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Humans can use optic flow to estimate distance of travel

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Abstract

We demonstrate that humans can use optic flow to estimate distance travelled when appropriate scaling information is provided. Eleven subjects were presented with visual targets in a virtual corridor. They were then provided with optic flow compatible with movement along the corridor and asked to indicate when they had reached the previously presented target position. Performance depended on the movement profile: for accelerations above 0.1 m/s^2 performance was accurate. Slower optic-flow acceleration resulted in an overestimation of motion which was most pronounced for constant velocity motion when the overestimation reached 170%. The results are discussed in terms of the usual synergy between multiple sensory cues to motion and the factors that might contribute to such a pronounced miscalibration between optic flow and the resulting perception of motion. © 2001 Elsevier Science Ltd. All rights reserved.

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1. Introduction

During forward self-motion, the movement of the images of objects in the environment creates a complex pattern of optic flow on the retina. This pattern of optic flow contains information about the amplitude and direction of the linear and rotational components of the self motion that created the flow (Harris, 1994; Lappe et al., 2000). Directional information about the translational component of the motion, often referred to as 'heading' after Gibson (1950), can be extracted and disentangled from confounding motion that might come from eye-in-head motion rather than motion of the whole person (Warren & Hannon, 1990; Royden, Banks, & Crowell, 1992; Stone & Perrone, 1997). Although the magnitude of the translational component of self motion is also present in the flow field, extracting it in the presence of rotational components is not trivial (Longuet-Higgins & Prazdny, 1980). Even after the translational components have been isolated from any rotational components, the motion of each point on the retina resulting from the translation depends both on the relative position of the object and observer, and also on the observer's own motion profile (Harris, 1994). Unless one of these is known, the motion signalled by the flow is ambiguous and could correspond to movement at interstellar speeds through a distant star field or at a walking pace down a corridor. To compare two motions (Bremmer & Lappe, 1999) or even to control some aspects of locomotion (Sun, Carey, & Goodale, 1992) this ambiguity does not matter, but to navigate effectively it is necessary to know distances relative to a fixed landmark. If a scale is provided from which relative positions can be determined, then the magnitude of the motion signalled by optic flow can theoretically be calculated. Despite the potential complications in using optic flow to deduce self-displacement, it has recently been shown that honeybees can use optic flow to judge flown distances (Srinivasan, Zhang, Lehrer, & Collett, 1996; Srinivasan, Zang, & Bidwell, 1997; Srinivasan, Zhang, Altwein, & Tautz, 2000). Can humans also estimate the distance

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they have moved using information derived from optic flow cues alone?

When optic flow occurs alone in the absence of other sensory cues to motion, it can evoke postural adjustments (van Asten, Gielen, & Denier van der Gon, 1988; Redfern & Furman, 1994) and the illusory perception of actual self-motion rather than the sensation of watching a moving world. This illusory sensation of motion is called 'vection' and has associated perceptions of displacement and speed (Previc, 1992; Howard & Howard, 1994). Vection is thus an existence proof that displacement information can be inferred from optic flow. Surprisingly, we were unable to find any studies that have quantified the magnitude of linear vection. We therefore developed a method for measuring the magnitude of vection and systematically explored the effect of optic flow velocity and acceleration on the perceived distance of motion.

2. Methods

2.1. Subjects

Eleven subjects (20–45 years old) participated in these experiments: nine (five females) for the constant velocity profiles and 11 (six females) for the constant acceleration profiles. All experiments abided by York University Policies for the Ethics Review Process for Research Involving Human Participants.

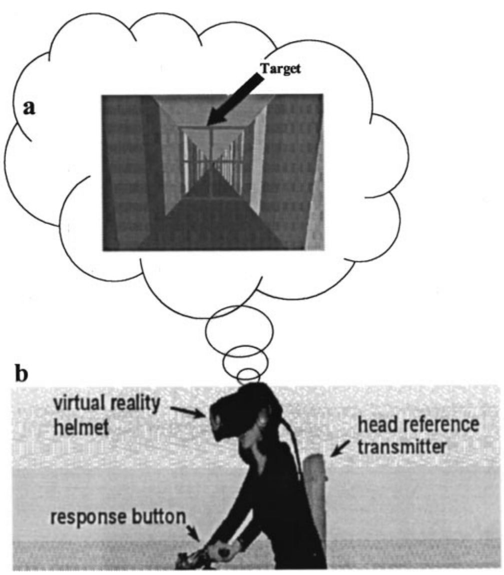

Fig. 1. The experimental arrangement. Subjects wore a virtual reality helmet (b) in which they viewed a simulated corridor (a). Also seen in the corridor is the target whose distance subjects had to match with their optic-flow induced motion.

2.2. Visual display

All experiments were performed using a virtual display presented in a head mounted display. Visual optic flow cues were generated by a SGI 02 computer and were presented on a single-view helmet mounted display (Liquid Image MRG field: 84° × 65°, resolution: 720 pixels × 240 pixels; video refresh rate: 60 Hz). The visual display simulated a three-dimensional corridor based on the dimensions of a typical corridor at York University (width = 2 m, height = 2.5 m and length = 50 m; Fig. 1(a)). Our subjects were all very familiar with the corridors on which our simulation was based and reported a strong, clear impression of size. Subjects were encouraged to obtain further scaling cues by moving their heads to obtain parallax and perspective cues. The display was the same in the two eyes: disparity cues were not simulated. The display was rendered using SGI's OpenGL library. The virtual world consisted of a small number of polygons and was not anti-aliased. Display imagery was updated at 20–25 Hz. The dark centre of the corridor reduced the possibility that significant aliasing effects occurred. The walls of the corridor were painted with vertical stripes (0.5 m wide) that changed colour on a random cycle at approximately 0.5 Hz during visual-motion trials. The changing colours of the bars discouraged subjects from tracking a particular bar on the wall near the target as a strategy to determine when they had reached a previously presented visual target. The effectiveness of this strategy was verified anecdotally by the authors by trying to disregard instructions and follow the bars. Following the bars was difficult at slow speeds and at higher speeds was impossible. A 6°-of-freedom head tracker monitored the position of the helmet (Flock of Birds range ± 4 feet; resolution: 0.07″ & 0.5°, sampling at 144 Hz). The computer updated the visual display so that when subjects wearing the helmet rotated or translated their heads, the view of the corridor shifted as it would if they were viewing a real corridor thus providing an immersive experience. The helmet was equipped with earphones through which subjects received pre-programmed audio instructions.

2.3. Calibration of the virtual visual world

Visually presented distances and sizes in the virtual world were carefully calibrated to the real world by having subjects view a simulated target at a specified distance in the virtual corridor (Fig. 1(a)). A real physical target of equal dimensions ($w = 2$ m, $h = 2.5$ m) was then placed at the same distance in front of the subject in the real world. The subject removed the helmet and reported whether the virtual target appeared the same distance away as the real target. The simulated focal length of the virtual reality display was

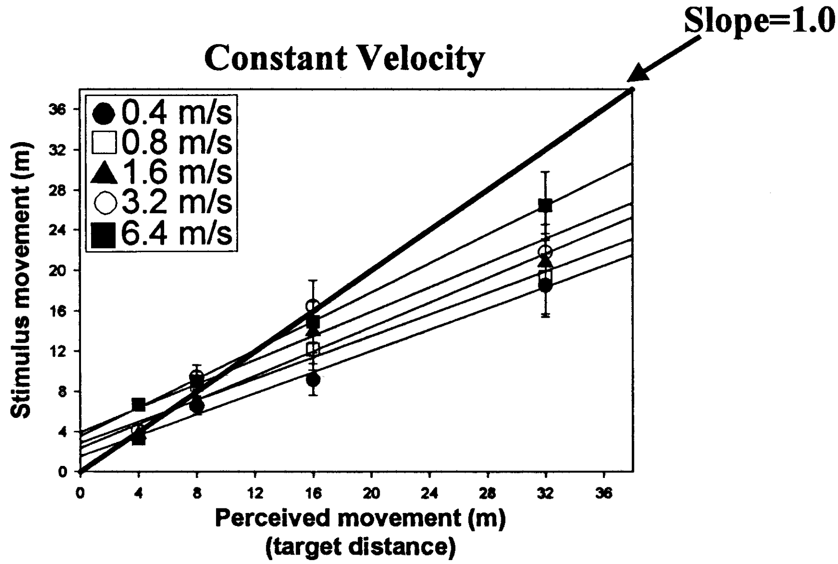

Fig. 2. The magnitude of perceived self motion evoked by optic flow simulating constant velocity motion. Each data point represents the average and standard error of nine subjects. The vertical axis represents the actual motion simulated by the optic flow, the horizontal axis represents the corresponding perceived movement. Since the 'perceived movement' corresponds to the target distance, it is the 'stimulus movement' that is the dependent variable. Linear regression lines are fitted for each velocity. A slope of 1.0 indicates accurate performance.

adjusted in software until the real and simulated targets matched.

2.4. Experimental procedure

To measure how far subjects thought they had travelled in response to optic flow alone we provided them with a visual distance to remember and then had them report when they thought they had moved through that distance. Before starting the experiment proper, subjects were given nine demonstration trials to familiarise them with the targets and with the task of judging target distances. They were also exposed to the different visual stimuli used in the subsequent experiments. During the trials subjects reported convincing vection. In both the demonstration and the experimental trials, no feedback about performance was provided. Subjects were instructed to move their heads around and from side to side to experience the immersive environment and to obtain parallax cues about the dimensions of the display and the target distance. This was a full, active virtual reality display so that subjects could rotate or translate their heads with appropriate perspective and view changes in the display.

A green line was drawn across the floor of the corridor at the subject's initial position as a reference mark. At the onset of each experimental trial, when the target appeared at a distance down the stationary corridor, subjects were encouraged to assess the distance to the target for at least 5 s. When they were ready, the subjects pushed a button, which caused the target to disappear and visual motion to commence. Simulated motion was in a straight line along the centre of the corridor. The subjects' task was simply to press the button when they felt they had reached the location previously occupied by the visual target. Visual motion was either at constant velocity (0.4, 0.8, 1.6, 3.2, or 6.4 m/s) or at constant acceleration (0.025, 0.05, 0.1, 0.2, 0.4, 0.8 and 1.6 m/s^2). All trials started from stationary. Constant velocity trials had an initial pulse of acceleration (change of velocity from zero to the experimental level) and constant acceleration trials had an initial pulse of jerk (change of acceleration from zero to the experimental level). Targets were presented at 4, 8, 16 or 32 m. Trials were presented in a random order.

2.5. Data analysis

Subjects' perceived motion corresponded to the perceived target distance, since they perceived they had travelled through the target distance when they pressed the button. This could then be compared with the actual amount of optical motion that they had experienced. We describe the ratio of the perceived movement to the stimulus movement as the 'perceptual gain'. Perceptual gain was measured from the slope of a regression fit to a plot of perceived versus actual motion (Figs. 2 and 3). A perceptual gain of unity was obtained if subjects moved to a position where the point on the wall that previously aligned with the target was now aligned with them. If subjects needed to pass by more stripes to achieve the perception of having passed through the target distance, this indicated a low perceptual gain (<1): if less stripe movement was required this indicated a higher perceptual gain (>1). Reliable comparisons between the data collected with

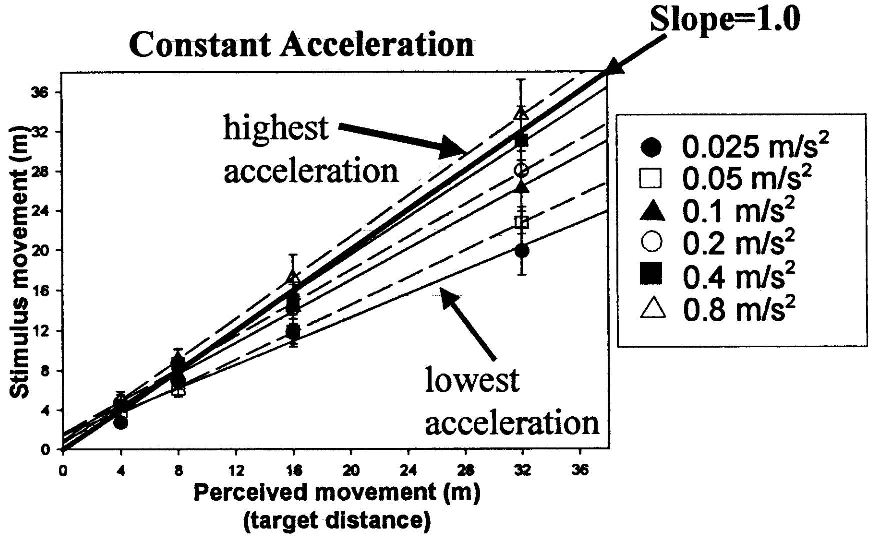

Fig. 3. The magnitude of the perceived self motion evoked by optic flow simulating constant acceleration motion. Format as for Fig. 2. Each data point represents the average and standard error of eleven subjects. Each condition was run only once by each subject (average standard error = 0.5, 0.8, 1.4 and 2.9 m for target distances of 4, 8, 16 and 32 m, respectively). There was a systematic variation with acceleration with lower accelerations having the highest perceptual gain (perceived motion/actual motion), i.e. shallowest slopes.

different accelerations and velocities were possible because the target distances were the same in each case and completely independent of the test motion.

3. Results

When the optic flow simulated linear forward motion at a constant velocity, subjects consistently pushed the button to indicate they had arrived at the target position after having travelled through only 60% of the target distance. This premature response indicated an overestimation of their self motion and yielded an average perceptual gain (perceived/actual distance; see Section 2) of 1.7 ± 0.07 (Fig. 2). Over the range of simulated velocities (0.4–6.4 m/s) there were no significant differences between the slopes ($F(4,162) = 1.09$ $P = 0.36$) or intercepts ($F(4,162) = 0.53$; $P = 0.71$).

When the optic flow simulated linear forward motion at a constant acceleration, the perceptual gain varied systematically with acceleration (Fig. 3). An ANOVA indicated a significant effect of target distance on the actual amount of movement required ($F(5,150) = 130.88$ $P < 0.001$), a significant effect of acceleration ($F(5,150) = 6.648$ $P < 0.001$) and a significant interaction between acceleration and distance ($F(15,150) = 1.93$ $P < 0.05$). The slopes of the linear regressions for the six accelerations (0.025–0.8 m/s^2) were significantly different from each other ($F(5, 242) = 4.63$; $P < 0.0005$). There were no significant differences between the intercepts ($F(5, 242) = 0.08$; $P = 0.99$). At the lowest acceleration used (0.025 m/s^2), the perceptual gain was 1.7. This was the same as the average value obtained using constant velocity.

Slowly accelerating optic flow seemed to be too powerful a cue to motion, creating an impression of excessive displacement. At accelerations > 0.2 m/s^2, the perceptual gain was unity. Fig. 4 plots the perceptual gain as a function of acceleration showing a regular,

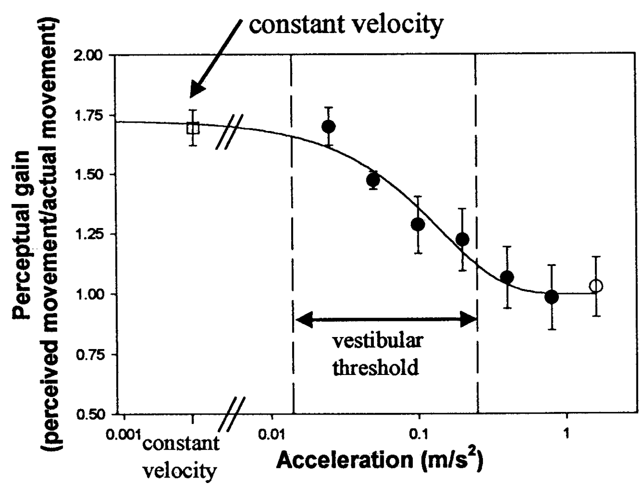

Fig. 4. Perceptual gain (perceived distance/actual distance; see Section 2) varied systematically with acceleration. Each data point (closed circles: ●) represents the mean and standard error of eleven subjects. Also shown is the perceptual gain at zero acceleration (constant velocity, open square: □). This point is the average of all the constant velocity trials, since there was no change in perceptual gain with velocity (Fig. 2). The perceptual gain for the acceleration of 1.6 m/s^2 was obtained separately with an additional six subjects (open circle: ○). There is a smooth sigmoidal transition between overestimation at low accelerations and accurate performance at higher accelerations. The region labelled 'vestibular threshold' represents the range of accelerations reported in the literature to correspond to vestibular thresholds (see text).

sigmoidal transition between these levels (Fig. 4). These data could not reflect a temporal bias to press before the target was reached since then the effect would then not decrease as acceleration increased. Unlike the perception of walking, whose accuracy varies with the distance walked (Loomis et al., 1993), the perceptual gain evoked by optic flow was constant for a given movement profile over the range of distances we tested.

4. Discussion

These experiments demonstrate that humans are able to use optic flow cues alone to estimate the distance they have travelled. Furthermore, there are systematic errors in the estimation of self displacement from optic flow that depend on the particular motion profile (Fig. 4).

There are two main features of our data. These features can best be described in terms of variation in the perceptual gain with motion profile. The perceptual gain describes the relationship between a given motion profile and the perceptual movement associated with it and is defined as the ratio of the perceived motion to the actual motion. Thus a high perceptual gain corresponds to subjects perceiving they have gone further than the actual motion, and a low perceptual gain corresponds to less sensation of motion. The two features of our data are that firstly, lower accelerations (<0.1 m/s^2) and constant velocity (0.4–6.4 m/s) motion profiles are associated with higher perceptual gains than higher accelerations (>0.1 m/s^2). This is illustrated by the shape of the curve in Fig. 4 which forms a sigmoid between the higher and lower gains as a function of acceleration. Secondly, lower accelerations (<0.1 m/s^2) are associated with perceptual gains greater than 1 whereas higher accelerations are associated with accurate judgements, that is a perceptual gain of close to unity. This is illustrated by the position of the curve of Fig. 4 on the vertical scale. The former effect indicates a variation in the effectiveness of visual optic flow cues as a function of acceleration of self motion, the latter indicates a miscalibration between actual and perceived motion.

4.1. Changes in visual perceptual gain as a function of acceleration

The variation in perceptual gain with acceleration cannot be explained as a general distortion of space within the virtual reality display. The target distances were the same for all motion profiles and yet led to different perceptual judgements. Therefore the effects must be due to the optic flow itself. All the constant velocity trials were associated with similar perceptual gains which were statistically independent of velocity over the range tested (0.4–6.4 m/s). While it remains possible that motion noise, such as jerkiness introduced by pixelation, might affect perceived motion (Troscianko & Fahle, 1988; Treue, Snowden, & Andersen, 1993; but see Zanker & Braddick, 1999), the consistency across all speeds shown in our constant velocity data suggests that our results for low acceleration movement are unlikely to be explained by such inadequacies of the display. The results are consistent with a variation in the processing of optic flow that depends on the self motion profile.

In our experiments, subjects were deprived not only of non-optic-flow visual cues to their motion, but also of vestibular, somatosensory and proprioceptive cues that would normally provide complementary information. For example, the otolith division of the vestibular system, the inner-ear organs stimulated by physical linear acceleration, normally plays a major role in humans' perception of self-motion, providing the movement has accelerations above vestibular threshold (Benson, Spencer, & Scott, 1986; Israel & Berthoz, 1989; Berthoz, Israel, Georges-Francois, Grasso, & Tsuzuku, 1995). For whole-body linear acceleration, the vestibular threshold seems to be around 0.1 m/s^2 (although studies have reported values ranging from 0.014 to 0.25 m/s^2; Gundry, 1978). This acceleration range corresponds to the range of optic flow accelerations associated with the transition between high and low perceptual gains (Fig. 4).

Thus higher visual perceptual gains are associated with accelerations that would normally not be accompanied by other cues, especially vestibular cues. The higher gains means that more emphasis is placed on visual information when other information is scarce and that the visual contribution is toned down or given lower weighting when other information is also available (as it is for other aspects of perception, e.g. Landy, Maloney, Johnston, & Young, 1995). The only problem with this apparently logical argument is that optic flow seems to be too effective at evoking a sensation of self motion. Visual perceptual gains are often too large, with constant velocity motion being associated with a perception of moving $1.7\times$ faster than the stimulus motion! Reducing the perceptual gain to unity hardly represents giving vision a lower weighting that allows other senses to contribute. Why might this be?

4.2. Miscalibration between actual and perceived motion

It was a somewhat unexpected result that subjects 'overestimated' their self-motion for simulated motions of constant velocity and low accelerations. However, a similar overestimation of motion has also been found when subjects are exposed to only vestibular cues during slow acceleration movement in the dark (Harris, Jenkin, & Zikovitz, 2000a,b). Furthermore, when judging time to contact for large objects under monocular conditions, contact is often expected too early (Gray & Regan, 1998; Regan & Gray, 2000).

The high perceptual gain for low acceleration and constant velocity movement cannot be explained in terms of a spatial distortion due to the virtual reality display since this would affect the perceived target distances for all movement profiles. However, the positioning of the graph of Fig. 4 on the vertical axis might result from the specifics of the environment that we used.

Our visual display was quite impoverished. The spatial resolution was poor with pixels subtending about 0.3° and the field was of limited extent. There were no binocular or stereoscopic cues to the structure of the world and accommodation was fixed optically. It seems counter-intuitive that a paucity of visual cues might enhance our subjects' sensation of self motion. However it remains possible that providing binocular optic flow, for example, might affect perceptual judgements. The structure of our display was a simple 2m-wide corridor with no texture on the floor or ceiling. These dimensions mean that subjects were less than 1m (orthogonally) from each of the walls. It is well known anecdotally that riding in a low-slung vehicle or travelling along a narrow tunnel, can enhance the sensation of speed of motion. The high perceptual gains experienced by our subjects might be related to this observation. Drs Harris and Jenkin are currently engaged in an extensive research programme to explore how enriching and varying the environment in various ways might affect the perception of self motion.

4.3. Implications

Overestimation of motion can occur under conditions in which we can expect to have only a single sensory cue available to estimate distance of travel. This was found both for optic flow stimuli in the present paper and for physical motion in the dark in a parallel study (Harris, Jenkin, & Zikovitz, 2000a,b). Overestimation might represent a built-in safety mechanism that instils caution under sensorially impoverished conditions. Thinking that a given distance has been traversed before it actually has been, reduces the chances of colliding with obstacles. In contrast, under conditions where we normally expect to have multiple systems providing mutually complementary estimates of the magnitude of self motion, we perform more accurately. The variation of perceptual gain with acceleration (Fig. 4) seems to represent a transition between these two strategies as subjects' perceptual gain goes from 1.7 (overestimation) to 1.0 (accurate). Our finding that optic flow gives a consistent sensation of self displacement means that navigation is possible using visual cues alone. However the systematic errors we have found for low acceleration motion profiles implies that we can only rely upon optic flow for navigation when the visual cues are strong.

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