Perception & Psychophysics
1986, 39 (5), 355-360

The role of optical velocity in the control of stance

THOMAS A. STOFFREGEN
Cornell University, Ithaca, New York

Two experiments were designed to investigate the use of optical flow for postural control as a function of its velocity, geometry, and retinal placement. In the first experiment, subjects were exposed to a room that moved at a velocity below the reported threshold for detection of point-light motion. In the second, the room was moved so that optical velocities were above this threshold. Compensatory sway was assessed for both lamellar and radial flow to central and peripheral areas of the retina. Compensatory sway was elicited with optical velocities below the point-light motion threshold, suggesting that this threshold is not relevant to the detection of egomotion. The results also indicate that the retinal periphery does not detect posture-relevant information from flow fields with a radial dynamic structure. Since the higher velocities used in the second experiment exceeded those generated by natural postural instabilities, it was concluded that radial flow in the retinal periphery is not used as a source of information for normal postural maintenance, and therefore that flow structure is an important factor in the detection and control of egomotion.

Stoffregen (1985) recently reported a series of experiments on the optical control of stance. These studies purported to demonstrate the importance of structure in optical flow fields as a determinant of their usefulness as sources of information for postural control. It was observed that the slight forward and back swaying that characterizes natural postural instabilities generates global optical flow, and that the structure of this flow in the ambient optic array varies depending on its proximity to the anterior/posterior line of motion.

With any linear motion, if we look in the direction of motion, optical flow expands radially outward from the point toward which we are moving and sweeps laterally past us, converging behind. If we look at different parts of this overall flow, we find different local structures. Near the line of motion, the pattern of flow is almost exclusively radial, whereas at those points where the flow sweeps past the observer, the lines of flow have become nearly parallel, much like the lines of longitude on a globe, which converge at the poles but are parallel at the equator.

Studies that have ignored this variation in flow structure have concluded that the periphery of the retina is dominant for the pickup of optical information specifying egomotion (Brandt, Dichgans, & Koenig, 1973), but Stoffregen's (1985) results suggested that this was true only when the periphery was presented with flow that had a particular structure, the nearly parallel arrangement described above (referred to as lamellar by Koenderink & van Doorn, 1981). The retinal periphery appears to be unable to detect posture-relevant information in radial flow patterns. Central retina shows a modest ability to detect such information from either radial or lamellar flow. A plausible conclusion is that flow structure is at least as important as retinal location in the control of stance.

However, there is another explanation for the observed results. Variations in the optical velocity of points in different parts of the array might account for the failure of peripheral retina to detect information for postural control from radial flow.[1] In an evenly cluttered environment, optical displacements caused by egomotion have the lowest magnitude, or velocity, near the focus of expansion.[2] Optical velocities increase with increasing eccentricity from the line of motion, until they reach a peak velocity at 90° from the line of motion. This means that, for a given linear motion of the observer, the slowest moving points are in the radially structured areas of flow, whereas the fastest points are found in areas of lamellar structure. It is possible, then, that for a given linear motion areas of the flow field that have a lamellar structure might have optical velocities above threshold, while, at the same time, optical velocities in radially structured flow might be below threshold.

This possibility may seem more plausible given the fact that the threshold for detection of point-light relative optical motion is higher in the periphery of the retina than at its center (Leibowitz, Johnson, & Isabelle, 1972). Calculations of the actual velocities generated by motion of the moving room in Stoffregen's (1985) earlier studies reveal that the radial portions of the flow were, in fact, below the point-light thresholds for the retinal periphery.

There are, however, factors suggesting that point-light thresholds are not relevant to the use of optical information for the control of stance.[3] First, thresholds, such as

These experiments were carried out at Cornell University in the laboratory of Eleanor J. Gibson. Her generous support is gratefully acknowledged. The data were reported in a talk at the Third International Conference on Event Perception and Action, Uppsala, Sweden, June 1985. Thanks are extended to Gary Riccio, James Cutting, Mark Schmuckler, and Rik Warren, who provided helpful comments on the manuscript. Requests for reprints should be sent to Thomas A. Stoffregen, who is now at AAMRL/HEF, Wright-Patterson Air Force Base, OH 45433.

those reported by Leibowitz et al. (1972), are typically determined through verbal reports of observed motion of a stimulus light against a black background (see Bonnet, 1982, for a review). Not only is such an impoverished display uncharacteristic of natural situations, but verbal reports require that the observer be conscious of the motion, whereas in the case of natural postural instabilities, the individual is essentially never aware that he or she is moving; the same is often true in studies of induced postural sway (e.g., Stoffregen, 1985). Consequently, sway-induction thresholds are likely to be lower than phenomenological thresholds.

An ecological analysis of translatory egomotion suggests that optical velocities of points in the array are not likely to be directly relevant to their use as sources of information for postural control. Optical velocity is a function not only of actual velocity of motion in the environment, but also of the distance between the observer and points or objects in the surround. That is, an object moving with a given speed will have a higher optical velocity when it is closer to the point of observation (the observer) than when it is further away. Therefore, optical velocity by itself does not provide useful information for postural control. For these reasons, it seems likely that variations in optical velocity were not an important factor in Stoffregen's (1985) reported failure of the retinal periphery to detect optical information for postural control from radial flow. Nonetheless, an explicit empirical test seems desirable.

Two experiments were executed to address this issue. In the first, a room was moved in such a way as to generate optical velocities that were below the thresholds reported by Leibowitz et al. (1972) at all points in the optic array. It was expected that observers would exhibit compensatory sway in response to these optical motions despite their reduced velocity. In the second study, the room was moved such that optical velocities were above the reported point-light thresholds for all areas of the retina. It was expected that radial flow would still fail to elicit postural responses when presented to the retinal periphery.

METHOD

Subjects

Twenty-eight paid adult subjects took part, 14 in each experiment. The subjects were recruited through public notice and by personal contact.

Apparatus

The materials, apparatus, and flow presentation conditions were identical to those used by Stoffregen (1985). The experimental room consisted of a cube, 2 m on a side, built of wood studs, with the interior faced with rigid cardboard, that was itself covered with a marbled adhesive plastic. The room was mounted on wheels such that it could be rolled backward and forward linearly. The subjects stood on the real floor and the room was moved around them. The subjects' compensatory sway was measured by a sway meter consisting of a potentiometer mounted on a rigid stand. A grooved wheel was attached to the axle of the potentiometer, and a weighted string passed over this wheel and around the subject's neck, where it was held by a clasp. In this way, the subjects' anterior/posterior sway could be measured with a resolution of 1 mm. A second potentiometer measured the motions of the experimental room. Outputs from both were fed into a PDP-11/34 computer for storage and analysis. Potentiometer outputs (spatial position) for the subject and the room were sampled every .5 sec. Room movements were generated manually.

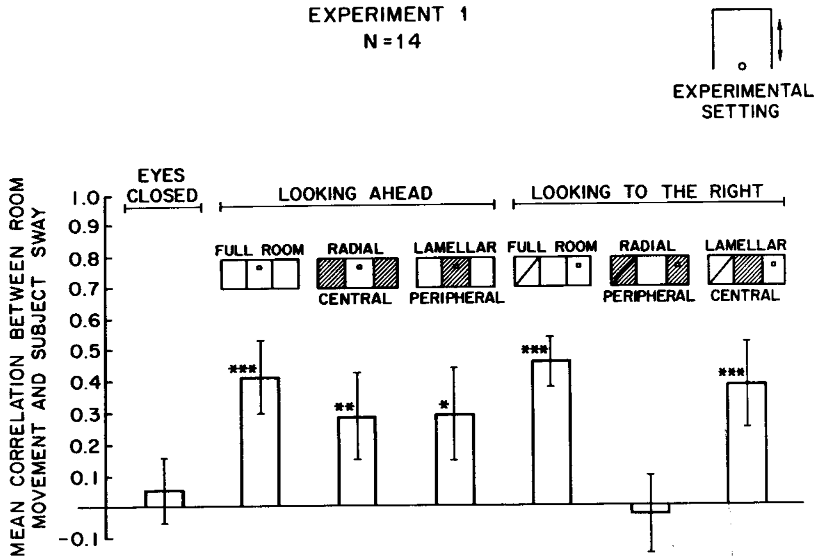

Figure 1. Conditions and results for Experiment 1. The experimental setting shows a top view of the room and the subject's placement within it. The small squares in the schematic illustrations of conditions indicate the area of gaze. The diagonal line through the left wall of the room in the looking-to-the-right conditions indicates that this wall was out of view behind the subject's head. Error bars indicate standard deviations. *$p < .05$. **$p < .01$. ***$p < .001$.

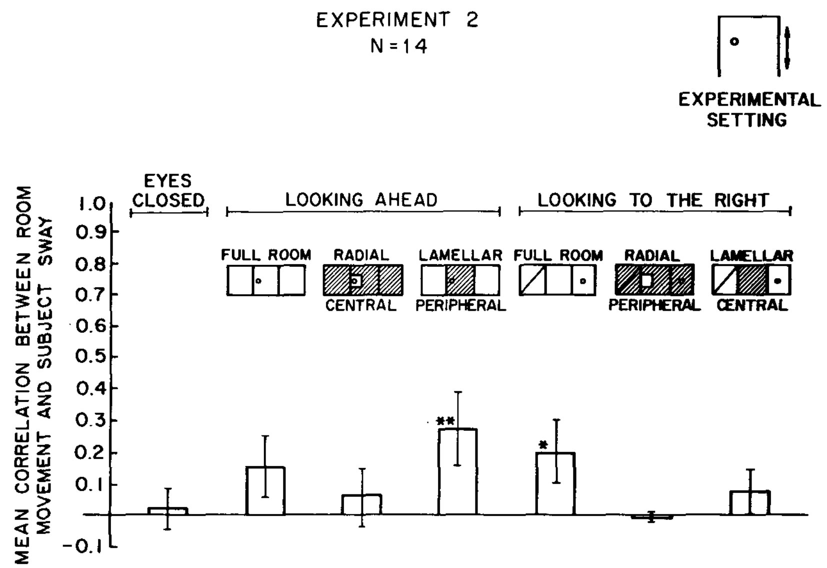

Figure 2. Conditions and results for Experiment 2. The experimental setting shows a top view of the experimental room and the subject's placement within it. The small squares in the schematic illustrations of conditions indicate the area of gaze. The diagonal line through the left wall in the looking-to-the-right conditions indicates that this wall was out of sight behind the subject's head. Error bars indicate standard deviations. $^*p < .05$. $^{**}p < .01$.

Presentation of optical flow generated by room motion was sometimes restricted. Standing within the room, but physically separate from it, were three open frames, one in front of each of the three vertical walls (the fourth wall of the room remained open, for access). These frames could be covered with rigid cardboard so as to occlude one or more of the walls of the moving room. The screens were stationary with respect to room movements. The subjects wore a visor that prevented them from seeing the ceiling at all times. An opaque panel could be attached to this visor to prevent vision out of the experimental room when the head was turned (see below for explanation).

Conditions

Flow presentation conditions were identical for the two experiments, and are illustrated schematically in Figures 1 and 2. The subjects were presented with the following seven conditions: eyes closed (control), nearly global flow (both looking ahead and looking to the right), exclusively lamellar flow, and exclusively radial flow. The latter two could each be presented to either the central or peripheral areas of the retina. Conditions were arranged in seven random orders, each of which was presented to 2 subjects in each experiment. When the subjects faced forward with the full room visible, lamellar flow projected to the retinal periphery while radial flow projected to the retinal center. When the subjects turned their heads to look at the right wall of the room, lamellar flow projected to the retinal center while radial flow projected to the retinal periphery. Radial exposures subtended 60° of visual angle in both experiments (appropriate areas of the front wall in Experiment 2 were occluded by stationary screens to make this possible; see Figure 2). Each subject received one trial in each condition. The trials lasted 1 min.

In Experiment 1, the room was moved in such a way as to generate optical velocities well below the thresholds for detection of point-light motion (Figure 3). In Experiment 2, room velocity was increased and the subjects were placed forward in the room (Figure 4), so as to further increase the optical velocities of the radial flow (they were also moved to the left so as to partially equalize visual angles of front and side walls).

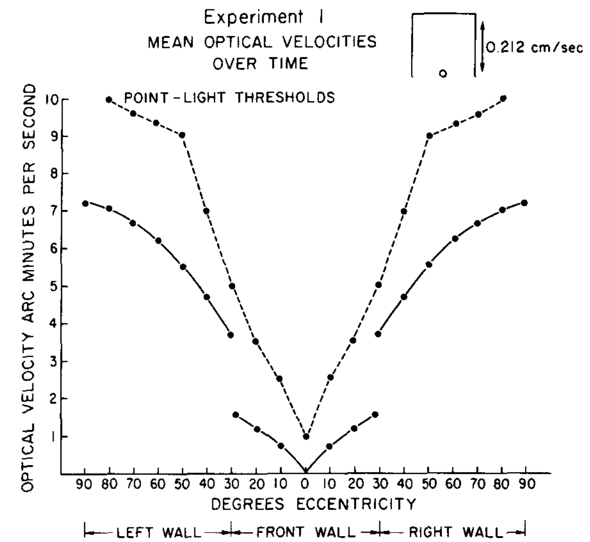

Figure 3. Optical velocities of points on the walls of the moving room in Experiment 1. For points on the side walls, velocities were calculated as the 2.5-cm displacement of the room, expressed as a change in visual angle for specific points relative to the point of observation, divided by the time taken for the room movement (12 sec in Experiment 1). For the front wall, the angular position of a given point relative to the point of observation was calculated for the endpoints of the room excursion. The angular difference between these two positions divided by the 12-sec time of the excursion yielded the mean velocity over time in arc minutes per second. Point-light thresholds are means taken from Leibowitz, Johnson, and Isabelle (1972). The superposition of velocity curves depicted is produced when the observer looks at the front wall.

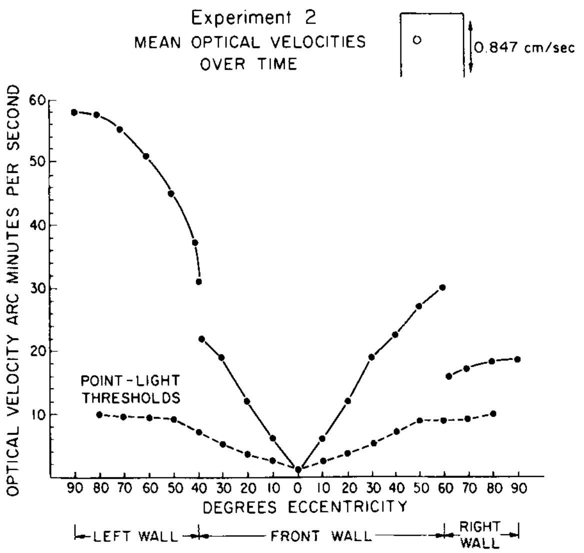

Figure 4. Optical velocities of points on the walls of the moving room in Experiment 2 (note the difference in scale on the ordinate from that of Figure 3). For points on the side walls, velocities were calculated as the 2.5-cm displacement of the room, expressed as a change in visual angle for specific points relative to the point of observation, divided by the time taken for the room movement (3 sec in Experiment 2). For the front wall, the angular position of a given point relative to the point of observation was calculated for the endpoints of the room excursion. The angular difference between these two positions divided by the 3-sec time of the excursion yielded the mean velocity over time in arc minutes per second. The asymmetry in angular velocities and visual angles of the three walls results from the asymmetric placement of observers within the room. Point-light thresholds are means taken from Leibowitz, Johnson, and Isabelle (1972). The superposition of velocity curves depicted is produced when the observer looks at the front wall.

Sample room motion records are shown in Figure 5. Accuracy and consistency of the room movements was high. Twelve pairs of randomly selected records of 1-min room motion were compared for each experiment. For Experiment 1, the mean correlation among these 12 pairs was .952; for Experiment 2 it was .651.

Procedure

Subjects were run individually. Each was asked to stand comfortably in the experimental room with weight on both feet. General instructions were given to stand still during trials, with the gaze fixed within a small square outlined on one of the walls (indicated in Figures 1 and 2) and without moving the head or arms. Instructions were given on each trial about where to look, as indicated above. On each trial, after a ready signal, the string from the sway meter was clasped around the subject's neck and calibrated to the center of the sway meter's scale. The experimenter then started a recording stripchart and commenced moving the room. The experimenter was not visible to subjects at any time during trials. At the end of the experimental session, the subjects were asked whether they had perceived any movement during the experiment, and if so whether the movement was of the room or of themselves (or both).

RESULTS

The data are mean correlations across subjects between room motion and subject sway for each condition. Responses in Experiment 1 (Figure 1) closely matched the original findings of Stoffregen (1985), showing that optical information for postural stability can be detected at velocities well below the thresholds for detection of point-light or object motion. An analysis of variance revealed a significant effect for conditions [$F(6,91) = 7.99$, $p < .001$], accounting for 35% of the variance in the data. As in the earlier study, lamellar flow was effective in inducing compensatory sway when presented to either central or peripheral retina; radial flow was effective only when presented to the retinal center. Bonferroni planned comparisons revealed that all experimental conditions except the radial peripheral condition produced significantly more sway than the eyes-closed control.

About one half of Stoffregen's (1985) subjects reported awareness of motion. Some felt that the room was moving, but most reported that they felt themselves to be moving. In Experiment 1 of the present study, with optical velocities half as great as in the earlier work, no subject reported awareness of motion, either of the room or of him- or herself.

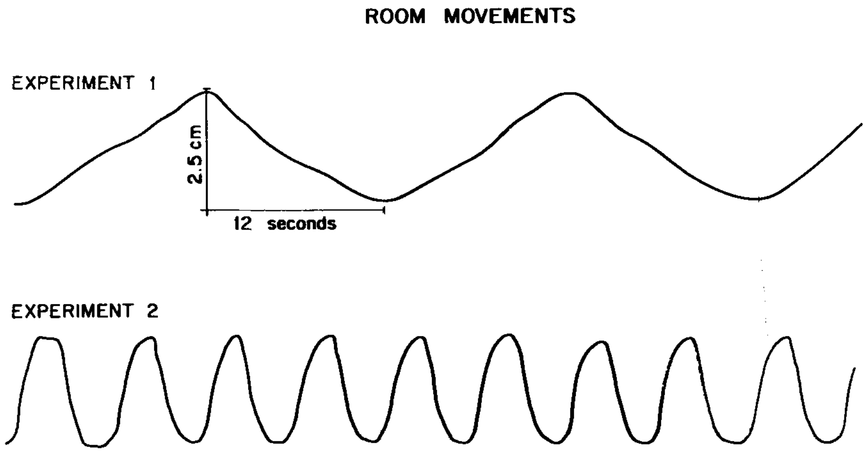

Figure 5. Records of room motion. The scale is the same on both records.

The optical velocities generated by room motion in Experiment 2 were much higher than those found with natural postural instabilities (Lee & Lishman, 1975), and were in general at least twice as great as those used by Stoffregen (1985). All observers reported awareness of the room motion; none felt themselves to be moving. An analysis of variance again revealed a significant effect for conditions [$F(6,91) = 4.59$, $p < .01$], accounting for 23% of the variance in the data. The data are presented in Figure 2. Compensatory responses were generally depressed relative to Experiment 1; indeed, with the Bonferroni correction for multiple comparisons, only two conditions produced significantly more sway than the eyes-closed control (lamellar peripheral and full room looking to the right).[4] Despite the fact that optical velocities of points in the radially structured areas of the array were above point-light motion thresholds for the retinal periphery, presentations of radial flow to the retinal periphery still failed to induce compensatory sway.

DISCUSSION

The present results indicate that optical velocity is not a factor in the failure of radially structured optical flow to induce compensatory postural adjustments when presented to the retinal periphery. This confirms Stoffregen's (1985) earlier finding that the retinal periphery is incapable of detecting stance-related information in radially structured flow, and the conclusion that flow structure in general is an important determinant of the usefulness of optical information for postural control.

The data also show that detection of large-field optical motions specifying egomotion is not related to or dependent on thresholds for the detection of point-light or object motion. It is not clear whether there is any meaningful lower threshold for detection of optical information specifying egomotion. Earlier studies have shown that with regard to illumination and acuity the visual system shows robust detection of egomotion down to the limits of static pattern detection (Berthoz, Pavard, & Young, 1975; Leibowitz, Shupert-Rodemer, & Dichgans, 1979). Sensitivity to low-velocity optical displacements specifying egomotion, particularly in the periphery of the array, may be similarly acute.

The observed breakdown in compensatory responses with high optical velocities most likely does not represent a failure of detection by the visual system. Instead, it seems probable that these high velocities are so far beyond the range of those generated by natural postural instabilities that the postural control system simply has not developed the ability to respond to them.

It therefore appears that optical velocity *is* an important factor in the control of stance, but not in the way previously supposed. When optical velocities become excessive, the postural system stops responding to the flow, regardless, apparently, of its structure. In this context, we see that in order for optical velocities in radially structured flow to be above point-light motion detection thresholds for the retinal periphery, they must correspond to simulated observer motions that are far more rapid than those characterizing actual postural instabilities (though they might also correspond to situations in which the distance between the observer and the surround was very slight, itself an atypical circumstance).

It is important to note that when optical velocities became so high that they were no longer useful to the postural control system (with the observer-surround distances of the present experiments), which happened in Experiment 2, all of the subjects reported that they noticed the room motion, whereas with the much slower motions employed in Experiment 1, no subject reported awareness of any motion. This result shows the irrelevance of thresholds derived from verbal reports (and thus requiring consciousness) to situations that, under natural conditions, typically do not involve conscious awareness. A number of similarities have been reported between verbal reports of perceived egomotion and postural responses to large-field optical flow, but there is no reason to believe that detection thresholds for the two should be the same.

It is interesting that, in Experiment 2, the optical displacements generated by movement of the room were perceived as object motion (motion of the room) rather than as egomotion, particularly in light of the fact that Brandt et al. (1973), using similarly high velocities, obtained consistent reports of perceived rotary egomotion with subjects placed within an optically rotating drum. Similarly, Andersen and Braunstein (1985) obtained subjective reports of perceived linear egomotion with presentations of high-velocity radially expanding flow to relatively small areas of the central retina. The reasons for this difference remain unclear.

CONCLUSION

The results of the present experiments appear to indicate that, over the range of natural postural instabilities, the optical velocities of flow fields are not an important factor in determining whether the information for egomotion in those flow fields will be useful for the control of posture. They also confirm Stoffregen's (1985) finding that the periphery of the retina is not able to pick up information relevant to postural control from flow that has a radial geometrical structure, thus indicating that flow structure is at least as important as retinal location for the detection of optical information specifying egomotion. The results of Experiment 1 also replicate an earlier finding (Stoffregen, 1985) that central areas of the retina are sensitive to posture-relevent information that has either radial or lamellar structure; this result does not fit comfortably into the notion that the retinal periphery is dominant for the pickup of information for egomotion.

Earlier work (e.g., Dichgans & Brandt, 1978; Howard, 1982; Johansson, von Hofsten, & Jansson, 1980) has concluded that the retinal periphery is dominant for the visual detection of egomotion. As discussed above, the repeated failure of the retinal periphery to successfully mediate postural adjustments when presented with radially structured flow undermines this view. Indeed, it may now be appropriate to wonder whether the retinal periphery is capable of detecting dynamic information from radially structured flow patterns under any conditions. Flow structure has not historically been treated as a variable in assessments of the capabilities of peripheral vision. We do not know, therefore, whether the periphery of the retina is able to detect optical information for a variety of types of locomotion (such as walking or flying), or for object motion (such as looming), when these types of information are carried in radially structured dynamic arrays.

It has been observed above that the present data suggest that thresholds for the detection of object motion are irrelevant to the pickup of information that specifies egomotion. If true, this should serve as a strong reminder of the importance of considering optical displacements not simply as projections on the retina. Rather, it is important to consider what event a given optical displacement is specific to in the real world, since different events, such as object motion and egomotion, can have very different affordances for action (Gibson, 1979).

REFERENCES

Anderson, G. J., & Braunstein, M. (1985). Induced self-motion in central vision. *Journal of Experimental Psychology: Human Perception & Performance*, **11**, 122-132.

Berthoz, A., Pavard, B., & Young, L. R. (1975). Perception of linear horizontal self-motion induced by peripheral vision (linearvection). *Experimental Brain Research*, **23**, 471-489.

Bonnet, C. (1982). Thresholds of motion perception. In A. Wertheim, W. Wagenaar, & H. Leibowitz (Eds.), *Tutorials on motion perception* (pp. 41-80). New York: Plenum Press.

Brandt, T., Dichgans, J., & Koenig, E. (1973). Differential effects of central versus peripheral vision on egocentric and exocentric motion perception. *Experimental Brain Research*, **16**, 476-491.

Cutting, J. (1986). *Perception with an eye toward motion*. Cambridge, MA: MIT Press/Brandford Books.

Dichgans, J., & Brandt, T. (1978). Visual-vestibular interaction: Effects on self-motion perception and postural control. In R. Held, H. Leibowitz, & H. Teuber (Eds.), *Handbook of sensory physiology* (Vol. 8, pp. 755-804). New York: Springer.

Gibson, J. J. (1950). *The perception of the visual world*. Boston: Houghton-Mifflin.

Gibson, J. J. (1979). *The ecological approach to visual perception*. Boston: Houghton-Mifflin.

Howard, I. (1982). *Human visual orientation*. New York: Wiley.

Johansson, G., von Hofsten, C., & Jansson, G. (1980). Event perception. *Annual Review of Psychology*, **31**, 27-63.

Koenderink, J., & van Doorn, A. (1981). Exterospecific component of the motion parallax field. *Journal of the Optical Society of America*, **71**, 953-957.

Lee, D. N., & Lishman, J. (1975). Visual proprioceptive control of stance. *Journal of Human Movement Studies*, **1**, 87-95.

Leibowitz, H., Johnson, C., & Isabelle, E. (1972). Peripheral motion detection and refractive error. *Science*, **177**, 1207-1208.

Leibowitz, H., Shupert-Rodemer, C., & Dichgans, J. (1979). The independence of dynamic spatial orientation from luminance and refractive error. *Perception & Psychophysics*, **25**, 75-79.

Stoffregen, T. A. (1985). Flow structure versus retinal location in the optical control of stance. *Journal of Experimental Psychology: Human Perception & Performance*, **11**, 554-565.

NOTES

1. The term "optical velocity" is something of a misnomer, insofar as it is construed to correspond to the physical velocity of objects in the world. Displacements of the projections of objects (or of the entire visual field) are specific to motions in the world, but the motions of the projections do not resemble those physical motions (Gibson, 1950, 1979). For example, physical velocities of objects and optical velocities of their projections frequently differ. The term, optical velocity, is here used to refer to the velocity of the displacement of a projection in the array.

2. This usage is based on Gibson's (1950) definition. There are a number of ways to mathematically describe the outflow of texture elements that is created by egomotion, and not all of them refer to the same point in space. See Cutting (1986) and Koenderink and van Doorn (1981) for discussions of this issue. The difference in descriptions does not affect the conclusions of the present study.

3. Bonnet (1982) distinguishes at least 11 kinds of thresholds for detection of optical motion. It is not clear which of these would be most relevant to the optical motions generated in the present experiments. The thresholds reported by Leibowitz et al. (1972) are used because they are the only ones that systematically estimate sensitivity as a function of retinal eccentricity.

4. Reports of perceived motion were not collected for individual conditions; it is possible that instances of perceived egomotion would be higher in the two conditions in which subjects did sway in response to room motion.

(Manuscript received August 19, 1985;
revision accepted for publication April 14, 1986.)