Use of central and peripheral optical flow in stance and locomotion in young walkers[†]

Thomas A Stoffregen[¶], Mark A Schmuckler, Eleanor J Gibson
Department of Psychology, Uris Hall, Cornell University, Ithaca, NY 14853, USA

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Abstract. Young walkers (up to 5 years of age) were presented with optical flow in a moving room. Flow was global or was restricted to either the center or the periphery of the visible optic array. On standing trials the response rate was greatest when peripheral flow was available. The availability of central flow had a smaller effect on standing, and the younger children showed greater response rates to frontal flow than did the older ones. There was a strong negative correlation between age and response rate for all conditions. Flow also affected stability during locomotion. Response rate was again related to the location of the available flow. It is concluded that children show the same relative sensitivity for flow in the periphery of the dynamic structure of the optic array as has been observed in adults, but that this differentiation of different areas of optical structure is not yet fully developed when children learn to stand.

1 Introduction

Several studies have demonstrated that adults show compensatory postural responses to large-field optical flow (Lee and Lishman 1975; Lestienne et al 1977), and that these responses are preferentially facilitated by flow from the edges of a display, rather than from its center (Brandt et al 1973; Stoffregen 1985; 1986). Lee and Aronson (1974) found that optical flow is also used by children in controlling standing posture. Their subjects exhibited more dramatic responses, such as falling down, than do adults (Kelso 1982). In children younger than 10 years old, Butterworth and Hicks (1977) and Forssberg and Nashner (1982) have observed that flow effects on posture are negatively correlated with age.

Given the observed difference between adults and children in responsiveness to the optical flow information for postural maintenance, it is reasonable to ask whether the center/periphery differences observed in adults would also be found in younger walkers. It is possible that during the process of learning to stand and walk, children are sensitive and responsive to any large-field optical motion, regardless of its location, and that spatial differentiation of flow develops later. Also, it is not known whether this effect would be preserved during locomotion, when optical information is being sampled for control of both locomotion and posture. This issue was not addressed in studies that have reported effects of optical flow on the control of locomotion (Lee and Young 1986; Owen and Lee 1987).

2 Method

2.1 *Subjects*

Fifty-four children participated, ranging in age from 10 months to 5 years, and in walking experience from 2 weeks to 4 years. Parents were recruited from birth announcements in the local newspaper, and were paid $3.00. The children were divided into two groups on the basis of age. The younger group consisted of thirty children

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[¶] Author to whom requests for reprints should be sent. Present address: Computer Technology Associates Inc., Suite 201, 14900 Sweitzer Lane, Laurel, MD 20707, USA.

under the age of 2 years (mean 15.77 months), whereas the older group included twenty-four children between the ages of 2 and 5 years (mean 3.4 years).

2.2 *Apparatus*

The study was performed in a moving room similar to that used by Lee and Aronson (1974). The cubical enclosure (2.5 m sides) was built of wood studs and mounted on four wheels so that it could be rolled over the floor (clearance 0.5 cm). The ceiling and three interior walls of the room were faced with rigid cardboard, which was covered with an optically textured (marble pattern) plastic adhesive paper. The fourth wall remained open, and the room had no floor. Illumination was provided by three incandescent lamps in reflectors above holes in the cardboard ceiling. The lamps were rigidly attached to the room, so that they moved when it did. Room motion was along an axis perpendicular to the open wall.

Standing within the room, but physically separate from it, were three open wood frames, linked together. One stood immediately in front of each of the three walls. Large sheets of plain rigid cardboard could be attached to the wood frames in such a way as to occlude individual walls of the room. The frames and the attached cardboard were both stationary with respect to room movements. The floor within the room was covered by a gymnastic mat (5 cm thick) to provide cushioning for falls. Experimental sessions were recorded on 0.5 in (VHS) color videotape with an RCA Newvicon color video camera.

2.3 *Procedure*

Subjects were run individually, except for one pair of older subjects, who were run simultaneously because they were siblings. The experimental setting is illustrated in figure 1a. The child and one of his or her parents entered the room, and the parent was instructed to sit facing out of the room. Parents were told that the object of the experiment was to see if the visible motion of the room walls would have any effect on their child's standing posture, and that they should encourage the child to stand facing them (ie into the room). They were told that any method of encouragement was acceptable, so long as the child faced into the room and stood unsupported. Parents were not instructed to either encourage or discourage walking (an experimenter did this when necessary).

Once the child was on his or her feet an experimenter moved the room by manually pushing or pulling one of its structural members. The room was moved alternately forward and back, through a distance of approximately 15 cm, each movement lasting

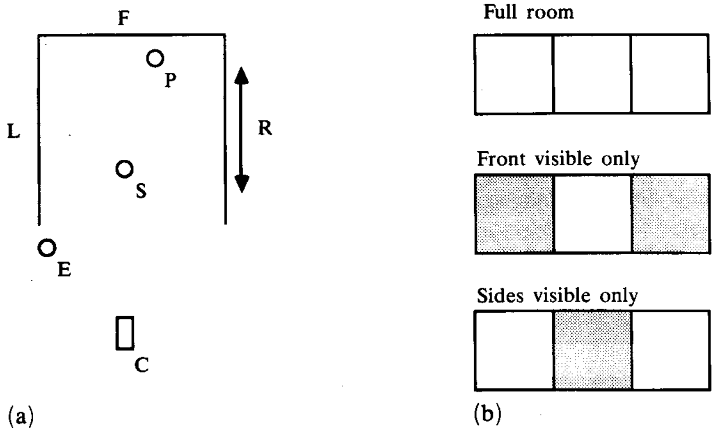

Figure 1. (a) Experimental setting. S, subject; P, parent; E, experimenter; C, video camera; L, F, R, left, front, and right walls of the experimental room. (b) Experimental conditions. Shaded walls were blocked by stationary opaque screens.

about 1.5 s. After each trial the experimenter waited until the child had regained a stable posture and was appropriately positioned before initiating the next movement. After several trials had been run in the initial condition the experimenter either installed or removed appropriate opaque screens to switch to the second condition, after which the session resumed as before. Within the constraints of the child's cooperation an attempt was made to run approximately equal numbers of trials in each condition. Parents were debriefed after each session.

2.4 *Conditions*

There were three experimental conditions: full room, in which the entire interior of the room was visible; sides visible only, in which the front wall was occluded by a stationary screen while the side walls remained visible; and front visible only, in which the left and right walls were occluded while the front wall remained visible (figure 1b). Each child participated in two conditions. All children were exposed to the full room, and half were exposed to each of the other two conditions. Half the children had the full room first, and half had it second.

The effective visual angles of these exposures varied owing to uncontrollable variations in subject position within the room. For a child standing as far as possible from the front wall the combined visual angle of the left and right walls was close to 120 deg, whereas the front wall subtended 60 deg visual angle. Positions further into the room resulted in larger effective visual angles for the front wall, with correspondingly smaller angles for the side walls.

Although the younger children, because of their smaller size, were able to walk comfortably within the confines of the experimental room, older children were not, as a rule, able to do so. For this reason, walking was not encouraged in the older group.

3 Results

The videotape records of experimental sessions were evaluated by two trained coders. The tapes were coded for the following data for each child for each condition: number of trials (room movements), response on each trial, the child's position in the room at the time of room movement, and whether the response was in the same direction as or in the opposite direction to the room motion.

Responses were broken down into two mutually exclusive categories that reflected differing magnitudes of response: staggers, and falls. Individual trials were assessed as being either standing, where the child was erect with both feet on the ground, or walking, in which the child walked along the axis of room motion. Trials were counted only if the anterior-posterior axes of the head and body were perpendicular to the front wall of the room. Other trials were excluded from the statistical analysis. The response rate for each subject was calculated as the number of staggers plus the number of falls, over the total number of trials. The number of trials per subject per condition ranged from two to nineteen, with a mean of seven. Inter-rater reliabilities were assessed for the trial quality, and response magnitude dimensions and were found to be above 0.97. Owing to the nature of the videotape records, blind coding was not possible.

Out of a total of 1166 standing and walking trials, only five responses were in the direction opposite to room motion, confirming the original findings of Lee and Aronson (1974), who found only two such responses in ninety-two trials(1).

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(1) Sways in the full-room condition occurred at a frequency comparable to that reported by Lee and Aronson (1974). Sways were not included in the statistical analysis, as they could be difficult to detect reliably through visual coding. This problem was especially acute in restricted flow conditions, where responses were expected to be reduced in magnitude. The exclusion of sways from our analysis also helped to minimize possible effects of coder bias. Staggers and falls were sufficiently unambiguous that they were easily detected even by naive viewers of the tapes.

As a measure of the children's normal stability, coders noted the number of falls that occurred between experimental trials, when the room was not moving. None were observed for the older children. Among younger children there was a mean of 0.83 falls per session without room movement, as opposed to a mean of 2.17 falls when the room was in motion. The no-movement fall rate was significantly greater than zero ($t_{29} = 3.02$, $p = 0.005$), indicating that the younger children had not completely mastered upright posture. However, the difference in fall rates between room movement and nonmovement was also significant ($t_{29} = 2.37$, $p = 0.024$). These statistics do not take into account the duration of movement versus nonmovement during parts of the sessions. On average, room movements occupied less than 20% of session time; the above statistical comparison is thus very conservative.

As noted above, subjects were free to move about the experimental room: there was thus a great deal of variation in the visual angles subtended by the front and side walls across trials. The minimum visual angle of the front wall was 60 deg, when subjects stood as far back in the room as possible. This position was rare, however, so that on the majority of trials the visual angle subtended by the front wall was considerably greater than 60 deg, with a possible maximum of approximately 120 deg. As a measure of the effect of visual angle, trials were coded for whether the child was in the front, middle, or rear third of the room (the boundaries between sections were clearly visible as creases in the gymnastic mat on the floor). Analyses of variance showed that position within the room did not affect response rate in any condition, with either age group.

3.1 *Standing trials*

Response rates for the three room conditions for standing and walking trials are shown in table 1, for younger and older subjects. For the younger children, room movements induced a level of compensatory responses significantly greater than zero in all cases, although the effect was smallest for the front-visible-only condition. The older children showed significant responses both for the full-room and for the sides-visible-only conditions, but not for the front-visible-only condition. Analyses of variance showed no significant differences in response rates between condition-order groups in the full-room (control) condition ($F_{1,27} = 0.598$, $p = 0.426$) for the younger children. The same was true for the two groups of older children ($F_{1,22} = 2.627$, $p = 0.12$), and so groups of subjects were combined within age groups for further analysis.

Table 1. Mean response rate [(staggers + falls)/total trials] to optical flow for younger (<2 years) and older (2-5 years) children (*N*, number of subjects).

Condition	Younger	*N*	Older	*N*
Standing				
Full room	0.657**	14	0.339**	12
Front visible only	0.193**	15	0.049	12
Full room	0.563**	15	0.169*	12
Sides visible only	0.449**	14	0.131*	12
Walking				
Full room	0.637**	14		
Front visible only	0.291**	14		
Full room	0.648**	12		
Sides visible only	0.607**	12		

* Mean response rate > 0, $p < 0.05$; ** mean response rate > 0, $p < 0.01$.

For each child a difference score was calculated by subtracting their response rate in the experimental condition (either sides visible only or front visible only) from that in the full-room condition. If response rates between control and experimental conditions did not differ, the difference score would be zero. Therefore, statistical tests evaluate the hypothesis that the mean differences did not equal zero. Eliminating central flow in the sides-visible-only condition did not cause a significant decrease in response rates for either the younger group ($t_{13} = 0.940$, $p = 0.364$) or the older group ($t_{11} = 0.700$, $p = 0.497$). Eliminating peripheral flow in the front-visible-only condition produced highly significant decreases in response rates both for the younger group ($t_{13} = 4.77$, $p < 0.001$) and for the older group ($t_{11} = 3.84$, $p = 0.003$). The effect of elimination of peripheral flow accounted for 63.6% of the variance in responses of the younger group, and 57.3% for the older group.

Comparisons between the two age groups revealed that in all conditions response rates were lower for the older children than for the younger ones. The age effect was significant in the full-room condition for both experimental groups (full-room control for front-visible-only group, $F_{1,24} = 7.22$, $p = 0.013$; full-room control for sides-visible-only group, $F_{1,25} = 11.90$, $p = 0.002$). The age effect was also significant for the sides-visible-only condition ($F_{1,24} = 11.06$, $p = 0.003$). There was a marginally significant effect of age for the front-visible-only condition ($F_{1,25} = 3.17$, $p = 0.087$).

The reduction in response rates for older children is particularly evident with falls, which were almost completely absent in the older age group (only two falls in four hundred and seventy-four trials, both in the full-room condition). There was a strong negative correlation ($r = -0.501$, $p < 0.0001$) between age and response rate for standing trials in the full-room condition (combining across age groups and condition groups; $N = 54$).

3.2 *Walking trials*

As discussed above, unrestricted walking within the room was possible only for the younger children, so only data from the younger group are presented here. Two of these children did not walk in one or both conditions, and were not included in the analysis. Of the remaining twenty-six children, twelve were in the full-room and sides-visible-only conditions, and fourteen were in the full-room and front-visible-only conditions. Response rates are presented in table 1. In all cases response rates were significantly greater than zero. There was no significant difference between the two groups of subjects in response rates for the full-room condition ($F_{1,25} = 0.008$, $p = 0.927$).

Evaluation of difference scores revealed that elimination of frontal flow in the sides-visible-only condition did not cause a significant decrease in response rates ($t_{11} = 0.78$, $p = 0.451$). Eliminating peripheral flow in the front-visible-only condition did, however, produce a significant decrease in response rates ($t_{13} = 3.84$, $p = 0.002$), accounting for 53.2% of the variance.

4 Discussion

4.1 *The control of stance*

The robust and highly consistent responses of all children in the full-room condition provide a strong replication of the results of Lee and Aronson (1974), showing that children who have only recently developed an upright posture are highly dependent on information in optical flow for the maintenance of postural stability. The strong effect of age on response rate confirms the results of Butterworth and Hicks (1977) and Forssberg and Nashner (1982), who found similar effects with related age groups, and extends the earlier findings to cover the present partial flow conditions.

The major result of the standing trials is the effect of the location of optical flow in the visual field. In both age groups the sides-visible-only condition was more effective in inducing compensatory responses than the front-visible-only condition, extending the findings of Stoffregen (1985). This result has recently been replicated by Bertanthal et al (1986). It thus appears that humans have a preference for the edges of the dynamically structured optic array in the control of stance at a very early age. These data also indicate that for children, as well as adults, the availability of flow to the fovea is not important in the use of optical information for the control of stance.

Although the younger group responded most strongly in the sides-visible-only condition, they also showed a significant level of responding in the front-visible-only condition. This indicates that the strong (but not exclusive) preference for peripheral flow found in adults is less fully developed in children who are just mastering upright stance. The lack of observed response to frontal flow in the older children does not imply that they had ceased to respond to posture-relevant information available in the front-visible-only condition. Instead, it reflects the limitations of the response measure (visible staggers or falls). With a more sensitive response measure, Stoffregen (1985; 1986) found small but consistent postural responses to frontal flow in adults.

A possible problem arises from the position of the parent between the child and the front wall. The parent occluded some portion of the front wall (at most about 20%), reducing the gross amount of optical flow from that wall. A direct assessment of the importance of this fact is not possible with the present data, but the role of visual angle as a function of the child's position within the room is relevant. As noted above, variations in the visual angle of the front wall (owing to variations in the children's position within the room) did not have a significant effect on response rates. This finding is consistent with that of Brandt et al (1973), who found that perceived egomotion in adults was robust over a wide range of visual angles of displayed flow.

4.2 *The control of locomotion*

In the walking trials, postural stability was affected by the visible movements of the room, and at the same time optical information was used in guiding locomotion, thus extending the work of Owen and Lee (1987). As with the standing trials, a strong preference for flow in the periphery of the dynamic structure of the optic array was apparent. Nevertheless, this preference was not exclusive: presentations of flow restricted to the center of the visual field resulted in a significant level of compensatory postural responses during locomotion, as well as during stance (see table 1). This indicates that parafoveal areas of the retina (and possibly the fovea as well) are capable of detecting information for postural control during visually guided locomotion.

4.3 *Flow structure versus retinal location*

The present results indicate that posture was more greatly affected by flow from the sides of the experimental room. Such effects have been interpreted by Dichgans and Brandt (1978) as indicating that the periphery of the retina is dominant for perception of egomotion. However, recent findings have brought this retinotopic interpretation into question. Stoffregen (1985) found that adults were preferentially sensitive to the dynamic structure of flow produced at the sides of a moving room, and that this sensitivity was largely independent of the area of the retina which sampled the flow(2). It thus seems likely that the children in the present study also differentiated between areas of flow on a spatiotopic rather than a retinotopic basis.

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(2) The optic array is defined in relation to a point of observation in space. Since the eye can rotate, the periphery of the retina and the periphery of the dynamic structure of the array need not correspond. This happens, for example, when an organism looks aside while locomoting. The center of flow geometry, the focus of optical expansion (Gibson 1950), will then project to the periphery of the retina (cf Stoffregen 1985). The words 'center' and 'periphery', when applied to the optic array, refer only to its dynamic geometric structure. The array itself covers 360°, and has no center or periphery as such.

4.4 *Geometric structure versus optical velocity*

The differentiation between information for postural control and information for guidance of locomotion observed in the present study could be based on existing differences in dynamic geometrical structure of flow, or on corresponding differences in optical velocity in different areas of the array. Optical velocity, however, is not a reliable source of information about egomotion, since it varies with the distance between the observer and the surround (Stoffregen 1986). Several findings suggest that the discrimination is based on variations in the geometric structure of optical flow rather than on differences in flow velocity. Postural responses in a variety of studies (including this study) with adults and children (Lee and Aronson 1974; Lee and Lishman 1975; Stoffregen 1985) have been elicited with flow velocities well in excess of those resulting from natural postural instabilities, implying at least that the absolute velocity of optical motion is not what determines its usefulness for controlling posture.

Also, recent work with adults (Stoffregen 1986) has concluded that geometric flow structure is more important than optical velocity in determining whether a given optical motion will elicit postural responses. It therefore seems possible that differentiations between areas of the optic array are based on variations in flow structure, in children as well as in adults. How the developing child learns to differentiate variations in flow structure is not yet known.

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