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RESEARCH ARTICLE

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The importance of perceived relative motion in the control of posture

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Abstract Two experiments investigated the role of optic flow in controlling posture. Both experiments measured postural sway in two virtual environments with different 3-D structure but the same optic flow. Observers attempted to maintain balance on one foot while viewing an object that appeared either rigid with respect to the environment or that appeared to move concomitantly with head movements. The apparent object motion concomitant with head motion was achieved by changing the perceived, but not physical, depth of the object. For both objects, the optic flow information was the same and only depth information was varied. Observers showed a decrease in stability (as measured by head sway) when viewing the object that appeared to move, suggesting that perceived relative motion, not optic flow, signals self-motion to the postural control system.

Keywords Posture · Vision · Human · Balance · Optic flow

Introduction

The significant role of vision in controlling posture (balance) is most easily demonstrated by simply closing one's eyes. Standing with eyes closed elicits two to three times more natural body sway than with eyes open (Begbie 1967; Diener et al. 1984; Edwards 1946; Paulus et al. 1984; Witkin and Wapner 1950). Additionally, perturbing the visual environment causes direction-specific perturbations in posture, showing the causal role of vision in maintaining balance (Warren et al. 1996). In a classic paradigm, sinusoidal motion of the visual environment causes a similar sinusoidal postural response at the driving frequency (Lee and Lishman 1975; Schöner 1991; Van Asten et al. 1988; Warren 1998; Warren et al. 1996). One interpretation is that observers adjust their posture to minimize the optic flow. Optic flow refers to the changing optic array, or the changing angular positions of points in the environment. Models based on optic flow do not require observers to have knowledge of distances to these points in the environment, as optic flow information is explicitly defined in the retinal image.

Some research using perturbed visual environments suggests that optic flow does not fully account for visually-controlled posture. Dijkstra et al. (1994) measured postural responses to an oscillating frontoparallel wall at multiple distances from a standing observer. As the distance increased from 25 to 200 cm, the optical expansion rate of the scene decreased by approximately 70%. The gain of the postural response, however, dropped by a mere 20%, suggesting that observers were adjusting their posture based on the distal motion of the 3-D environment rather than the proximal motion of the changing optic array (see also Dijkstra et al. 1992 for a similar result).

Van Asten et al. (1988) found that standing observers occasionally showed 180° phase shifts in their postural adjustments while viewing a sinusoidally oscillating optic flow pattern. In their task, observers fixated a small stationary disk in the middle of the oscillating display. The authors suggest that the phase shifts they observed could be due to the observers' interpretation of the moving display. Scene motion could be interpreted as self-motion through the environment (resulting in postural responses in phase with the stimulus motion) or as motion of the central fixation disk (resulting in postural response out of phase with the stimulus motion). This suggests that the interpretation of the structure of the environment can have a profound impact on postural adjustments.

Results from experiments on unperturbed visual environments, which measure natural body sway in the presence of a stable environment, provide conflicting evidence on the role of optic flow in posture. Lee and Lishman (1975) measured standing posture in a large theatre. Observers either fixated a distant wall or were

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given a nearby object (45 cm away) to fixate. Nearly all observers showed a reduction in body sway when the near object was added. They ascribed this effect to more salient optic flow when the near object was fixated. Stoffregen et al. (1999) replicated this finding and added the missing condition where observers fixated the distant target in the presence of the near target. Here, the optic flow (external to the eye) was precisely the same, but observers were still more stable when fixating the near target. The authors suggested that greater stability was required for observers to adequately fixate the near target (since postural sway of 1 cm requires larger angular eye movements to maintain fixation on the near object than to fixate the far wall). They concluded that optic flow is not the only variable used in controlling posture, and that "suprapostural" tasks, such as fixating different parts of the visual scene, are also important.

In light of the evidence that optic flow alone does not control posture, we propose an alternative hypothesis: that perceived self-motion relative to the environment ("perceived relative motion") controls posture. Sometimes perceived relative motion is specified by the pattern of optic flow, in which case it appears that optic flow is causal. In some situations, however, the pattern of optic flow is not predictive of perceived relative motion. For example, modifying binocular disparity (differences in the two retinal images caused by the horizontal separation of the eyes) can change perceived relative motion without changing the optic flow. To distinguish the causal roles of the two variables, optic flow and perceived relative motion, the current experiments employed a type of perceived motion known as apparent concomitant motion.

Misperception of the distance to a stationary object results in perceived motion of the object when the observer undergoes head translations. Figure 1 shows geometrically how this phenomenon, known as apparent concomitant motion (Gogel 1990), arises for a single point. Under the assumption that visual direction is perceived correctly, under-perception of distance causes apparent motion in the same direction as head motion, and over-perception of distance results in apparent motion in the opposite direction as head motion. The magnitude and direction of the apparent concomitant motion are represented by the equation

$$W' = K'(1 - D'/D)$$

where W' is the perceived motion of the object, K' is the sensed self-motion, D is the physical distance to the target, and D' is the perceived distance to the target. A positive W' corresponds to apparent motion in the same direction as head motion, and a negative W' is apparent motion in the opposite direction. Additionally, the magnitude of the apparent motion depends both on the magnitude of observer head motion and the error in perceived distance. Figure 2 shows how the same phenomenon applies to a more complex object whose depth is misperceived because of a depth reversal produced by changes in

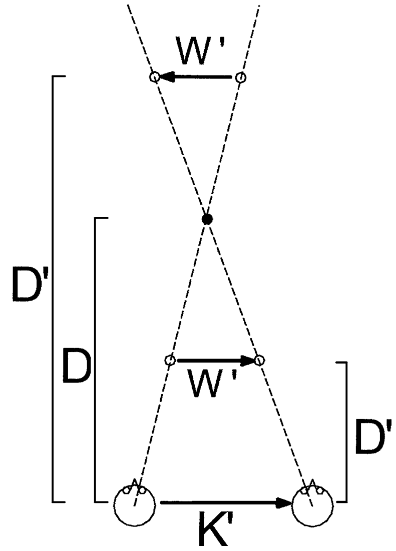

Fig. 1 Apparent concomitant motion for a single point. When its distance is under-perceived (D'), it appears to move in the same direction as head motion. When distance is over-perceived, it appears to move opposite head motion

binocular disparity. The misperception of depth within a complex object causes apparent concomitant motion; in this case it is a mixture of apparent rotation and apparent nonrigidity of shape.

This misperception of depth and the consequent apparent concomitant motion can be easily induced with perceptually reversible objects, like a 3-D wire-frame cube or a concave mask (which appears convex). Particularly good examples of apparent concomitant motion can be seen in the paintings of the artist Patrick Hughes (Papathomas 2002; Wade and Hughes 1999).

Whether distances to the object features are perceived veridically or not has no impact on the optic flow. In the optic array, each point that makes up an object is defined

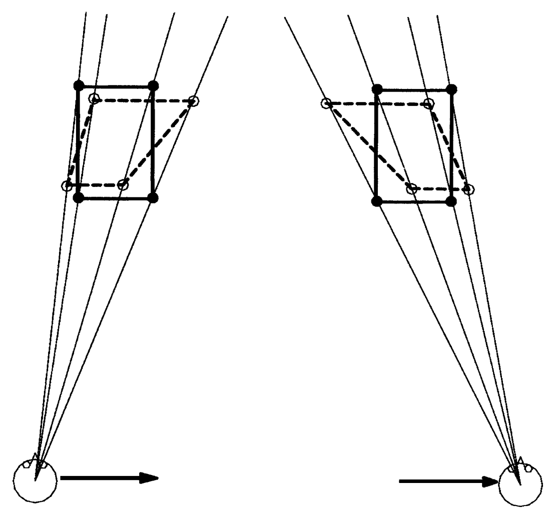

Fig. 2 Apparent concomitant motion of a complex object. The locations of the physical points are misperceived. The perceived points (*open dots*) now define a truncated pyramid which moves concomitantly with head motion

by its angular position in the projective image; optic flow refers to short-term changes in the angular positions of environmental points. Perceived distance has no influence on optic flow. Accordingly, regardless of how the object in Fig. 2 is perceived (whether veridically as concave or erroneously as convex), observer motion produces equivalent changes in the optic array over time, and thus equivalent optic flow. The optic flow stimulus (O) can be defined as a function of the observer's state vector (S), which includes both head position and head velocity, and the environmental structure (E):

$$O = f(S, E)$$

Additionally, if optic flow were the only visual stimulus involved in controlling posture, then an observer's postural response (R) to a particular optic flow stimulus (O) is given by:

$$R = g(O)$$

This makes explicit the prediction that if optic flow is the only visual stimulus used in postural control, then the same head motion in the same environment must produce the same postural response. According to this control rule, observers with the same initial state vectors (centered and stationary heads) should exhibit postural sway that is the same, on average, regardless of the perceived distance to environmental points.

Our alternative hypothesis is that perceived self-motion relative to an internal model of the environment controls posture. In the case of a purely stereoscopically-defined environment, the internal model of the environment (M) is a function of both the optic array (A) and binocular cues (B):

$$M = j(A, B)$$

Postural responses (R) are based on one's state vector (S) and the internal model of the environment (M):

$$R = k(S, M)$$

According to this control rule, changing an observer's internal model of the environment (by changing the binocular cues for example) will change their postural response, even for the same state vector.

Lasley et al. (1991) investigated the effect of the wallpaper illusion (improper convergence and fusion of a periodic stimulus) on postural stability. Observers viewed either a periodic stimulus (a vertical square wave grating) or a periodic stimulus with non-periodic features (letters scattered randomly across the display). The addition of the non-periodic features resulted in greater stability, presumably because the periodic stimulus was causing binocular convergence at the wrong distance. The authors suggest that this convergence error (causing false fusion, or the wallpaper illusion) led to disorientation. It is possible that the disorientation was a result of apparent concomitant motion due to misperceived distance, but this link was not explored.

The following experiments employed apparent concomitant motion to create two conditions with different perceived 3-D structure (in one condition, depth was misperceived) but the same optic flow. Observers stood on one foot and tried to maintain balance in the presence of a complex virtual object that either appeared stationary or appeared to move concomitantly with head motion. If posture is controlled by optic flow alone, then changing perceived 3-D structure and perceived relative motion should not affect the observers' abilities to stabilize themselves. If, however, perceived self-motion relative to the environment is important in maintaining balance, altering the perceived self-motion relative to the environment (specifically, apparent concomitant motion in one condition and none in the other) should alter postural stability.

Experiment 1

Methods

Participants

Eight undergraduate students at the University of California Santa Barbara participated for course credit. All observers were verified to have normal visual acuity and at least 80% stereopsis as measured by a Keystone orthoscope. All observers gave their informed consent prior to participation. The protocol was approved by the local Human Subjects Committee, and was therefore performed in accordance with the ethical standards specified by the 1964 Declaration of Helsinki.

Stimuli

In the normal stereo condition, observers viewed the inside of a simulated box within a virtual environment, as though they were peering in through an open end. The box was defined stereoscopically by 1,750 luminous points, and subtended approximately 53°×53° of visual angle. However, the field of view in the display was only 50°×38°, and thus the entirety of the stimulus was visible only with head movements. The points had been cast onto the simulated box from a fixed location such that they were uniformly distributed in terms of visual angle, so there were no texture cues when the box was viewed from this location. The simulated dimensions of the box were 1 m wide, 1 m tall, and 4 m deep, and centered at eye height. The observer was positioned 1 m from the closest side in the virtual space.

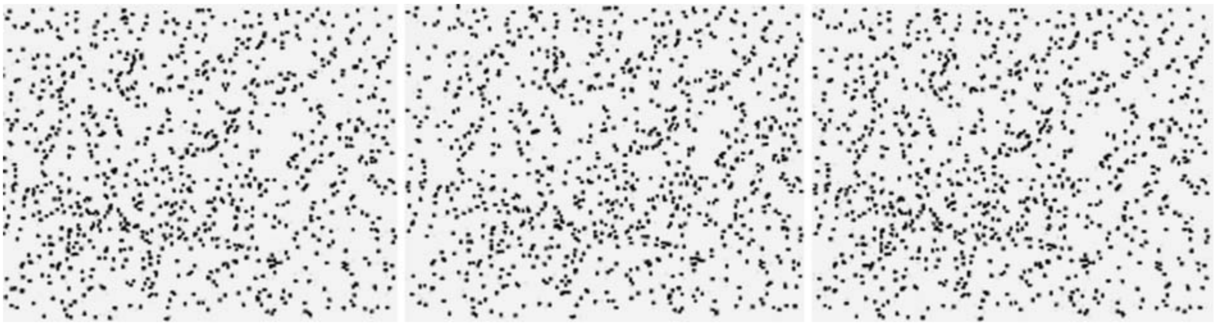

Fig. 3 For crossed fusion, the left pair represents the reverse-stereo stimulus and the right pair shows the normal stereo stimulus. For uncrossed fusion, the left pair is the normal stereo stimulus and the right pair is the reverse-stereo stimulus

In the experimental condition, stereo cues were reversed so that distances to some of the points defining the box were under-perceived and some of the distances were over-perceived. Essentially, the images presented to the two eyes were exchanged. Figure 3 shows the perceived objects for both conditions. When stereo cues were appropriate, the box appeared very nearly stationary and rigid as the observer's head moved laterally. When stereo cues were reversed, the object appeared to be a convex truncated pyramid. As the observer's head moved laterally, there was now very significant apparent concomitant motion. The perceptually near surface appeared to move very prominently in the same direction as the head. The perceptually far surface appeared to move against the head. These two translatory motions were seen as nonrigid rotation of the truncated pyramid. Self-motion in the fore-aft direction also caused some apparent concomitant motion due to the changing disparity cues when the observer moved towards or away from the display. In this case, the front surface of the pyramid appeared to move towards or away from the head. While it was not experimentally controlled, the most natural point of fixation was the center of the display (the far surface of the stationary box and the near surface of the truncated pyramid).

Note that, without providing access to the experimental stimulus, it is difficult to portray the reversed-stereo percept, and the stereograms in Fig. 3 demonstrate only slight apparent concomitant motion. Artist Patrick Hughes has developed a fascinating artistic technique called "reversperspective" that demonstrates the same phenomenon (Papathomas 2002; Wade and Hughes 1999). In many cases, he employs a truncated pyramid as his canvas and paints a scene with strong perspective cues that elicit illusory depth perception opposite the depth of the pyramid. Especially when viewed monocularly, this discrepancy creates large apparent concomitant motion. We considered using this type of stimulus as a way of manipulating perceived depth in our experiment but decided against it because it is difficult, if not impossible, to manipulate perceived depth using perspective cues while keeping the optic flow constant.

Materials

All stimuli were presented using immersive virtual reality experienced through a head-mounted display (Virtual Research V8) with 640×480 resolution LCD panels refreshed at 60 Hz. The field of view was 50° horizontal by 38° vertical. Projectively correct stereoscopic images were rendered by a dual 800 MHz processor PC and nVidia Quadro4 550 XGL graphics card. The interpupilary distance was set at 6 cm for all observers. Observer head orientation was measured with a three-axis orientation sensor (Intersense IS300) and head position was tracked three dimensionally by a passive optical position sensing system (developed in house and capable of tracking position with a resolution of 0.2 mm). The end-to-end latency, or the delay between head motion and display update was 42 ms[1]. Head position was recorded at 60 Hz. The head tracking data were used to update the perspective image sent to the two eyes, so that the images of the box were appropriate. The head-mounted display is subject to some pincushion distortion. However, the central surface of the object (the back of the box or the front surface of the pyramid) subtended only 11.4° of visual angle and the distortion of the display is limited to the edges of the LCD panels.

During testing, observers stood at the center of a 120×120 cm wooden table with a 100 cm diameter circle cut out of the center. The table was 90 cm tall. This was used as a safety precaution in case observers became extremely destabilized.

Procedure

Observers were instructed to stand on one foot while viewing the stereo-defined object in front of them. This one-foot stance was adopted in order to induce instability and maximize effect size. Observers stood at the center of the wooden table, the perimeter of which they could touch to brace themselves to avoid falling. They were instructed

[1] The system latency consists of 33.3 ms due to double-buffering of the graphics card (running at 60 Hz), plus an average of 8.3 ms (range of 0–16.6 ms) asynchrony between the position tracker frame rate (60 Hz) and graphics frame rate (60 Hz).

to use their hands only if they thought they were about to fall.

Before each trial, the experimenter verified verbally that the test object was seen properly (as a box or a pyramid, depending on the condition). As soon as the observer was standing on one foot, the trial began. After 60 seconds, a bell indicated that the trial was over and observers were allowed to relax for a short time. Before the next trial began, the stereo cues were reversed by switching the images sent to the two eyes. When this was completed, the experimenter again verified verbally that the test object was seen properly.

Design

Each observer completed four trials of 60 seconds each, two with normal stereo and two with reversed stereo cues. Observers were tested standing on one foot for the first trial, and then alternated the testing foot for each subsequent trial to avoid fatigue. Testing foot and normal/reversed stereo conditions were fully crossed such that observers were tested on each foot in each condition.

Analysis

The dependent measure in all conditions was the amount of body sway while observers attempted to maintain stability on one foot. This was measured as the standard deviation of the head position for each trial, in both the lateral and anterior-posterior (AP) body axes, as other researchers have done (Lasley et al. 1991; Okuzumi et al. 1996; Riley et al. 1997; Stoffregen et al. 1999). The standard deviation was averaged across left and right feet for each observer.

Results

Preliminary analyses suggested that observers who were generally less stable also tended to be more affected by the experimental manipulation. This is evident in the correlation between average stability (the average of the standard deviations from the two experimental conditions) and effect magnitude (the difference between the standard deviations from two conditions, reversed stereo minus normal stereo). Correlations were high for both lateral and AP body axes (r=0.42 and 0.44, respectively, see Fig. 4. Note that, while data from Experiments 1 and 2 are both presented in Fig. 4, the correlations reported were computed separately for each experiment). Given this relationship, log standard deviation values are used for all subsequent analyses. In the data plots, the corresponding untransformed values are shown on the ordinates.

Individual observer data as well as mean data are plotted in Fig. 5. On average, observers were significantly less stable in both lateral and AP body axes when viewing the reversed stereo stimulus [$t(7)=4.35$, $p<0.01$, $t(7)=3.44$, $p=0.01$, for lateral and AP body sway, respectively]. Only one subject showed the reverse effect. The experimental manipulation accounted for a large percentage of the variance of the log standard deviation scores in both body axes (ω^2=0.47 and 0.32 for lateral and AP, respectively). Observers were also significantly less stable in the lateral compared to the AP body axis [$t(7)=2.667$, $p<0.05$].

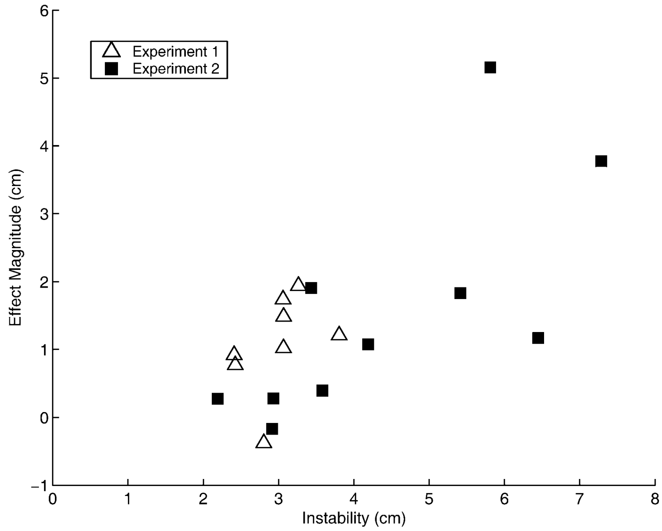

Fig. 4 Relationship between general instability and effect magnitude for both experiments (lateral body axis only). Each point represents a single observer

Discussion

Changing the perceived relative motion while leaving optic flow unchanged caused greater postural instability in

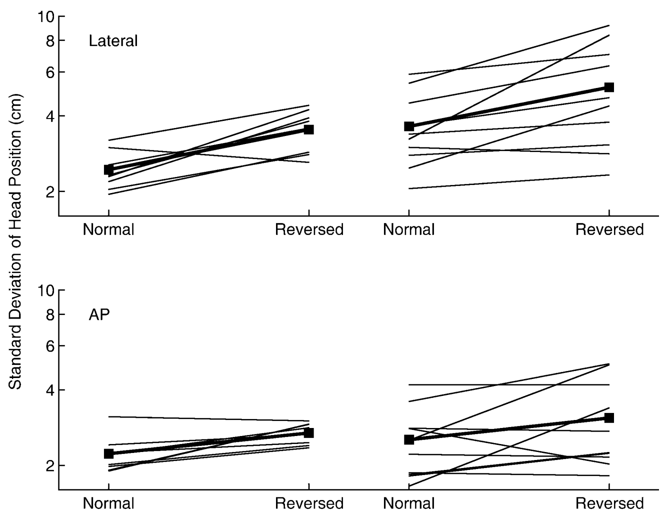

Fig. 5 Standard deviation of head position in lateral (*top graph*) and AP (*bottom graph*) body axes when viewing normal and reversed stereo stimuli. Experiment 1 data are plotted on the left and Experiment 2 data are plotted on the right. Thin lines represent single observers and thick lines represent means

both lateral and AP axes. In the case where the object was perceptually stationary, observers had good access to their current position relative to the object in front of them and were able to adjust their posture accordingly. When the object appeared to move concomitantly with head motion, self-motion relative to the environment was no longer obvious, and feedback to the postural control system was thus less effective. If optic flow were the only visual stimulus involved in postural control, then we would have expected no effect of changing binocular disparity, but this is clearly not the result obtained.

Although the center of the display seemed to be the most natural location to fixate in both conditions, this was not experimentally controlled. Different fixation patterns could have played a role in the decreased stability when the stereo cues were reversed. Additionally, the convergence distance when fixating the center of the display differed slightly between the two conditions. Finally, the amount of apparent concomitant motion that observers perceived was not assessed. To address these issues, a second experiment was conducted using stimuli very similar to those from Experiment 1.

Experiment 2

Experiment 2 differed from Experiment 1 in the following important ways: 1) A fixation target was added in the center of the display, 2) the convergence to the fixation target was matched for the two conditions, 3) the size of the box was modified slightly, and 4) observers made judgments of perceived stimulus size and apparent concomitant motion.

Methods

Participants

Ten undergraduate students at the University of California Santa Barbara participated for course credit. All observers were verified to have normal visual acuity and at least 80% stereopsis as measured by a Keystone orthoscope.

Stimuli

The dimensions of the stereoscopically defined box were modified slightly from Experiment 1. The simulated dimensions of the box were 0.5 m wide, 0.5 m tall, and 1.5 m deep. The observer was positioned 1 m from the box. The visual stimulus subtended 28°×28° of visual angle.

A small red square measuring 1°×1° of visual angle was added to the center of the display. With normal stereo cues, the fixation target appeared to rest on the far surface of the box. With reversed stereo cues, the fixation target appeared on the front surface of the truncated pyramid.

When the stereo cues were reversed, the convergence distance of the fixation target was adjusted to match its distance in the normal stereo condition. This was accomplished using two CRT displays that temporarily took the place of the two LCD displays in the head-mounted display (one for each eye). The stimulus object was positioned in the same way in virtual space as it would later be in the experiment, causing its screen image to be roughly centered in each CRT display. Head tracking was turned off so that the image of the object remained stationary on each of the screens. For each display, a small vertical line was marked on the glass surface of the CRT just in front of the image of the red fixation target. Reversing the stereo cues caused slight displacements of the images of the red fixation target. Thus, with the stereo cues reversed, the two screen images were moved horizontally (in graphics screen memory) so that the red fixation target was now aligned with the physical marks on the screen. The amount of the shift in the graphics screen buffer was recorded and used subsequently in the experiment, guaranteeing that the right and left eye images of the fixation target had identical screen positions in the normal and reversed stereo conditions. Thus, the convergence distance to the 3-D fixation target was the same in the two conditions. Perceptually, however, the fixation target appeared closer in the reversed stereo condition than in the normal stereo condition, for the perceived distance of a point in a 3-D configuration depends upon both its disparity with respect to other points in the configuration and the convergence distance of the “reference point” of the configuration, which is approximately its centroid (Foley 1980).

Procedure

The procedure for assessing postural sway in the normal and reversed stereo conditions was exactly the same as in Experiment 1. Once this was completed, observers were asked to make a series of perceptual judgments about stimulus size and apparent concomitant motion.

Perceived size of the fixation target was measured by asking observers to indicate the width of the red square with the spacing between the palms of the two hands; observers could not see their hands, but sensed their separation using proprioception. The distance between the palms was measured by the experimenter. In addition to the small 1°×1° fixation target used during the posture experiment, observers also made size judgments of two larger squares (2°×2° and 4°×4° of visual angle). In total, observers judged the size of the fixation target for the three different angular sizes in the context of both normal and reversed stereo stimuli. The order of the normal and reversed stereo stimuli was counterbalanced, and target angular size was varied randomly on each trial.

Apparent concomitant motion was assessed by instructing the observer to move their head laterally between two cushions placed on either side of their head. The cushions were separated by 60 cm. During multiple side-to-side motions of the head, observers reported how far the fixation target appeared to move laterally. To report apparent concomitant motion, they separated their palms by the same amount that the fixation target had appeared to move. Apparent concomitant motion in the same direction of the head was signed positive and apparent concomitant motion against the head was signed negative. Observers made these judgments for both normal and reversed stereo stimuli.

Results

As in Experiment 1, observers who were less stable on average tended to be more affected by the experimental manipulation (r=0.72 and 0.45 for lateral and AP body axes, see Fig. 4). Given this relationship, log standard deviations are used in all Experiment 2 analyses. Individual and mean data are plotted in Fig. 5. Replicating the results of Experiment 1, observers were, on average, significantly less stable in the lateral body axis when viewing the reversed stereo stimulus ($t(9)=3.73$, $p<0.01$). Unlike Experiment 1, stability in the AP axis was not significantly different in the two experimental conditions ($t(9)=1.71$, *ns*). The smaller statistical significance in Experiment 2 is not due to differences in mean instability, but rather to larger variance in the second experiment (see Fig. 5).

Figure 6 shows geometric means of size estimates for the three target sizes (geometric means were used because the size estimates were highly variable and positively skewed). Size estimates are, on average, 1.7 times smaller for the reversed compared to the normal stereo stimuli, demonstrating that the fixation target in the reversed stereo stimulus was perceived as being closer than the fixation target in the normal stereo stimulus. This variation in perceived size is expected from size-distance invariance, a perceptual law relating perceived size, perceived distance, and the angular size of the visual target (Gilinsky 1951; Gogel 1990; McCready 1985). The following relationship is supported by the literature: $S'=D'\tan\Theta$, where S' is perceived target size, D' is perceived target distance, and Θ is target angular size.

Apparent concomitant motion judgments for normal and reversed stereo stimuli are shown in Fig. 7 (note that arithmetic means were used here, because variability was relatively low and subjects occasionally reported negative values). Again, the comparatively large apparent concomitant motion reported under reversed stereo viewing conditions indicates that the location of the fixation target was perceived as being closer in the reversed stereo than the normal stereo stimulus. In principle, it is possible to work backwards to determine the perceived distance of the fixation target using either the size estimates or the apparent concomitant motion estimates obtained in this experiment. However, the values of perceived distance derived from the two estimates (size judgments and apparent concomitant motion judgments) are only in rough agreement with each other.

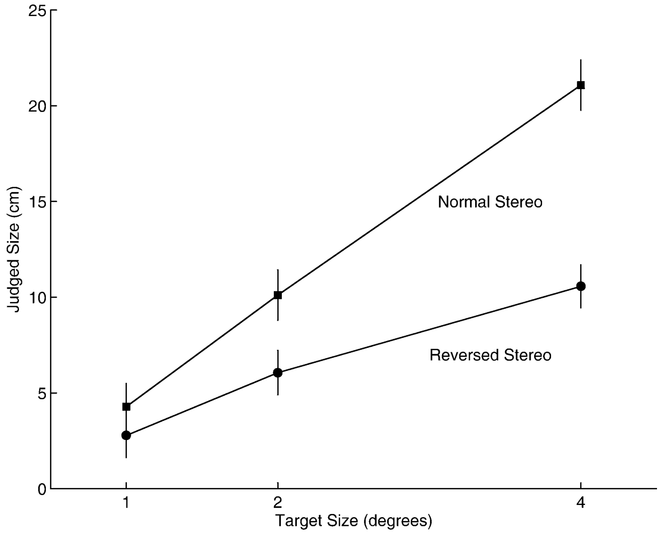

Fig. 6 Size judgments obtained for both normal and reversed stereo stimuli. Error bars represent ±1 standard error of the mean

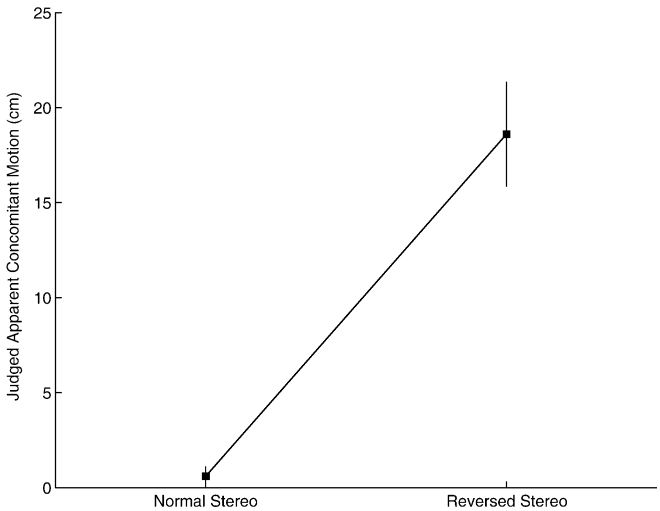

Fig. 7 Apparent concomitant motion judgments for both normal and reversed stereo stimuli. Error bars represent ±1 standard error of the mean

Discussion

Experiment 2 replicated the primary finding of Experiment 1: that changing perceived relative motion while leaving optic flow unchanged causes greater postural instability. Experiment 2 also showed that this effect is not due to different fixation patterns or different convergence distances. In addition, size judgments obtained in Experiment 2 confirmed that the fixation target in the reversed stereo stimulus was perceived to be nearer than the fixation target in the normal stereo stimulus. In combination with the apparent concomitant motion judgments, it is clear that the objects were being perceived similarly to those depicted in Fig. 2, and that the reversed stereo stimulus moved concomitantly with subjects' head motions. Most importantly, the reversed stereo object, which produced more apparent concomitant motion, also resulted in greater instability. When the object was perceived as stationary, changing self-position relative to that object was used to make postural adjustments. When the object was perceived to move concomitantly with head motion, changing self-position relative to that object was not obvious, resulting in weaker visual feedback to the postural control system.

As in Experiment 1, observers who were less stable on average were more destabilized by the apparent concomitant motion. It could be that the unstable observers had poorer access to vestibular and proprioceptive information, causing a general instability as well as a heavier weighting of visual cues. Thus, when viewing the apparent concomitant motion display, these unstable observers became even less stable. A good test of this hypothesis would be to perform the same experiment on patients with bilateral vestibular damage. These patients rely even more heavily on visual information to control balance, and should therefore show an even larger effect of our manipulation.

General discussion

These results add to the growing body of literature questioning the role of optic flow in controlling posture (Dijkstra et al. 1994; Stoffregen et al. 1999; Van Asten et al. 1988). The optic flow of our stimulus object was unaffected by the reversal of binocular disparity (and the subsequent change in perceived depth). Since postural instability increased with the consequent apparent concomitant motion, it is plausible that the input to the postural control system is the apparent motion of the fixated object relative to self. Work by Beusmans (1998) makes a similar point by showing that heading judgments are based on perceived self-motion relative to a 3-D environment and not just the changing optic array. Our view raises the question of whether optic flow itself is ever directly accessible. An alternate view posits that all actions are based on a 3-D representation of the environment, and aspects of optic flow (such as global expansion and motion parallax) can only be attended to through effortful "deconstruction" of the 3-D world into its perspective components. Attention to aspects of the flow field may be subject to the same difficulties as attention to aspects of the perspective image when viewing a 3-D world. In the case of the perspective image, Brunswik has shown that judgments of object angular size are more difficult and error-prone than judgments of distal size (Brunswik 1941, 2001; see also Thouless 1931), indicating that the perspective view is not easily accessible. In the case of the moving perspective image, Gogel (1980) has used the apparent concomitant motion phenomenon to show that object motion can be perceived in a direction opposite to retinal motion. In summary, optic flow (changes in the perspective image) may be accessible only indirectly, mediated through the observer's 3-D representation of the world.

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