered to an ethics protocol approved by the ethics committee at the University of New South Wales.

**Stimuli**

The experimental apparatus and presentation of optic flow were identical to the previous experiment. We presented three main conditions of optic flow: pure radial flow simulating self-motion in depth; radial flow with added angular viewpoint oscillation; radial flow with continuous added angular oscillation in one direction (either CW or CCW). The velocity of continuous rotational motion of 62.8°/s matched to the peak velocity of the display with added sinusoidal
angular oscillation. The oscillating motion condition was the same as the 20° condition of the previous experiment. We used this condition because it had a velocity envelope that did not generate saturated vection.

**Procedure**

Observers viewed radial flow displays according to the same procedures as the previous experiment. However, we also instructed observers to close one eye or cover one eye with a patch. This was performed to eliminate binocular cues to the depth of the closely-viewed visual display.

We used the psychophysical rating paradigm of the previous experiment to present the three conditions of optic flow to observers in blocks of randomized trials. We used fixation conditions again in Experiment 2 to encourage stable central fixation. Although we found no effect of fixation in Experiment 1, we compared fixation conditions to ascertain whether fixation modulated vection to spiral motion, which generates torsional nystagmus. Fixation and non-fixation conditions were presented in two separate blocks, which were counterbalanced across observers. We obtained measures of vection strength as in the previous experiment, and analyzed the results using a repeated-measures ANOVA.

**Results and discussion**

The bar-plot in Figure 5 shows mean and standard errors of vection strength ratings for the three experimental conditions with and without fixation. A repeated-measures ANOVA found a significant main effect of angular display type on the strength of vection in depth, $F(2, 12) = 15.74, p < 0.0005$. There was no significant main effect of fixation on vection strength, $F(1, 6) = 0.03, p = 0.878$. There was no significant interaction effect on vection strength between fixation and different angular display conditions, $F(2, 12) = 0.36, p = 0.71$. A post-hoc repeated-measures t test found no significant overall difference between continuous spiral rotation and pure radial flow on vection strength ($t_6 = 2.12, p = 0.08$). However, vection strength was greater overall for oscillating angular oscillation than for pure radial flow ($t_6 = 8.42, p < 0.0005$) and continuous spiral rotation ($t_6 = 3.13, p < 0.01$). These results together are consistent with the view that increased vection strength depends on alternations in the direction of retinal motions that accompany changes in simulated viewpoint orientation. An increase in engagement of eye movements per se cannot account for the vection increases. This is because a decline in vection was observed with spiral viewpoint oscillations, which would have increased ocular motor activity in that condition.

**Experiment 3**

Experiment 2 found evidence to suggest that the strength of vection in depth depends on variation in the velocity of local retinal motion generated by optic flow. Continuous spiral motion generated vection that was no greater than pure radial flow alone. Vection strength was only increased by oscillating changes in simulated angular head orientation. The changing pattern of velocity vectors should reduce the amount of adaptation to unidirectional local motion, which might increase sensitivity to radial flow simulating self-motion in depth. If vection in depth is increased by reduced neural fatigue of visual motion detectors during angular display oscillation, then the MAE duration should be shorter following prolonged viewing of radial flow with angular oscillation, compared with pure radial flow or radial flow with continuous spiral rotation.
Method

Observers

Seven adult observers with normal or corrected-to-normal visual acuity participated in the present study. Aside from the authors (JK and SK), the observers were completely naive to the design of the current experiment. All procedures adhered to an ethics protocol approved by the ethics committee at the University of New South Wales.

Stimuli

The experimental apparatus and presentation of optic flow was identical to the previous experiment (Experiment 2). However, fixation was always presented to ensure that observers maximally adapted to the visual motion displays. After each 40 s presentation of a given radial flow condition, the visual motion paused and a clear MAE was observed for a period of time. The MAE was consistently reported as the experience of illusory contraction of the random dot display.

Procedure

Observers viewed radial flow displays according to the same procedures as the previous experiment. However, they were instructed to attend to their subjective experience of radial contraction—the MAE of radial expansion—and press the spacebar as soon as the experience of MAE ceased. The duration of the MAE was determined as the time elapsed between depressing of the spacebar and cessation of physical radial motion. Results were analyzed using a repeated-measures ANOVA and post-hoc t tests.

Results and discussion

The bar-plot in Figure 6 shows mean and standard errors of radial MAE durations for the three radial flow display conditions. A repeated-measures ANOVA found a significant main effect of angular display type on the strength of vection in depth, \( F(2, 12) = 42.65, p < 0.0001 \). A post-hoc repeated-measures t test found no significant overall difference in MAE duration between continuous spiral rotation and pure radial flow (\( t_6 = 0.06, p = 0.96 \)). The duration of the MAE following angular oscillation was significantly shorter than that following pure radial flow (\( t_6 = 8.00, p < 0.0005 \)) and continuous spiral rotation (\( t_6 = 6.53, p < 0.001 \)). Together with the results of the previous experiment, the reduced MAE following adaptation to oscillating radial flow suggests that angular viewpoint oscillation increases vection strength by reducing visual adaptation to optic flow.

Following the experiment we asked four of the observers what they experienced. All reported an illusory sensation of backwards self-motion—a putative vection aftereffect (VAE)—as reported in recent studies (Seno et al., 2010; Seno, Palmisano, & Ito, 2011). However, the sensation was conflated with the MAE to 2D motion, as our observers reported that the sensation of backwards self-motion only lasted for the duration of illusory radial display contraction. The aftereffects reported here can most easily be explained by adaptation to 2D retinal motion, rather than an independent adaptation of higher-order global motion detectors. We examine further implications of the findings obtained here in the General discussion.

General discussion

The current study aimed to determine whether angular viewpoint oscillation within the roll plane (i.e., about the z-axis) could increase vection in depth. In Experiment 1, we found that increasing the amplitude of either angular or linear 0.5 Hz viewpoint oscillation increased the strength of perceived linear vection in depth and reduced vection onset latencies. In Experiment 2, we found that vection strength was greater when viewing radial flow with added angular oscillation. Vection was weaker when continuous spiral
rotation was added to radial flow. Experiment 3 confirmed that the duration of the MAE was shorter following viewing of radial flow with angular viewpoint oscillation, compared with pure radial flow with or without continuous spiral rotation.

These findings are consistent with the view that added viewpoint oscillation increases vection by reducing adaptation to 2D visual motion. According to this view, radial flow with angular oscillation generated superior vection to pure radial flow displays, because it varies the local direction of retinal motion over time, thus reducing adaptation to unidirectional visual motion. Continuous angular rotation forces the peripheral radial flow elements to follow spiral motion trajectories, but in a manner that holds the local direction of visual motion approximately constant. This preservation of local motion directions would have served to fatigue the activity of local visual motion detectors. As a result, spiral radial flow generated vection that was no better than pure radial flow alone.

An alternative view proposed in the literature is that increased retinal motion generated by optic flow produces the strongest vection. Palmisano et al. (2012) examined vection induced during optic flow simulating forward self-motion across a moving ground plane. They found that a horizontally oscillating fixation point generated vection that was comparable to the vection obtained with added horizontal viewpoint oscillation. Palmisano et al. (2012) did find that the duration of the motion aftereffect (MAE) was on average shorter in fixation point oscillation conditions compared with pure radial flow, but this decline in MAE duration did not reach significance. Based on those data, the authors concluded that the increase in strength and decline in onset latency of vection with fixation point oscillation was most consistent with the dependence of vection on an increase in the speed of retinal motion, rather than retinal adaption. If vection strength critically depends on increased retinal motion, then we would have expected to obtain greater vection using displays with added continuous angular viewpoint rotation. This would be expected because continuous angular rotation maintains a higher velocity over time, relative to the velocity envelope of 0.5 Hz viewpoint oscillation. Contrary to this proposal, vection was not increased with continuous angular rotation, and only increased with alternating angular viewpoint oscillations.

A unifying explanation for the viewpoint oscillation and fixation-point oscillation effects on vection is the change in velocity of retinal motion over time. We found that angular viewpoint oscillation generated not only greater vection strength (Experiment 2), but also shorter MAE durations compared with pure radial flow and radial flow with continuous spiral rotation (Experiment 3). Our 40 s presentations of angular oscillation and spiral inducers were longer than the 15 s presentations of radial flow presented by Palmisano et al. (2012), which may account for the stronger significant effects observed here. The increase in vection strength can therefore be explained by reduced adaptation to the changing direction of retinal motion produced by angular oscillations, an effect which would sustain sensitivity to the radial expansion of optic flow. This finding is consistent with the findings of Kim et al. (2012), who found that adding horizontal angular viewpoint oscillation to radial flow was sufficient to increase vection strength. They also found that vection strength was predicted by increased variation in eye movement relative to the focus of expansion, which would have generated further variations in retinal motion. In direct support of this explanation, Palmisano and Kim (2009) found that instructing observers to regularly look around the optic flow display promoted better vection than stable central fixation. This vection advantage can be attributed to the systematic change in central retinal motion (and its adaptation) that occurs when observers shift their gaze around the focus of expansion. This effect also accounts for the increase in vection that occurs during eccentric viewing in optic flow (Kim & Palmisano, 2010). In that study, variation in smooth pursuit OFRs was found to generate better vection, especially during periods when OFR velocity declined over time. It would therefore appear that it is not the overall increase in retinal motion that matters, but rather, variation in the direction and velocity of visual motion across the retina that is critical for viewpoint oscillation advantages in vection.

One potential caveat on the interpretation of the current results is that the added angular oscillations would have simulated changes in head orientation that could conflict with otolithic signals concerning the upright head posture of our observers. It is unlikely that this potential conflict accounts for the poor effect of continuous angular rotation on vection in depth, as viewpoint oscillation/jitter advantages in vection tend to be robust against changes in visual-vestibular conflict (Allison, Zacher, Kirollos, Guterman, & Palmisano, 2012). The potential role of vestibular interaction could be verified in future studies that tilt observers en bloc when viewing angularly rotating optic flow. At present, we conclude that the findings from the experiments reported here and in previous studies can be best explained by adaptive processes underlying visual motion encoding.

Keywords: vection, retina, motion, aftereffect, MAE

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