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Consistent stereoscopic information increases the perceived speed of vection in depth

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Abstract

Previous research found that adding stereoscopic information to radially expanding optic flow decreased vection onsets and increased vection durations (Palmisano S, 1996 *Perception & Psychophysics* 58 1168-1176). In the current experiments, stereoscopic cues were also found to increase perceptions of egospeed and self-displacement during vection in depth - but only when these cues were consistent with monocularly-available information about self-motion. Stereoscopic information did not appear to be improving vection by increasing the perceived maximum extent of displays or by making displays appear more three-dimensional. Rather, it appeared that consistent patterns of stereoscopic optic flow provided extra, purely binocular information about egospeed, which resulted in faster/more compelling illusions of self-motion in depth.

Keywords

vection, speed, depth, consistent, information, perceived, increases, stereoscopic

Disciplines

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**CONSISTENT STEREOSCOPIC INFORMATION INCREASES THE PERCEIVED
SPEED OF VECTION IN DEPTH**

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Keywords: stereopsis, self-motion, vection, speed, optic flow

ABSTRACT

Previous research found that adding stereoscopic information to radially expanding optic flow decreased vection onsets and increased vection durations (Palmitano S, 1996 *Perception & Psychophysics* **58** 1168-1176). In the current experiments, stereoscopic cues were also found to increase perceptions of egospeed and self-displacement during vection in depth - but only when these cues were consistent with monocularly-available information about self-motion. Stereoscopic information did not appear to be improving vection by increasing the perceived maximum extent of displays or by making displays appear more three-dimensional. Rather, it appeared that consistent patterns of stereoscopic optic flow provided extra, purely binocular information about egospeed, which resulted in faster/more compelling illusions of self-motion in depth.

1 Introduction

Due to their horizontal separation, different patterns of optic flow¹ are presented to the left and right eyes during self-motion (see Figure 1). Despite this fact, many theorists have assumed that monocularly-viewed optic flow provides all the information required to perceive self-motion (Gibson 1950; Gibson et al 1955; Gordon 1965; Heeger and Jepson 1990; Koenderink 1990; Koenderink and van Doorn 1981; 1987; Longuet-Higgins and Prazdny 1980; Nakayama and Loomis 1974; Owen et al 1981; 1987; Warren 1990). For example, it has been suggested that observers could use the focus of expansion of each optic flow - the point of zero optical velocity specified locally or globally - to determine their direction of self-motion (Gibson et al 1955). Similarly, Warren (1990) proposed that observers might perceive their speed of self-motion based on the global optical flow rate – the speed of self-motion (V) scaled in altitude units (h). For self-motion over a ground plane, he showed that the global optic flow rate could be calculated from the angular speed ($d\beta/dt$) of any texture element E in the flow field:

$$V/h = (d\beta/dt) / \sin\alpha \sin^2\beta, \quad [1]$$

where β is the angle between E and the destination point and α is E 's eccentricity. The speed of self-motion could also be perceived based on the optical edge rate of this ground plane optic flow - the rate at which local discontinuities cross a fixed point of reference in the observer's field of view (e.g. a wing tip - Denton 1980; Larish and Flach 1990; Owen et al 1981; 1987). However, while research has shown that monocularly-viewed optic flow is sufficient to induce perceptions of self-motion (Andersen and Braunstein 1985; Brandt et al 1973; Telford et al 1992; Telford and Frost 1993), mounting evidence indicates that stereoscopic information can enhance this subjective experience.

<INSERT FIGURE 1 ABOUT HERE>

A number of studies have shown that stereoscopic and optic flow processing interact in the perception of heading (one aspect of self-motion perception). In the first of these, van den Berg and Brenner (1994) found that adding stereoscopic information to radial flow (simulating self-motion in depth through a 3-D cloud of dots) made heading estimates up to four times more resistant to randomly-directed motion noise. However, this improvement did not appear to be due to changing disparities - since observers were just as accurate when each dot had a fixed binocular disparity throughout the display². Similarly, Grigo and Lappe (1998) showed that binocular disparity information also effects heading judgments in the presence of unidirectional motion noise. They found that heading perceptions induced by radial flow were more accurate when binocular disparity indicated that a superimposed pattern of horizontally translating dots was in the foreground, as opposed to the background. Based on these findings, it has been proposed that binocular disparity information about depth order improves heading perception by allowing the visual system to remove the effects of eye-motion³ - since the focus of expansion of retinal flow typically corresponds to the direction of fixation, not the direction of self-motion (Regan and Beverley 1982).

Research has also found a 'stereoscopic advantage' for the visually induced experience of self-motion - known as "vection". In this study, Palmisano (1996) presented observers with stereoscopic and control displays simulating self-motion in depth relative to a 3-D cloud of randomly-positioned square objects. For all of the display sizes, speeds and densities tested, stereoscopic information was found to improve the illusions of self-motion in depth induced by

radial flow (even when monocular viewing of these displays already produced compellingvection). Specifically, this stereoscopic information was found to decreasevection onsets and increasevection durations. Thus, it would appear that stereoscopic optic flow provided additional binocular information about either self-motion or distance/depth which was used in the visual perception of self-motion.

One possible explanation for this stereoscopic advantage forvection is that additional *dynamic* information in stereoscopic optic flow increased the perceived speed of illusory self-motions in depth. Since global optical flow rate and optical edge rate information about egospeed would have been less than ideal for the displays used in the above study, which simulated non-planar environments with irregular/random spacing⁴, additional binocular information might have been required to make the observer's perceived speed more consistent with the actual speed simulated by the display. In principle, stereoscopic optic flow could have provided extra purely binocular information about the speed of self-motion in depth. As an observer moves towards a stationary, rigid configuration with a constant depth difference, its relative horizontal disparity will increase exponentially due to its decreasing viewing distance (see Figure 2A). Thus, the configuration's rate of changing disparity, or its interocular velocity differences, could be used to calculate the speed of his/her self-motion in depth (the rate of change of the viewing distance) after being scaled by a constant (e.g. the configuration's depth difference - see Figure 2B). Two potential stereoscopic cues to the speed of self-motion in depth are derived in the Appendix [Equations A4 and A7]. If these or other dynamic binocular cues were used, they might have resulted in faster perceived speeds self-motion (ie closer to simulation than to reality), as well as a more compelling subjective experience {since faster self-motions, both real and illusory, tend to produce more compelling subjective experiences of self-motion (eg Brandt et al 1973)}.

<INSERT FIGURE 2 ABOUT HERE>

Alternatively, additional *static* binocular information about distance and depth in stereoscopic optic flow could have improved vection by scaling the perceived speed of self-motion in depth. In principle, observers could have determined their speed of self-motion (V) by multiplying the angular speed ($d\beta/dt$) of any projected texture element (E) by its perceived absolute egocentric distance (S):

$$V = (S \times d\beta/dt) / \sin(\beta), \quad [2]$$

where β is the visual angle between E and the destination point, and $d\beta/dt$ is the change in this angle over time (see Figure 3). While monocularly-viewed optic flow only specifies absolute egocentric distances when the speed of self-motion is known, vergence information in stereoscopic optic flow would have provided the absolute egocentric distance of texture elements 1-2 metres from the observer (Foley 1985; Foley and Richards 1972; Gogel 1977; Gogel and Sturm 1972; Richards and Miller 1969), and disparity information could have been used to determine the distances of the remaining objects (Wallach and Zuckermann 1963). Thus, if egospeed was perceived in this manner, stereoscopic optic flow should have induced faster perceived speeds of self-motion (i.e. more compelling vection) than monocularly-viewed optic flow, because its vergence and disparity information about distance and depth would have indicated that texture elements were further away from the observer {ie perceived V increases with perceived S }.

<INSERT FIGURE 3 ABOUT HERE>

Both of the above explanations of the stereoscopic advantage assume that stereoscopic information increases vection speed - either directly (by providing dynamic binocular information about the speed of self-motion in depth) or indirectly (by scaling monocularly-determined vection speed with static binocular information about distance). Currently, there is little available empirical evidence for either proposal. Monen and Brenner (1994) have performed the only study examining the effect of stereoscopic information on the perceived speed of self-motion in depth. Using computer generated displays simulating self-motion over a ground plane of either dots or lines, they found that observers were actually worse at detecting changes in the speed of self-motion in depth when stereoscopic information was available. However, this finding is counter-intuitive, since one would expect that at the worst, performance should be equal across stereoscopic and control conditions. It is also worth noting that the occurrence of vection was not explicitly measured in this experiment. So it is possible that observers may not have been experiencing vection during these briefly presented accelerating displays (each was shown for only 5s and represented a self-motion which would normally have been accompanied by vestibular stimulation).

1.2 Overview of Experiments

The present experiments examined the vection induced by three different types of stereoscopic radially expanding optic flow. In stereoscopic 'consistent' displays, the horizontally disparate patterns of optic flow provided consistent binocular and monocular information about self-motion and the 3-D layout - both indicated that the observer was moving through a 3-D environment extending from 1.75m to 20m along the depth axis. Conversely, stereoscopic 'conflicting-far' and 'conflicting-near' displays provided binocular information that conflicted with monocular

information about self-motion and the 3-D layout - suggesting that the observer was stationary relative to a 2-D environment lying either 100m or 1.75m away (the relative horizontal disparities of any two objects was zero and did not change over time). Since objects in a conflicting-far display should appear to be much further away than objects in a conflicting-near display, it was predicted that the conflicting binocular cues in the former would have little effect on the perceived 'three-dimensionality' of the environment (this would be based mostly on monocular information). However, since the simulated distance of objects in a conflicting-near display was less than 2m, it was expected that the stronger binocular flatness cues in this type of display would cause scenes to appear much less three-dimensional {While self-motion relative to a near 3-D environment would result in large relative disparities between objects and significant changes in disparity over time, self-motion relative to a distant 3-D environment (with the same dimensions) would result in smaller relative disparities between objects and more modest changes in disparity over time}. Experiment 1 examined these geometrical predictions about the perceived 3-D layout of scenes represented by consistent, conflicting-far and conflicting-near displays using the method of magnitude estimation (Stevens 1957).

Experiment 2 was designed to address the following questions: (1) does adding consistent stereoscopic information to optic flow result in faster vection speeds? and (2) can an equivalent increase in vection speed be produced by conflicting-far displays? The logic underlying the latter question is as follows. If the stereoscopic information in consistent displays does increase vection speed by increasing the perceived distance of environmental objects, then conflicting-far displays should produce a similar (or even greater) improvement - since vergence and disparity information should indicate that objects in conflicting-far displays are further away than those in consistent displays. However, if the stereoscopic information in consistent displays increases vection by

providing extra, purely binocular information about the speed of self-motion in depth, or by making the perceived environment appear more three-dimensional, then conflicting-far displays might demonstrate little improvement.

2 Experiment 1: Effects of stereo on perceived 3-D Layout

This experiment examined the perceived 'three-dimensionality' and perceived maximum extent in depth of scenes induced by consistent, conflicting-far and conflicting-near patterns of radially expanding optic flow. Based on geometrical prediction, it was expected that scenes represented by consistent displays would be rated as being more three-dimensional than those represented by conflicting-far and conflicting-near displays. It was also predicted that scenes represented by consistent and conflicting-far displays would be rated as having greater perceived maximum extents in depth than those represented by conflicting-near displays.

2.1 Method

2.1.1 Observers. Nine male and eleven female undergraduate psychology students (aged between 17 and 35 years) participated in this experiment for course credit. All had either normal or corrected-to-normal vision and a stereoacuity of 20s of arc or better at a distance of 40cm. None had previously experienced illusions of self-motion in the laboratory. Four additional observers failed to meet the visual criteria for this experiment and a fifth discontinued the experiment after experiencing motion sickness.

2.1.2 Design. Two independent variables were examined in this experiment. (i) Display type. Stereoscopic displays were consistent, conflicting-far or conflicting-near patterns of radially

expanding optic flow. (ii) Display speed. Each display simulated one of three speeds of self-motion: 2.4m/s, 4.8m/s and 7.2m/s. Two dependent variables were recorded - each in a separate testing session. In one session, observers rated the perceived 'three-dimensionality' of the scene represented by each display. In the other session, observers rated the perceived maximum extent of the display along the depth dimension (i.e. the perceived egocentric distance of the furthest object in the display). The order in which these two ratings were obtained varied randomly from observer to observer.

2.1.3 *Apparatus.* Displays were generated on a Macintosh G4 personal computer and rear projected onto a mylar screen by a Sanyo XGA 2200 Projector (resolution was 1024 H x 768 V). This screen subtended a visual angle of 64° H x 64° V when observed through a large, cylindrical viewing tube attached to the head-and-chin rest 1.75m distant (the tube blocked the observer's view of his/her stationary surroundings - which included the screen's frame). Stereopsis and occlusion always indicated that the inducing display - seen at the far end of this viewing tube - was in the background (vection has been shown to be dominated by optic flow from the perceived background - Ohmi and Howard 1988; Telford et al 1992). All three types of stereoscopic displays were viewed with the aid of anaglyph glasses.

2.1.4 *Visual Displays.* Three types of stereoscopic inducing display were used in this experiment - consistent, conflicting-far and conflicting-near displays. Each simultaneously presented red (2.6cd/m^2) and cyan (3cd/m^2) patterns of moving objects on a white background (11cd/m^2), which were then viewed through red-cyan anaglyph glasses (at these intensities there was minimal leakage between the two eyes). In consistent displays, each pair of red and cyan moving objects

had a horizontal screen disparity - ranging from 0 to 1.95 degrees - which represented the fused object's simulated distance from the observer (ranging from 1.75m to 20m). In conflicting-far displays, the horizontal screen disparity of each pair of red and cyan moving objects (2.09 degrees) always indicated that the fused object lay 100m from the observer. In conflicting-near displays, the horizontal screen disparity of each pair of red and cyan moving objects (0 degrees) indicated that the fused object lay on the screen 1.75m away. During conflicting-far and conflicting-near displays, these horizontal disparities were relative to the aperture of the viewing tube (in consistent displays there were also non-zero disparities between the different objects in the optic flow).

The monocular information in all three types of display simulated constant velocity forwards self-motion in depth through a 20m deep, 3-D cloud of 200 randomly positioned objects (filled-in squares). This monocular information about self-motion and 3-D layout was provided by varying each object's velocity and total area as a function of its simulated location in depth (objects ranged in size from 0.12° - 1.5°). A constant density was maintained by replacing each object as it disappeared from view. When an object moved off the screen, it was moved to the furthest simulated distance along the depth axis (20m) at the same horizontal and vertical coordinates (using monocular cues in conflicting-far and conflicting-near displays or both monocular and binocular cues in consistent displays). All displays had a frame rate of 60Hz and were symmetrical about both horizontal and vertical axes. Since it was assumed that a stationary object might impair visual illusions of self-motion, displays were viewed without an explicit fixation point. Thus, the observer was able to track individual objects as they appeared to approach him/her.

Prior to the presentation of each of these types of stereoscopic display, observers were presented with a pair of nonius lines - one red, one cyan - separated by a horizontal disparity representing the furthest distance simulated by each display (1.75m, 20m or 100m - Mitchell and Ellerbrock, 1955;

Hebbard, 1962). They then altered their vergence until the targets were aligned before triggering the experimental display.

2.1.5 Procedure. Prior to the experiment, observers were first given the Randot stereovision test (to ensure that they could perceive static stereoscopic depth) and then given practice using nonius lines to alter their vergence appropriately for the different stereoscopic displays. They were then randomly assigned to an experimental order - this determined which of the two dependent variables would be obtained in the first testing session. Since the method of magnitude estimation was used, the first display in each testing session set the modulus for the observers' ratings (Stevens 1957). This standard stimulus was a consistent stereoscopic display, which simulated the slowest speed of self-motion (2.4m/s). After a period of 60s had elapsed, half of the observers were told that "you are to rate the perceived three-dimensionality of this scene as '50'". This rating indicates how far apart the objects in this scene are separated from each other in depth. So a rating of '0' would indicate that all the objects appeared to be at the same distance from you - like squares on a wall". The remaining observers were told that "you are to rate the perceived distance of the furthest object in this display as '50'". So you would rate a display where the furthest object appeared to be at the same distance as the screen⁵ as '0"'. Four practice trials then followed. Prior to the first of these, observers were told that they were to rate the perceived 'three-dimensionality' or 'maximum extent' of each display on the barchart presented at the end of the trial (this had a scale of 0-100 with 5-point intervals). They were also instructed that if they experienced double vision during any display, they were to press any key on the keyboard to register that there was a problem with that trial. The experimental trials were then presented in a random order - each had a duration of 60s and an inter-trial interval of 20s. After each stimulus condition had been presented twice, there was

a five minute break before the second block of trials was run to record the remaining dependent variable.

2.2 Results and Discussion

Separate repeated measures ANOVAs were performed on the observers' ratings of the scene's 'three-dimensionality' and maximum extent along the depth axis (see Figures 4A and 4B for the means). Greenhouse-Geisser corrections were applied to all post-hoc contrasts to prevent type 1 errors. Display type was found to have significant main effects for both ratings of the three-dimensionality of displays [$F_{2,38} = 65.65$, $p < .0001$] and ratings of maximum extent along the depth axis [$F_{2,38} = 88.77$, $p < .0001$]. Contrary to predictions, conflicting-far displays were not rated as having significantly different maximum extents along the depth axis compared to consistent displays [$F_{1,19} = 1.52$, $p > .05$]. However, both conflicting-far and consistent displays were rated as having significantly greater maximum extents in depth compared to conflicting-near displays [$F_{1,19} = 118.25$, $p < .0001$; $F_{1,19} = 146.54$, $p < .0001$]. As expected, scenes represented by consistent displays were rated as being significantly more three-dimensional than those represented by conflicting-far displays [$F_{1,19} = 21.86$, $p < .0001$] and conflicting-near displays [$F_{1,19} = 116.77$, $p < .0001$]. However, the scenes represented by conflicting-far displays were also rated as being significantly more three-dimensional than those represented by conflicting-near displays [$F_{1,19} = 37.57$, $p < .0001$]. So clearly, as predicted, the binocular flatness information in conflicting-far displays had a lesser effect compared to conflicting-near displays.

<INSERT FIGURE 4 ABOUT HERE>

Display speed was also found to produce significant main effects for both ratings of display three-dimensionality [$F_{2,38} = 14.12$, $p < .0001$] and perceived maximum extent along the depth axis [$F_{2,38} = 4.23$, $P > .04$]. Increasing the simulated speed of self-motion from 2.4m/s to 4.8m/s led to significant increases in observers' ratings of scene depth [$F_{1,19} = 7.14$, $p < .02$] and maximum extent [$F_{1,19} = 13.49$, $p < .0009$] for all three types of stereoscopic display. However, increasing the simulated speed of self-motion from 4.8m/s to 7.2m/s had no significant effect on ratings of depth and maximum extent [$F_{1,19} = .12$, $p > .05$; $F_{1,19} = 2.22$, $p > .05$]. No two-way interactions (ie between display type and display speed) reached significance in this experiment.

There were no reports of double vision during any of the trials. In observer debriefing after the experiment, 16 of the 20 observers spontaneously reported experiencing illusions of self-motion during these experimental sessions (the remaining 4 observers did report experiencing illusory self-motion when prompted). This is an important finding, since observers had not been informed of this possibility at any stage of the experiment. Another finding of interest was that observers appeared to have greater difficulty distinguishing consistent from conflicting-far displays (compared to the task of distinguishing conflicting-far from conflicting-near displays) when they were later shown these displays during debriefing.

3 Experiment 2: Effects of stereo on vection

Experiment 2 examined whether adding stereoscopic information to optic flow can improve vection (directly or indirectly) by increasing the perceived speed of self-motion in depth. Vection onsets, speeds and perceived illusory self-displacements were recorded for the consistent, conflicting-far and conflicting-near stereoscopic displays examined in Experiment 1. Based on the perceived distance findings of the previous experiment, one possibility was that the vergence and disparity

information in both consistent and conflicting-far displays would increase vection speed by similar amounts (relative to conflicting-near displays) by increasing perceived environmental distances.

3.1 *Method*

The apparatus and visual displays were identical to those used in Experiment 1 - with the following extension. In this experiment, observers moved an Apple Pro optical sensor mouse (10.5cm long by 5.8cm wide) between two tracks on the table in front of them (each was 72cm long, 1cm wide and 0.5cm high) to represent their perceived speed of self-motion in depth (the two tracks had a horizontal separation of 7cm).

3.1.1 *Observers.* An additional 20 observers (Ten males and ten females, aged between 17 and 32 years) participated in this experiment. Their monocular and stereoscopic acuity criteria were identical to those of Experiment 1. None had previously experienced illusions of self-motion in the laboratory. Three additional observers failed to meet the visual criteria for this experiment (they failed the Randot stereovision test) and a further two discontinued the experiment after experiencing motion sickness.

3.1.2 *Design.* Three dependent variables were measured for each trial. (i) Vection tracking latency - the time from the start of the display until the observer first moved the mouse continuously for a period of 1s or longer. Trials which failed to meet this criterion (i.e. non-vection trials) were given a tracking latency of 60 seconds (equal to the total trial length). (ii) Tracking speed - the mean of all significant mouse displacements per unit time recorded after the first 1s. (iii) Total tracking

displacement - calculated by adding together all of the significant individual mouse displacements for each trial.

These vection tracking measures were similar to those used previously by Telford and colleagues (Telford et al 1992; Telford and Frost 1993). The instantaneous mouse position (in mouse units) was sampled 8 times per second - producing 480 stored data points for each 60s trial {the computer's 'tickcount' was obtained simultaneously to ensure that mouse positions were obtained at equal time intervals}. When observers experienced vection, they moved the mouse across the table in only one direction (away from them, along the mouse's y axis), and then they picked up mouse and reset it to the initial position after each track. Since the data was collected continuously, zero values were recorded during the reset intervals (see Figure 5). These values were considered as missing data and were not included in the resultant means (non-zero traces lasting less than 0.25s were also not used in any of the onset, speed or displacement calculations). Zeros from resets were differentiated from zeros due to non-tracking by the length of time it took to reset the mouse (this was highly consistent both within and between observers - see Figure 5). Prior to statistical analysis, mouse units were converted to cm and vection onsets, mean tracking speeds and the total tracking displacements were determined for each 1 minute trial.

<INSERT FIGURE 5 ABOUT HERE>

3.1.3 Procedure. After passing the Randot stereovision test and completing the nonius line practice, observers were told that they would be shown displays of moving objects and that: "sometimes the objects may appear to be moving towards you; at other times you may feel as if you are moving towards the objects. Your task is two-fold. If the objects appear to be moving then

press down on the mouse and hold it down as long as the objects continue to move. However, if you feel that you are moving then move the mouse along the track on the table in front of you - like so. Move the mouse at the speed you appear to be moving at and keep it moving as long as the experience continues". The instruction to press down on the mouse button during perceived object motion was aimed at reducing the likelihood that experimenter demands would force observers to perceive self-motion on every trial. Observers were also instructed that if they experienced double vision during any display, they were to press any key on the keyboard to register that there was a problem with that trial. After four practice trials, the experimental trials were then presented in a random order - each had a duration of 60s and an inter-trial interval of 20s (identical to the conditions in Experiment 1). Each stimulus condition was presented twice - once in the first testing session and then again in the second testing session (there was a 10 minute break between sessions to prevent fatigue). Following this experiment, the perceived three-dimensionality and the perceived maximum extent of the consistent, conflicting-far and conflicting-near displays was assessed for these new observers. The results confirmed the perceived 3-D layouts of each of these displays found in Experiment 1.

3.2 Results and Discussion

Vection was reported on 309 of the 360 trials (20 subjects responding twice to 9 stimuli). Of the 51 trials which failed to induce vection, 8 had consistent displays, 22 had conflicting-far displays, and 21 had conflicting-near displays. There were no reports of viewing difficulties during any of the trials. Separate repeated measures ANOVAs were performed on the three different vection measures: latency to tracking onset (Figure 6A), average tracking speed (Figure 6B) and total

tracking displacement (Figure 6C). Greenhouse-Geisser corrections were applied to all post-hoc contrasts to prevent type 1 errors.

Display type produced significant main effects on all three of these vection tracking measures {tracking onsets $F_{2,38} = 3.72$, $p < .04$; tracking speeds $F_{2,38} = 7.63$, $p < .002$; and total tracking displacements $F_{2,38} = 4.63$, $p < .02$ }. As can be seen in Figure 6A, consistent displays were found to produce significantly shorter vection onsets than conflicting-far [$F_{1,19} = 5.17$, $p < .04$] and conflicting-near displays [$F_{1,19} = 6.08$, $p < .02$]. However, conflicting-far displays were not found to produce significantly different vection onsets to conflicting-near displays [$F_{1,19} = 0.04$, $p > .05$]. These findings replicate and extend those of the earlier vection study (Palmisano 1996), showing that only consistent stereoscopic information results in decreased vection onset latencies.

<INSERT FIGURE 6 ABOUT HERE>

As predicted, consistent displays were found to produce significantly faster average vection speeds [$F_{1,19} = 13.60$, $p < .001$] and significantly larger tracking displacements [$F_{1,19} = 6.23$, $p < .02$] than conflicting-near displays. Importantly, while Experiment 1 found that consistent and conflicting-far displays did not produce significantly different perceived maximum extents in depth, consistent displays were found to produce significantly faster average vection tracking speeds [$F_{1,19} = 8.78$, $p < .008$] and significantly larger tracking displacements [$F_{1,19} = 7.58$, $p < .01$] than conflicting-far displays. Similarly, while conflicting-far displays had greater perceived extents in depth and appeared more three-dimensional than conflicting-near displays in Experiment 1, vection tracking speeds and total tracking displacements were not significantly different for conflicting-far and conflicting-near displays [$F_{1,19} = 0.53$, $p > .05$; $F_{1,19} = 0.07$, $p > .05$]. These

findings are not consistent with the proposal that vergence and disparity information about distance and depth improves vection by scaling/increasing the perceived speed of self-motion (this predicted that vection speed would increase with the perceived egocentric distance of the optic flow). They also provide little support for the notion that stereoscopic optic flow improves vection by making the optic flow appear more three-dimensional.

Consistent with the findings of previous vection studies, display speed was found to produce significant main effects on all vection measures {tracking onsets $F_{2,38} = 14.94$, $p < .0001$; tracking speeds $F_{2,38} = 11.25$, $p < .0001$; and tracking displacements $F_{2,38} = 36.96$, $p < .0001$ }. Increasing the simulated speed of self-motion from 2.4m/s to 4.8m/s significantly decreased vection onsets [$F_{1,19} = 16.70$, $p < .001$] and significantly increased vection tracking speeds [$F_{1,19} = 22.05$, $P < .0001$] and total tracking displacements [$F_{1,19} = 61.855$, $p < .0001$]. Increasing the simulated speed of self-motion from 4.8m/s to 7.2m/s did not have a significant effect on vection tracking onsets [$F_{1,19} = 1.21$, $p > .05$] or vection tracking speeds [$F_{1,19} = 0.45$, $p > .05$]. However, this speed manipulation did significantly increase the overall tracking displacement for the trial [$F_{1,19} = 12.07$, $p < .001$]. So while the vection onsets and tracking speeds were similar for 4.8m/s and 7.2m/s displays, observers appear to have made more tracking movements during the 7.2m/s displays. One possible explanation for this discrepancy between the different measures is that the null finding for vection tracking speeds reflects a motor, rather than a perceptual, limitation - observers may have been unable to move the mouse fast enough to match the simulated speed in 7.2m/s displays. No two-way interactions between display type and display speed reached significance for any dependent variable examined in this experiment.

4 General Discussion

The current experiments found that only consistent stereoscopic information improved the vection induced by radially expanding optic flow. While the scenes depicted by consistent and conflicting-far displays appeared more three-dimensional and had greater perceived maximum extents in depth than those represented by conflicting-near displays, only consistent displays were found to induce shorter vection onsets, faster vection speeds or larger illusory self-displacements than conflicting-near control displays. These results are not consistent with the proposal that vergence and disparity-based information about distance and depth improves vection by scaling the perceived speed of the illusory self-motion. Nor are they consistent with the notion that this stereoscopic information improves vection by simply increasing the perceived three-dimensionality of the display. Rather, it appears that the presence of changing-disparities and interocular velocity differences in consistent displays improved vection directly - by providing extra, purely binocular information about self-motion in depth (binocular disparities and interocular velocity differences never changed during conflicting-far and conflicting-near displays).

While local changes in binocular disparity and local interarray velocity differences have been shown to provide information about the direction and speed of object motion in depth (Beverley and Regan 1973; 1975; Brooks and Mather 2000; Harris and Watamaniuk 1995; Portfors-Yeomans and Regan 1996; 1997; Regan 1993; Regan et al 1979), it appears that global changes in binocular disparity and global interocular velocity differences can provide useful information about the speed of self-motion in depth. Since the monocularly-available information about the speed of self-motion was less than optimal for displays used in the current study⁴, the dynamic binocular information in consistent displays appears to have been required to make the perceived speed of self-motion more consistent with the actual speed simulated by the inducing display. These findings appear to be compatible with those of Gray and Regan (1997), who found that adding

consistent stereoscopic information to displays with changing-size cues to motion in depth, resulted in time-to-contact estimates which were closer to the simulated time-to-contact. However, it is worth noting that while stereoscopic improvements in the current study were produced by *increasing* the perceived speed of *self-motion* in depth, stereoscopic improvements in the Gray and Regan study were achieved by *reducing* the perceived speed of *object-motion* in depth. It was also possible that the presence of global changes in binocular disparity and global interocular velocity differences acted as ecological cues to self-motion - biasing the observer to perceive self-, rather than object-, motion in depth. This ecological account could explain the faster vection onsets found for consistent displays in both this and the previous study (compared to control displays without changing disparities or interocular velocity differences).

While the current experiments found little support for the notion that purely binocular information about the 3-D layout of the environment can improve visual illusions of self-motion, they do not rule out this possibility. Since all of the displays tested already contained relative size and motion cues to depth order, and eye-movements were accompanied by extraretinal information, it is certainly possible that binocular information about the 3-D layout might be required to produce compelling vection in the absence of these monocular cues. Consistent with this notion, studies have shown that binocular disparity information about depth order can improve heading perceptions by removing the effects of motion noise from optic flow (van den Berg and Brenner 1994; Grigo and Lappe 1998) and disambiguating the direction of self-motion from opponent motion (Roy and Wurtz 1990; Roy et al 1992). Recent research has even demonstrated that binocular depth perception can be enhanced by the stereoscopic optic flow produced by typical self-motions (Ziegler and Roy 1998).

Research has shown that far from being redundant, horizontally disparate patterns of radially expanding flow can provide additional, purely binocular information, which is used in the perception of self-motion in depth. However, the current study found that stereoscopic patterns of optic flow which increased perceived 3-D layout of the environment, but provided no additional information about the nature of the self-motion, resulted in little or no vection improvement. These results suggest that the stereoscopic advantage for vection was produced by the extra, purely binocular information about the speed of self-motion in depth - based on properties of either the pattern of changing-disparities and/or the pattern of interocular velocity differences in consistent stereoscopic radial flow. It is concluded that, at least in the case of self-motion in depth, the final vection experience is jointly determined by the available binocular and monocular information about self-motion.

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Figure Captions

Figure 1: A schematic representation of the stereoscopic optic flow produced by self-motion through a 3-D cloud of randomly positioned points. Each line segment pair represents the optical velocity of a texture element (on two horizontally separated, planar projection surfaces). Note: in the stereoscopic displays used in the current study texture element size also increased as simulated distance from the observer decreased.

Figure 2: (A) Change in the relative horizontal disparity of two texture elements (E1 and E2) in degrees as the observer moves towards them at 1m/s. This configuration of two elements (separated in depth by 1m) was initially a distance of 20m from the observer. (B) The instantaneous rate of changing disparity produced by three different speeds of observer motion (1m/s, 2m/s, 5m/s) towards the same configuration. To calculate the absolute speed of self-motion in depth (Change in the viewing distance/s), the observer would have to scale his/her rate of changing disparity by a constant (e.g. depth of the configuration).

Figure 3: Distance scaling of vection speed. As the observer O moves with a velocity V towards D, any texture element E's optical speed will be $d\beta/dt$ - where β is the angle between OD and OE and S is the distance OE. So V can be determined by scaling E's optical speed by its egocentric distance.

Figure 4: The effect of display speed on the scene's (A) perceived depth and (B) perceived maximum extent in depth for consistent, conflicting-far and conflicting-near radially expanding flow (Experiment 1). Error bars represent standard errors of the means.

Figure 5: Example of a mouse trace for a vection trial. This figure shows a 19s fragment of a 60s mouse tracking trial. Vection tracking begins 22.6s after stimulus onset and continues after the 35s mark shown above - right until the end of the trial. The high resolution of this trace shows the consistency in the reset times within a trial. The average mouse reset time for this trial was 0.78s and the standard deviation was 0.13s.

Figure 6: The effect of display speed on (A) vection onsets, (B) vection tracking speeds and (C) total tracking displacements for consistent, conflicting-far and conflicting-near radially expanding flow (Experiment 2). Error bars represent standard errors of the means.

Figure A1: The relative horizontal disparity of two texture elements E1 and E2 (δ_{E1E2}) is the difference in their absolute horizontal disparities (ie $\delta_{E1} - \delta_{E2}$). This relative horizontal disparity will depend on D_{E1} and D_{E2} (the absolute egocentric distances of E1 and E2) and I (the interocular distance). [ie $\delta_{E1E2} \approx I(D_{E1}-D_{E2})/D_{E1}^2$]

Figure A2: Stereoscopic information about the speed of self-motion in depth. As an observer moves with a velocity V towards a rigid configuration (ie E1 and E2 separated by a constant depth Z), viewing distances will decrease (ie $D_{E1}' < D_{E1}$ and $D_{E2}' < D_{E2}$) and relative horizontal disparity will increase (ie $\delta'_{E1E2} > \delta_{E1E2}$). The rate of change in this disparity potentially provides information about the speed of self-motion in depth.

$$\{ie \quad dD_{E1}/dt \approx [IZ/d(\delta_{E1E2})/dt]^{1/2} \approx [IZ / (d(\phi_{1L}-\phi_{2L})/dt - d(\phi_{1R}-\phi_{2R})/dt)^{1/2}\}$$

Figures

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I

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Footnotes

¹Gibson defined the optic array as the pattern of emitted or reflected light converging to any single point which could be occupied by an observer (Gibson 1950; 1979). Since each point of observation has a unique optic array, as an observer moves through an environment, the optic array changes continuously, giving rise to optic flow. So unlike the retinal flow presented to an observer, optic flow is unaffected by eye-motion.

²The findings of van den Berg and Brenner are however controversial. Research by Ehrlich and colleagues (1998) appears to show that stereoscopic information does not effect the accuracy of heading estimates during simulated eye-rotation.

³According to this notion, the visual system uses binocular disparity (or monocular depth cues) to determine the most distant points in the flow, and then estimates the flow due to eye-motion based on the motion of these points. Once the effects of eye-motion have been removed, the focus of expansion of the remaining flow (due to self-motion) could then be used to accurately determine the direction of self-motion.

⁴Equation 1 will fail when the observer travels relative to complex, non-planar environments – such as a three-dimensional cloud of randomly positioned objects – where the observer's relative altitude will vary from texture element to texture element. Similarly, the optical edge rate will provide increasingly distorted estimates of the speed of self-motion for environments with irregular/random spacing. Thus, if the speed of self-motion is perceived in terms of either of these monocular sources of information, perceptions will be more accurate for ground plane as opposed to cloud optic flow.

⁵The screen was not visible during the experiment, it served as an implicit reference for the observer's ratings of the maximum extent of the display.

Appendix

Potential (dynamic) stereoscopic cues to the speed of self-motion in depth

The following is based on Harris and Watamaniuk's (1995) derivation of stereoscopic cues for the speed of object motion in depth. First I will define the relative horizontal disparity of two texture elements E1 and E2 (δ_{E1E2}) as the difference between the angles they subtend for each eye:

$$\delta_{E1E2} = \delta_{E1} - \delta_{E2} \quad [A1]$$

Where δ_{E1} is the absolute horizontal disparity of E1 and δ_{E2} is the absolute horizontal disparity of E2. The well known equation which approximately relates the relative horizontal disparity δ_{E1E2} (in radians) with the depth difference between E1 and E2 (i.e. $D_{E1} - D_{E2}$) is as follows:

$$\delta_{E1E2} \approx I(D_{E1} - D_{E2}) / D_{E1}^2, \quad [A2]$$

where E1 and E2 are distances D_{E1} and D_{E2} from the observer and I is the interocular distance (see Figure A1). This equation assumes that: (1) D_{E1} and D_{E2} are greater than I; and (2) E1 and E2 are not too far from the median plane of the head. Now if E1 and E2 are a stationary, rigid configuration (i.e. they have a constant depth difference $Z = D_{E1} - D_{E2}$), then as the observer moves towards them, their relative horizontal disparity will increase due to the decreasing viewing distance:

$$d\delta_{E1E2}/dt \approx IZ/d(D_{E1}^2)/dt \quad [A3]$$

In principle, the configuration's rate of changing disparity ($d\delta_{E1E2}/dt$) could be used to calculate the speed of self-motion in depth - the rate of change in the configuration's viewing distance (dD_{E1}/dt) - after being scaled by the depth difference (Z):

$$dD_{E1}/dt \approx [IZ / d\delta_{E1E2}/dt]^{1/2}, \quad [A4]$$

This equation has the additional assumption that $d\delta_{E1E2}/dt$ must be greater than zero (See Figure A2). Equation A4 can also be written in terms of interarray velocity differences (ie the differences in the image velocities of texture elements projected onto two horizontally separated optic arrays), as follows:

$$dD_{E1}/dt \approx [IZ / d(\delta_{E1} - \delta_{E2})/dt]^{1/2}, \quad [A5]$$

$$dD_{E1}/dt \approx [IZ / d((\phi_{1L} - \phi_{2L}) - (\phi_{1R} - \phi_{2R}))/dt]^{1/2}, \quad [A6]$$

$$dD_{E1}/dt \approx [IZ / (d(\phi_{1L} - \phi_{2L})/dt - d(\phi_{1R} - \phi_{2R})/dt)]^{1/2}, \quad [A7]$$

where E1 has the monocular azimuths (ϕ_{1L}, ϕ_{1R}) , and E2 has the monocular azimuths (ϕ_{2L}, ϕ_{2R}) (See Figure A2). If Z is known, equations A4 and A7 could be used to calculate the absolute speed of self-motion in depth. Otherwise, these equations could provide information about changes in the speed of self-motion in depth over time.