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# Perceiving self-motion in depth: the role of stereoscopic motion and changing-size cues

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# Perceiving self-motion in depth: the role of stereoscopic motion and changing-size cues

## Abstract

During self-motions different patterns of optic flow are presented to the left and right eyes. Previous research has, however, focussed mainly on the self-motion information contained in a single pattern of optic flow. The current studies investigated the role that binocular disparity plays in the visual perception of self-motion, showing that the addition of stereoscopic cues to optic flow significantly improves forwards linear vection in central vision. Improvements were also achieved by adding changing-size cues to sparse (but not dense) flow patterns. These findings showed that assumptions in the heading literature that stereoscopic cues only facilitate self-motion when the optic flow has ambiguous depth ordering, do not apply to vection. Rather, it was concluded that both stereoscopic and changing-size cues provide additional motion in depth information which is used in perceiving self-motion.

## Keywords

role, depth, cues, motion, size, self, perceiving, changing, stereoscopic

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# PERCEIVING SELF-MOTION IN DEPTH:

## The role of stereoscopic motion and changing-size cues

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## ABSTRACT

During self-motions different patterns of optic flow are presented to the left and right eyes. Previous research has, however, focussed mainly on the self-motion information contained in a single pattern of optic flow. The current studies investigated the role that binocular disparity plays in the visual perception of self-motion, showing that the addition of stereoscopic cues to optic flow significantly improves forwards linear vection in central vision. Improvements were also achieved by adding changing-size cues to sparse (but not dense) flow patterns. These findings showed that assumptions in the heading literature that stereoscopic cues only facilitate self-motion when the optic flow has ambiguous depth ordering, do not apply to vection. Rather, it was concluded that both stereoscopic and changing-size cues provide additional motion in depth information which is used in perceiving self-motion.

Of all the senses known to be involved in self-motion perception - the vestibular, auditory, somatosensory, proprioceptive and visual systems - vision appears to play the dominant role (Benson, 1990; Howard, 1982). This is demonstrated by the fact that compelling illusions of self-motion can be induced by visual information alone. For example, when subjects are placed in a 'swinging room' - where the walls and ceiling swing back and forth - they soon experience the illusion that they themselves are swaying (Lee & Aronson, 1974; Lee & Lishman, 1975; Lishman & Lee, 1973). Similarly, when subjects are placed inside a 'rotating drum' - a rotating cylinder with a patterned inner wall - they quickly experience an illusion of self-rotation (Brandt, Dichgans & Koenig, 1973; Mach, 1875). These illusions occur because the swinging room and the rotating drum duplicate the visual stimulation that normally occurs during real self-motions.

**INSERT FIGURE 1 ABOUT HERE**

A major visual stimulus for self-motion perception is optic flow or the temporal change in the pattern of light intensities at the moving point of observation (Gibson, 1966; Warren, Morris & Kalish, 1988). Gradients of optical velocity contain several potential sources of information about observer motion through three-dimensional space (Gibson, Olum & Rosenblatt, 1955). There is the perspective change in location of objects in the optic array (which shall be referred to as 'motion perspective') and their optical expansion/contraction (which shall be referred to as 'changing-size')[1].

During self-motions different patterns of optic flow are presented to the left and right eyes (due to the separation of the eyes and their different angles of regard - see Figure 1.). Theorists have, however, generally focussed only on the motion perspective information contained in a single pattern - assuming that this is sufficient to accurately perceive self-motion (eg Gibson, 1950; Gibson, Olum & Rosenblatt, 1955; Gordon, 1965; Heeger & Jepson, 1990; Koenderink, 1990; Koenderink & van Doorn, 1981; 1987; Lee, 1980; Longuet-Higgins & Prazdny, 1980, Nakayama & Loomis, 1974). Accordingly, the role that stereoscopic information plays in self-motion perception has received little attention.

Recently, however, van den Berg and Brenner (1994b) have shown that in some situations, heading perception (one aspect of self-motion perception) can be improved by the addition of stereoscopic cues. Their earlier research had found that heading estimates were error prone in the presence of motion noise, when displays simulated observer motion through a cloud of dots (van den Berg, 1992; van den Berg & Brenner, 1994a). They subsequently discovered that when binocular disparities were added to these 'cloud' displays heading estimates became up to four times more resistant to noise. Changing disparity was not essential for this improved heading performance, as subjects performed just as well when each dot had a fixed retinal disparity for the duration of the display (in this case only motion perspective simulated self-motion in depth). Van den Berg and Brenner concluded that

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[1] This distinction was based on the fact that most computer generated vection stimuli consist of a moving pattern of dots - each dot's size remaining constant regardless of its simulated location in depth. Motion perspective information, as defined above, must therefore be responsible for the illusion of self-motion in these situations. Whether changing-size information can produce a similar effect is yet to be

stereoscopic vision improves heading perception indirectly by providing the depth order of the objects in the flow (rather than by providing additional motion in depth information). Furthermore they argued that other depth cues, such as occlusion or texture gradients, might improve heading judgements in a similar fashion.

There is reason to believe that stereoscopic information might also enhance the subjective experience of self-motion, known as vection. In their study, Andersen and Braunstein (1985) simulated forwards self-motion through a three-dimensional cloud of dots. The perceived 'three-dimensionality' of these displays was manipulated by altering the motion-based cues to self-motion in depth. They found that the more three-dimensional the inducing displays appeared the stronger the self-motion perception in central vision. Although Andersen and Braunstein did not investigate the role of stereoscopic cues on vection, an argument can be mounted on the basis of their data. If it is assumed that adding stereoscopic information to inducing displays makes them appear more three-dimensional, it follows that such displays might produce stronger vection (in central vision) than those with motion perspective alone.

The current experiments investigated whether the addition of stereoscopic information to optic flow would increase forwards linear vection in central vision. They were designed to determine whether any such increases were due to improved depth ordering or to additional motion in depth information. In addition, a further two experiments examined whether another source of motion in depth information (changing-size) could also produce an advantage for vection.

## GENERAL METHOD

### Subjects

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ascertained.

These were students in an introductory psychology course who received course credit for their participation. All had normal or corrected-to-normal vision and had no previous laboratory experience with illusions of self-motion. Different subjects were used in each of the four experiments.

### Visual Displays

All displays simulated forwards self-motion through a cloud of randomly-positioned stationary objects. The objects were either filled-in squares or dots which moved at a constant rate along the z-axis towards the observer (the projection plane and the observer's viewpoint remained fixed). A constant density was maintained by replacing each object as it disappeared from view at the opposite end of space (a simulated distance of 20m). All displays had a frame rate of 60 Hz.

Stereoscopic displays presented horizontally disparate patterns of optic flow to the two eyes. This was achieved by presenting the disparate views in different colours on a single display, which was then viewed through red-cyan anaglyph glasses. To fuse these displays, subjects needed to verge behind the screen. Thus, prior to their presentation, subjects were shown a pair of vertically displaced nonius lines - one red, one cyan - separated by a disparity representing the furthest distance simulated by the display[2] (Mitchell & Ellerbrock, 1955; Hebbard, 1962). They then had to alter their convergence until the nonius targets were aligned, before triggering the stereoscopic display.

Non-stereoscopic displays were of two types. Monocularly-viewed displays presented a single pattern of optic flow to one eye. Binocularly-viewed non-stereoscopic displays presented the same pattern of moving objects to both eyes

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[2] Since nothing else was visible during the nonius displays, this disparity was relative to the screen

(producing slightly different flow patterns due to the different positions of the two eyes). Prior to the monocularly-viewed displays, subjects were told to lower an eye patch over their right eye. Before binocularly-viewed non-stereoscopic displays, subjects were presented with a pair of nonius lines set at zero disparity (since subjects had to verge on the screen to view these displays). After lowering the eye-patch or verging on the screen, subjects then triggered the non-stereoscopic display.

## EXPERIMENT 1

This experiment compared the vection induced by stereoscopic and monocularly-viewed displays simulating self-motion in depth. In the case of stereoscopic displays, vergence was consistent with the presence of three-dimensional, virtual space behind the screen. Non-stereoscopic displays were viewed monocularly to remove any vergence-based flatness information (Richards & Miller, 1969; Gogel & Sturm, 1972).

Both stereoscopic and monocular displays had changing-size as well as motion perspective information about self-motion in depth. Since each display was relatively free of motion noise[3] - unlike those of van den Berg and Brenner - and extra-retinal information accompanied flow due to eye-movements, the depth order should have already been provided by these two monocular cues. That is, objects with larger relative sizes and faster relative velocities should have appeared to be nearer to the observer (Braunstein & Andersen, 1981; Hochberg & Hochberg, 1952). Accordingly,

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border.

[3] It has been argued correctly that the display resolution used might have created a limited amount of motion noise. Heading perception appears quite robust in the presence of moderate amounts of motion noise and only breaks down when substantial individual differences are introduced (van den Berg, 1992). It seems unlikely then that stereoscopic cues improved vection merely by overcoming this small amount of noise.

any stereoscopic advantage could be assumed to be result of additional motion in depth information.

## Method

**Subjects.** Seven male and nine female subjects (aged between 17 and 32 years) participated in the experiment.

**Design.** Three independent variables were examined. (1) *Display type.* Displays were either stereoscopic or non-stereoscopic optic flow patterns. Both stereoscopic and non-stereoscopic displays had motion perspective and changing-size cues consistent with self-motion in depth. Square size ranged from the single pixel size of .07° to 1.2°. (2) *Display speed.* Each display simulated one of three speeds of self-motion: 2.4m/s, 4.8m/s or 7.2m/s. (3) *Display density.* Each display had one of two object densities: 20 or 30 visible objects per eye.

**Apparatus.** Displays were generated on a 486-DX personal computer and presented on a superVGA monitor (with a 1024 H x 768 V pixel resolution). The screen of this monitor subtended a visual angle of 30° H x 24° V when viewed from a chin rest 50cm away. Since self-motion perception has been found to be dominated by the motion of the perceived background (Ohmi, Howard & Landolt, 1987; Ohmi & Howard, 1988; Telford, Spratley & Frost, 1992), inducing displays were presented 20cm behind a large cardboard mask. Kinetic occlusion and stereoscopic (when present) depth cues always indicated that the display was in the background, while the mask was in the foreground. This mask was placed in front of the subject and two large partitions placed on either side to restrict his/her vision. Only the monitor could be seen through a square window at the far end of this black 'viewing booth' (1m wide x 2m deep x 2m high). Subjects wore anaglyph glasses to view all the displays - the lenses of which were red and cyan coloured camera filters. During monocular trials subjects wore an eye-patch under these glasses to ensure that luminance and contrast were constant across viewing conditions.

**Procedure.** Prior to the experiment, subjects were given the Randot stereovision test to ensure that they could perceive static stereoscopic depth (the criterion was a stereoacuity of 20 seconds of arc or better at a distance of 40cm). They were then given practice using the nonius lines to alter their convergence. On completing this practice, they 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 to press the mouse button down when you feel as if you are moving and hold it down as long as the experience continues. If you don't feel as if you are moving then don't press the mouse button" (instructions modified from Andersen & Braunstein, 1985). Subjects were also informed that each display had a fixed duration of 3 minutes and an inter-trial interval of 20s. Further, they were instructed that if they experienced double vision during a display, they were to press any key on the keyboard and this would register that they had trouble with that trial. After two practice trials, the experimental displays were presented in a random order.

## Results and Discussion

Self-motion was reported in 184 of the 192 trials (16 subjects responding to 12 stimuli). Separate repeated measures ANOVAs were performed on the onset and duration data. The means are shown in Figures 2A and 2B. Stereoscopic displays were found to produce significantly faster onsets [$F(1,15) = 9.803$, $p < .007$] and longer durations of vection [$F(1,15) = 18.00$, $p < .0007$] than monocularly-viewed displays. In all displays, the depth order was unambiguously specified by relative size and motion cues. Thus, adding consistent stereoscopic information should not have affected the perceived depth order. However, the changing disparities were providing additional, purely binocular information about each object's motion in depth. So, it appears that the stereoscopic cues were improving vection by providing extra motion in depth information.

**INSERT FIGURE 2 ABOUT HERE**

Overall, faster simulated speeds of self-motion produced faster onsets [F(2,30) = 9.411, p < .0007] and longer durations of vection [F(2,30) = 15.570, p < .0001]. However, it was found that display density did not significantly effect vection onset [F(1,15) = 1.436, p > .05] or duration [F(1,15) = .379, p > .05]. These speed and density findings are consistent with previous studies using time-based measures of self-motion perception (Andersen & Braunstein, 1985; Telford & Frost, 1993).

It is interesting to note the 2-way interaction between display type and display speed for vection onset [F(2,30) = 3.970, p < .03]. As the speed of simulated self-motion increased the magnitude of the stereoscopic advantage decreased. This pattern also appears to be present in duration data - however, in this case, the interaction failed to reach significance [F(2,30) = 1.676, p > .05].

## EXPERIMENT 2

Previous research has shown that the larger the retinal area of motion stimulation the stronger the resulting self-motion perception (Brandt, Dichgans & Koenig, 1973; Held, Dichgans & Bauer, 1975). Similarly, the more moving elements there are in the optic flow the stronger the self-motion perception (Held, Dichgans & Bauer, 1975). Thus, it was possible that the stereoscopic advantage found previously only occurred because weak or impaired self-motion stimuli were used. The current experiment attempted to determine whether the stereoscopic advantage would persist when observers were presented with larger patterns of optic flow with more moving objects (ie more compelling self-motion displays).

In the first experiment, stereoscopic and non-stereoscopic displays involved different viewing conditions - binocular and monocular viewing respectively. It was possible that stereoscopic displays might have induced stronger vection merely because they had binocular viewing. To overcome this potential confound, the vection induced by binocularly-viewed non-stereoscopic flow was also assessed in the present study. This condition merely presented a single pattern of moving objects to both eyes[4]. If present, vergence information about the display's flatness would have been weak given the large viewing distance of 1.5 metres.

Also in the previous experiment, accommodation would have indicated that both stereoscopic and monocularly-viewed displays were two-dimensional, which might have impaired vection in central vision (Andersen & Braunstein, 1985). The effectiveness of accommodation as a cue to depth rapidly diminishes as the distance of an object from the observer increases (Fisher & Ciuffreda, 1988). Accordingly, the current study reduced the potential confound of accommodation by seating subjects at a distance of 1.5 metres from the screen.

## Method

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[4] This should not be confused with a synoptic display, where identical patterns of optic flow are

**Subjects.** Four male and five female subjects (aged between 18 and 47 years) participated in this experiment.

**Design.** Two independent variables were examined. (1) *Viewing Type.* Displays were either viewed binocularly or monocularly. Binocular conditions were either stereoscopic or non-stereoscopic. As in the previous experiment, both stereoscopic and non-stereoscopic displays had motion perspective and changing-size cues consistent with self-motion in depth. Square size ranged from the single pixel size of .12° to 1.5°. (2) *Display Speed.* Each display simulated one of two speeds of self-motion: 2.7m/s and 4m/s. All displays consisted of 50 objects which moved along the z-axis towards the observer.

**Apparatus.** Displays were generated on an IBM 486-DX personal computer and projected onto a white mylar screen (151x113cm) by a Sony VideoGraphic projection TV (with a resolution of 1024 H x 768 V pixels). The screen subtended a visual angle of 54° horizontally and 41° vertically when viewed from a head and chin rest 1.5 metres away. A viewing tube was attached to the head and chin rest which occluded the rest of the room from sight.

**Procedure.** Prior to the experiment, subjects were given the Randot test and practiced using nonius lines to alter their convergence. Since the method of magnitude estimation was used, the first display of each testing session was used to set the modulus for subjects' strength ratings (Stevens, 1957). This standard stimulus, assumed to be the optimal vection display, had stereoscopic depth cues and simulated the fastest speed of self-motion (4m/s). After a period of 70s had elapsed, subjects were asked whether they felt "as if they were moving or stationary". If subjects responded that they were moving, they were told that the strength of their feeling of

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presented to each eye (which potentially provides stereoscopic information that all the objects in the visual field are infinitely distant).

self-motion corresponded to a value of "70" (with zero representing stationary). This number (the modulus) was entered on a barchart which appeared directly after the display timed out. Two practice trials then followed. Prior to the first of these, subjects were told that (1) they have to press the mouse button as soon as they feel as if they are moving; and (2) they have to rate the strength of their feeling of self-motion (with respect to the modulus "70") on the barchart following each trial. The experimental trials were then presented in a random order - each had a duration of 90s and an inter-trial interval of 30s. Following the first testing session, there was a five minute break before the second testing session was run.

## Results and Discussion

As expected the larger, denser inducing stimuli used in this experiment appeared to be more compelling than those used previously. Vection was reported on every trial by all nine subjects. Further, vection onsets were generally much faster than those found in the previous experiment (15.66s compared to 24.08s).

Separate repeated measures ANOVAs were performed on the onset and rating data. Each of the ANOVAs analysed families of planned contrasts and controlled the familywise error rate at .05. The means are shown in Figures 3A and 3B. Stereoscopic displays were found to produce faster vection onsets [$F(1,8) = 8.74$, $p < .05$] and stronger vection ratings [$F(1,8) = 13.49$, $p < .05$] than monocularly-viewed displays. Similarly, stereoscopic displays produced faster onsets [$F(1,8) = 5.45$, $p < .05$] and stronger ratings [$F(1,8) = 19.00$, $p < .05$] than binocularly-viewed non-stereoscopic displays. However, there was no significant difference between onset times for binocularly- and monocularly-viewed non-stereoscopic displays [$F(1,8) = .056$, $p > .05$]. Nor was there any significant difference between the magnitude estimates for these two conditions [$F(1,8) = .015$, $p > .05$]. The above results demonstrate that the stereoscopic advantage is not restricted to weak or impaired self-motion stimuli. Displays which induced compelling illusions of self-motion were still improved by the addition of stereoscopic information. This suggests that the process underlying the stereoscopic advantage is a stable phenomenon.

**INSERT FIGURE 3 ABOUT HERE**

Consistent with the previous experiment, displays simulating faster self-motions were found to produce significantly faster onsets [F(1,8) = 8.508, $p < .05$] and significantly stronger ratings of vection [F(1,8) =35.246, $p < .05$].

Due to the other manipulations performed in this experiment - ie increasing the area of stimulation and the number of moving contrasts - it is difficult to determine the effect of reduced accommodation on self-motion perception. It is possible that the weakening of accommodation-based depth cues helped produce the more compelling self-motion perceptions in this experiment.

## EXPERIMENT 3

The conclusion reached in the previous experiments was that the stereoscopic advantage resulted from the additional motion in depth information provided by the stereoscopic cues. If valid, this suggests that vection might also be improved by other, non-stereoscopic motion in depth cues.

Regan and his colleagues have argued that changing-size and stereoscopic motion stimuli generate signals that converge at the same 'motion in depth stage' of the visual system (Regan & Beverley, 1979; Regan, Beverley & Cynader, 1979). They showed that if a stimulus' changing-size and changing disparity cues indicated opposite directions of motion in depth, it was possible to completely cancel the impression of motion in depth. This finding suggests that adding changing-size cues to optic flow patterns should also lead to faster vection onsets and longer vection durations.

In this experiment, the vection induced by optic flow with changing-size cues to motion in depth was compared to that produced by optic flow without these cues. Both types of display were viewed monocularly and had motion perspective information about depth order and motion in depth. Since the depth order should already be provided by motion perspective (each display was relatively free of motion noise and flow due to eye-movements was accompanied by extra-retinal information), any changing-size advantage could be assumed to be due to additional motion in depth information.

## Method

The equipment and procedure was identical to those of the first experiment with the following exceptions. All displays were non-stereoscopic and viewed monocularly. As a result, subjects were not presented with nonius lines to alter their convergence prior to the experimental displays.

**Subjects.** Ten male and ten female subjects (aged between 18 and 36 years) participated in this experiment.

**Design.** Three independent variables were examined. (1) *Display type.* Displays were optic flow patterns either with or without changing-size cues to motion in depth. In changing-size displays, each object's velocity and total area varied as a function of its simulated location in depth. The objects, filled-in Squares, ranged in size from .06° to 1.21°. In the case of same-size displays, each object's velocity varied as a function of its simulated location in depth, but it's total area remained a constant .12°.

(2) *Display speed.* Each display simulated one of three speeds of self-motion: 2.4m/s, 4.8m/s or 7.2m/s. (3) *Display density.* Each display had one of two object densities: 20 or 30 visible objects per eye.

## Results and Discussion

Self-motion was reported in 223 of the 240 trials (20 subjects responding to 12 stimuli). Separate repeated measures ANOVAs were performed on the onset and duration data. The means are shown in Figures 4A and 4B. Displays with changing-size cues to motion in depth produced significantly faster onsets [$F(1,19) = 13.719$, $p < .002$] and longer durations of vection [$F(1,19) = 21.667$, $p < .0002$] compared to displays without these cues. In all trials, unambiguous depth order information should have been provided by the motion perspective. Thus, it appears that changing-size cues can also increase vection in central vision by providing additional information about each object's motion in depth.

**INSERT FIGURE 4 ABOUT HERE**

There are, however, results which conflict with this argument. A study by Telford and Frost (1993) found that the addition of changing-size cues to optic flow did not increase subjects' perception of self-motion in depth. There are a number of possible explanations for this discrepancy with the current finding. The first is that each subject in the Telford and Frost experiment saw only one of the two depth conditions tested (changing-size or same-size optic flow). This 'between-subjects' design might not have provided a sensitive enough estimate of the effect that changing-size cues have on vection (especially if this effect was small in magnitude). The second is that Telford and Frost used a smaller range of possible sizes (.15°-.45° compared to .06°-

1.21°). Finally, it is possible that their null finding reflects a ceiling effect. The larger number of moving objects in their displays (500 as opposed to the 20 or 30 objects used here) might have produced optimal vection when only motion perspective information was present.

Unlike previous studies, display speed did not have an overall effect on vection onset [F(2,38) = 1.443, p > .05] or duration [F(2,38) = 3.035, p > .05]. However, there was a significant effect of display density on vection onset. Denser, 30-object displays produced significantly faster vection onsets than the sparser, 20-object displays [F(1,19) = 6.3435, p < .02]. This suggests that display density might have been the critical difference between the current findings and those of Telford and Frost.

## EXPERIMENT 4

This experiment explored one of the possible causes of the discrepant findings of Telford and Frost (1993). It reinvestigated the effect of changing-size cues on vection using denser patterns of optic flow than experiment 3 (50 or 100 objects). All displays were viewed monocularly and had motion perspective information consistent with self-motion in depth.

### Method

The design, equipment and procedure were identical to those in the previous experiment, with the exception that two higher object densities were used (50 or 100 objects as opposed to 20 or 30 objects). The maximum density of 100 objects (400 less than in Telford and Frost's experiment) was chosen to maintain the frame rate at 60Hz (the same frame rate used for the displays in experiments 1-3).

**Subjects.** Ten male and eleven female subjects (aged between 17 and 29 years) participated in this experiment.

### Results and Discussion

Self-motion was reported in 243 of the 252 trials (21 subjects responding to 12 stimuli). Separate repeated measures ANOVAs were performed on the onset and duration data. The means are shown in Figures 5A and 5B. For the denser displays used in this experiment, the addition of changing-size cues to motion in depth did not produce significantly faster vection onsets [$F(1,20) = 3.5273$, $p > .05$]. Nor, did these cues lead to significantly longer vection durations [$F(1,20) = .015$, $p > .05$.]. The fact that the changing-size advantage, found in the previous experiment, was eliminated by increasing the display density suggests that changing-size cues have a less robust effect on vection than stereoscopic information (since stereo still improved the vection induced by very compelling self-motion stimuli in experiment 2).

**INSERT FIGURE 5 ABOUT HERE**

It is also of interest to note that display density did not have a significant effect on vection in this experiment. 100-object displays did not produce significantly different vection onsets [$F(1,20) = .278$, $p > .05$] or vection durations [$F(1,20) = .463$, $p > .05$] compared to 50-object displays. Thus, if a ceiling effect was responsible for the decreased effectiveness of changing-size cues, then vection was at maximal levels for 50-object displays.

One resolution of the findings of these two experiments, may be that sparse optic flow is analysed in a different (but not necessarily less effective) manner to dense flow. Since sparse flow has fewer moving elements than dense flow, its motion perspective information about self-motion is often weaker/less reliable. So it would be adaptive, in the case of sparse flow, for the visual system to extract all the available information about self-motion (to compensate for the less reliable motion perspective). This may account for the changing-size advantage found for sparse flow in experiment 3. In the case of dense flow, however, motion perspective information may be sufficient to determine the nature of self-motion. In such a situation (eg experiment 4), it is possible that only motion-based information about self-motion is extracted.

A related possibility, suggested by one reviewer, is that with higher density same-size displays, dots in certain proximity might have been perceived as a configuration (ie the vertices of an invisible object). This would also explain the equivalent vection induced by the high density same-size and changing-size displays used in the current experiment - since both would contain similar optical expansion information.

One potential criticism of this experiment is that the denser displays used would have led to an increased probability of objects overlapping. Without differences in colour and contrast, these objects would appear to merge (as opposed to one occluding the other) and this might have impaired (albeit briefly) relative depth perception. There are several counters to this criticism. Firstly, such overlaps were rare even for the densest displays (which had a 1/5 of the dots used in the Telford and Frost study). Secondly, this account would predict that 100-object displays should produce a greater number of overlaps, and thus weaker self-motion perception, than 50-object displays. This prediction was not, however, supported by the data.

## GENERAL DISCUSSION

It is possible that, in the case of heading perception, stereoscopic depth cues are only useful for disambiguating impaired self-motion information (ie optic flow patterns complicated by head- or eye- movements). In such situations, stereoscopic information could be used to provide the depth order of objects in these flow patterns. Van den Berg and Brenner argue that depth order is important in heading perception because the most distant points in the flow provide the most reliable estimates of head- and eye- rotations. Using such estimates, flow components due to head- or eye- movements can be subtracted, leaving optic flow based solely on self-motion. The focus of expansion of this untainted flow can then be used to determine the direction of self-motion.

In the case of self-motion perception, however, stereoscopic information appears to play an additional role. In experiment 1, where depth order was already unambiguously provided by relative size and motion, vection was still improved by the addition of stereoscopic motion cues. It appears that this 'stereoscopic advantage' was due to the extra, purely binocular information about motion in depth.

Changing-size cues to motion in depth were also found to increase perceptions of self-motion in depth. In experiment 3, where depth order should have been unambiguously provided by motion perspective, the addition of changing-size cues further improved vection. These findings sit well with the idea that changing-size and stereoscopic motion channels converge at the same 'motion in depth stage' of the visual system (Regan & Beverley, 1979; Regan, Beverley & Cynader, 1979).

It appears then that accounts based solely on monocular motion perspective are incomplete. Stereoscopic and changing-size cues provide additional motion in depth information which is used in perceiving self-motion. This motion in depth information might improve vection directly by providing more accurate estimates of heading and egospeed. Alternatively, the improvement might be achieved indirectly by making self-motion displays appear more three-dimensional -stereoscopic and changing-size cues might produce an apparent expansion of the depth axis. Since the subjects were travelling through virtual space, the larger the perceived extent of that space, the greater the perceived change in location per unit of time, and thus the stronger the self-motion perception.

Of these two explanations, the 'direct' account has the least empirical support. In many conditions, heading estimates based on motion alone are very precise, leaving little room for improvement by stereoscopic or changing-size cues (eg Warren & Hannon, 1988). Similarly, Monen and Brenner (1994) have found that subjects are actually worse at detecting simulated changes in ego-velocity when stereoscopic information is available. However, the latter is not strong evidence against the 'direct' account, since a fair test should produce at worst equal performance in stereoscopic and control conditions.

Although the effects of stereoscopic and changing-size based information on vection were similar, the stereoscopic advantage appeared to be more robust than that produced by changing-size. Experiment 2 showed that the vection induced by compelling self-motion displays was still improved by the addition of stereoscopic information. However, changing-size cues were not always effective in improving vection. In experiment 4, which used dense displays, the addition of changing-size cues was found to have no effect on vection.

What might underlie the differences between these two advantages? One possibility is that the link between stereoscopic motion and motion perspective is stronger than the link between changing-size and motion perspective. This explanation rests on two assumptions. The first being that stereoscopic motion is encoded as the different relative velocities of an object in each eye rather than its changing binocular disparity (Regan, Beverley & Cynader, 1979b). The second being that motion perspective is encoded as the relative velocities of different objects in the environment. If both cues are encoded on the basis of relative velocity, it seems likely that they might be processed in a similar manner. Thus, if motion perspective information is preferred in optimal stimulus conditions, it might be more difficult to disregard stereoscopic motion cues compared to changing-size.

The alternative explanation is that the display characteristics might have favoured motion in depth perception based on stereoscopic motion. Regan and his colleagues have shown that changing disparity produces more effective motion in depth perception than changing-size for fast moving objects observed for a reasonable period of time (eg 1s - Regan & Beverley, 1979). The reverse was found for briefly glimpsed, slow moving objects. Thus, the fast display speeds and long observation times used in the present experiments, might have led to the more compelling stereoscopic perceptions of self-motion in depth.

Finally, the current research has shown that the addition of consistent stereoscopic motion and changing-size cues can improve vection in central vision. These results further highlight the differences between central and peripheral self-motion perception. Previous research suggests that central vision is specialised for the perception of self-motion in depth, whereas peripheral vision has no such specialisation (Andersen and Braunstein, 1985; Stoffregen, 1985; Telford & Frost, 1993). Since central vision is stereoscopic, it seems ideally suited for this specialised role. It is possible that stereopsis may have even played a role in the evolution of the central-peripheral differences in self-motion perception.

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## AUTHOR NOTE

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## FOOTNOTES

[1] This distinction was based on the fact that most computer generated vection stimuli consist of a moving pattern of dots - each dot's size remaining constant regardless of its simulated location in depth. Motion perspective information, as defined above, must therefore be responsible for the illusion of self-motion in these situations. Whether changing-size information can produce a similar effect is yet to be ascertained.

[2] Since nothing else was visible during the nonius displays, this disparity was relative to the screen border.

[3] It has been argued correctly that the display resolution used might have created a limited amount of motion noise. Heading perception appears quite robust in the presence of moderate amounts of motion noise and only breaks down when substantial individual differences are introduced (van den Berg, 1992). It seems unlikely then that stereoscopic cues improved vection merely by overcoming this small amount of noise.

[4] This should not be confused with a synoptic display, where identical patterns of optic flow are presented to each eye (which potentially provides stereoscopic information that all the objects in the visual field are infinitely distant).

## FIGURE CAPTIONS

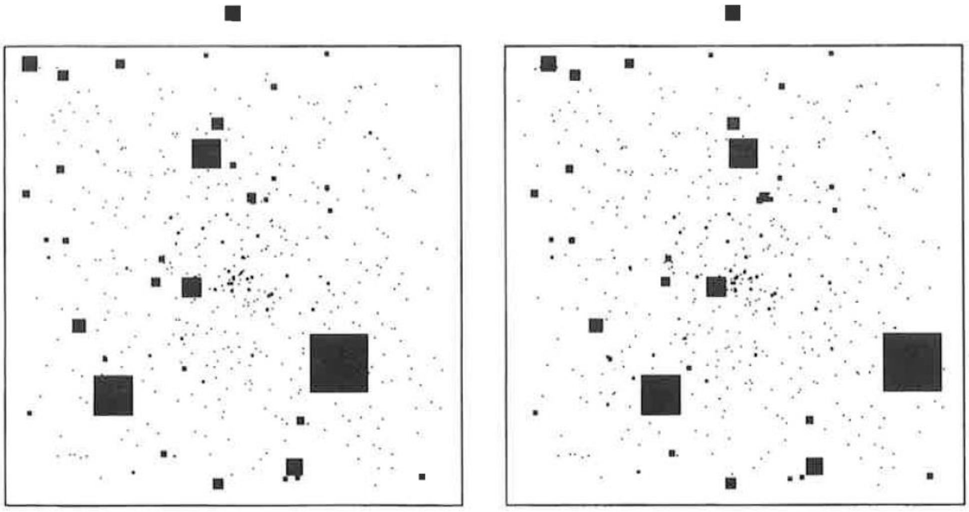

**Figure 1.** A stereogram representing the different optic arrays presented to the left and right eyes at any one point in time (Converge in order to fuse the two images).

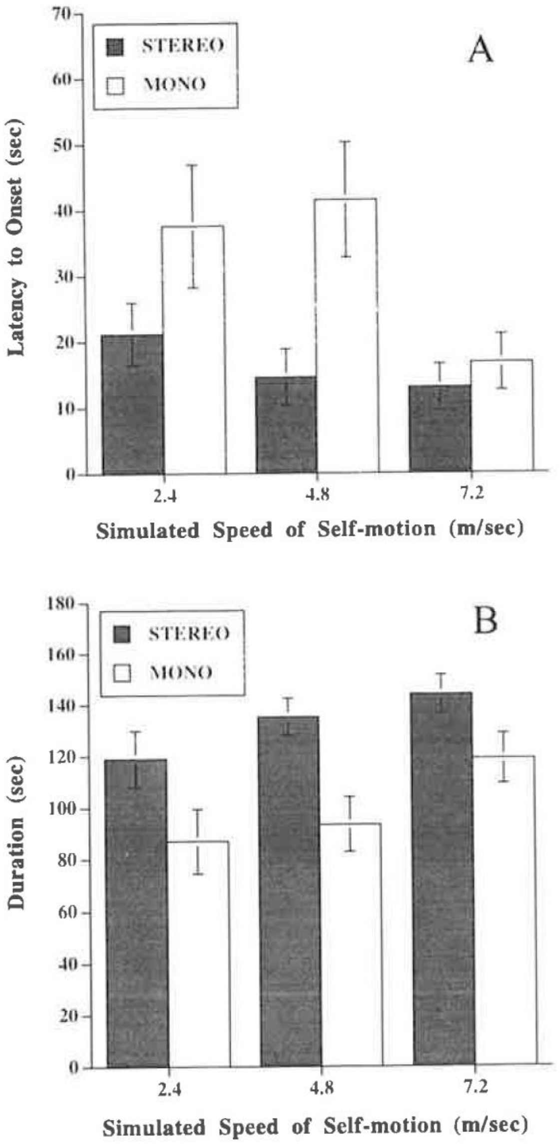

**Figure 2.** The effect of display speed on (A) vection onsets and (B) durations for stereoscopic (Stereo) and non-stereoscopic (Mono) displays (Experiment 1). Error bars represent standard errors of the means.

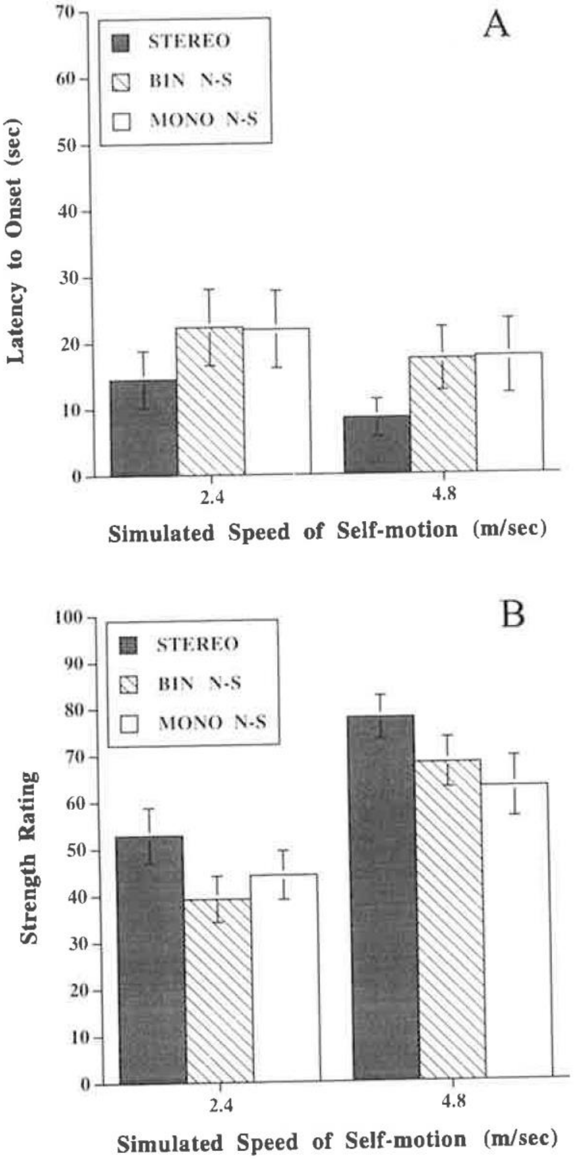

**Figure 3.** The effect of display speed on (A) vection onsets and (B) ratings of vection strength for stereoscopic and non-stereoscopic displays (Experiment 2). Non-stereoscopic displays were viewed either binocularly (Bin N-S) or monocularly (Mono N-S). Error bars represent standard errors of the means.

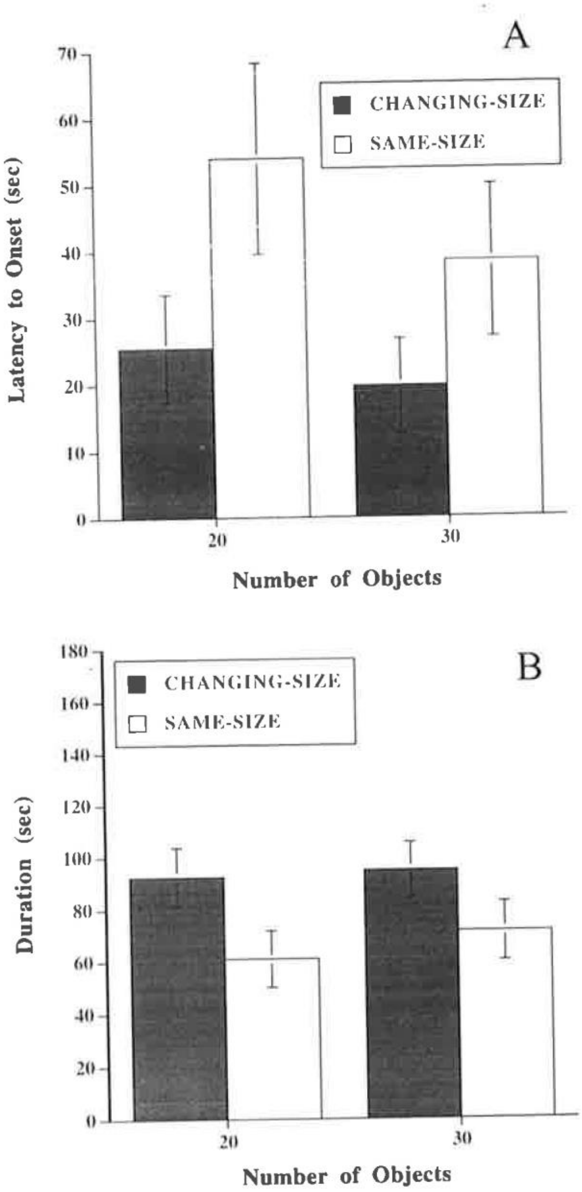

**Figure 4.** The effect of object density on the (A) vection onsets and (B) durations for displays with and without changing-size cues to motion in depth (Experiment 3). Error bars represent standard errors of the means.

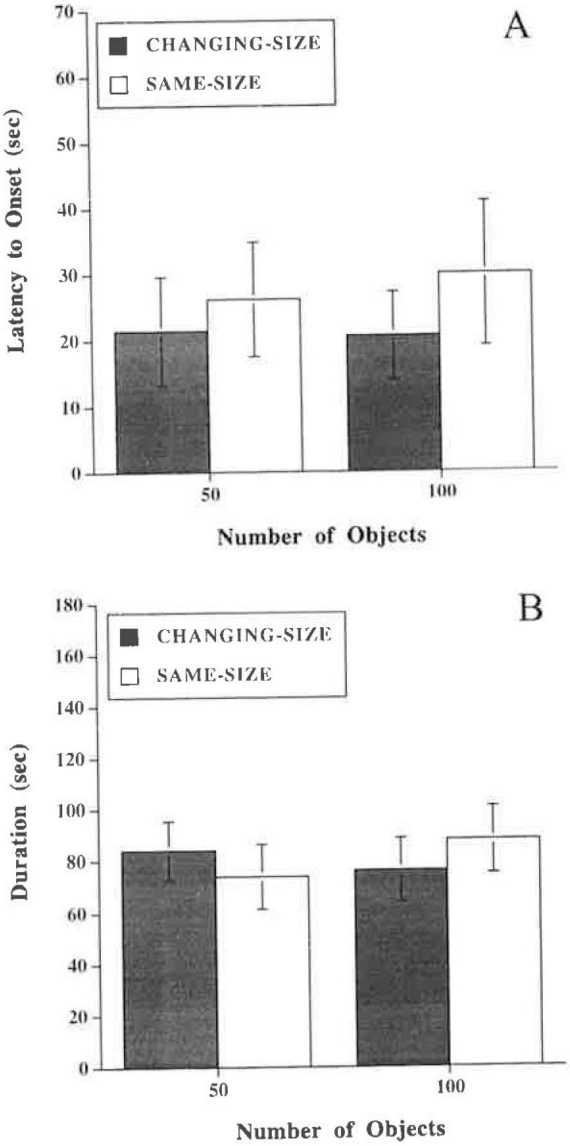

**Figure 5.** The effect of object density on the (A) vection onsets and (B) durations for displays with and without changing-size cues to motion in depth (Experiment 4). Error bars represent standard errors of the means.