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ORIGINAL ARTICLE

Heading Perception in Patients with Advanced Retinitis Pigmentosa

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ABSTRACT: *Purpose.* We investigated whether retinis pigmentosa (RP) patients with residual visual field of <10° could perceive heading from optic flow. *Methods.* Four RP patients and four age-matched normally sighted control subjects viewed displays simulating an observer walking over a ground. In experiment 1, subjects viewed either the entire display with free fixation (full-field condition) or through an aperture with a fixation point at the center (aperture condition). In experiment 2, patients viewed displays of different durations. *Results.* RP patients' performance was comparable to that of the age-matched control subjects: heading judgment was better in the full-field condition than in the aperture condition. Increasing display duration from 0.5 s to 1 s improved patients' heading performance, but giving them more time (3 s) to gather more visual information did not consistently further improve their performance. *Conclusions.* RP patients use active scanning eye movements to compensate for their visual field loss in heading perception; they might be able to gather sufficient optic flow information for heading perception in about 1 s. (Optom Vis Sci 2002;79:581–589)

Key Words: heading, retinitis pigmentosa, optic flow, eye movement, focus of expansion, mobility

When an observer moves in a stable environment, the pattern of light reflected to the moving eye undergoes a lawful transformation known as optic flow.[1, 2] Optic flow can provide a visual basis for the control of human mobility because it contains information about the observer's direction of self-motion, the heading. For example, when the observer is moving on a straight path with no eye, head, or body rotation, optical velocity vectors in the image plane on the retina radiate outward from a "focus of expansion" (FOE) that stays constant in the image plane. This FOE indicates the observer's heading direction (Fig. 1). It has been shown that normally sighted observers could locate FOE and judge heading with an accuracy of 1° to 2° visual angle for a variety of surface types (e.g., a ground plane, a frontal surface, and a three-dimensional random-dot cloud).[3–5]

Several researchers have examined how the size of the field of view influences the observer's heading perception. It is possible that a large field of view surrounding the observer is important for detecting the direction of self-motion in the environment because information throughout the flow pattern specifies self-motion. If so, a restricted field of view should result in a lower sensitivity to self-motion and a reduced accuracy in heading perception.[6, 7] However, using a small field of view of 10° in diameter, Warren and Kurtz[8] as well as Crowell and Banks[9] have found that as long as the simulated FOE is within the small field, heading perception can be as accurate as when the field of view is 40° wide. Cornelissen and van den Dobbelsteen[10] simulated field loss by locking a 5° field of view to observers' gaze direction and asked them to look at their perceived heading direction in the flow. Although it took subjects longer to respond with a 5° than with a 40° field of view (>30% increase), heading errors were <4° at the lowest speed tested (1 m/s). This was within the required heading perception accuracy (6°) for successful way finding.[11] Thus, all these findings indicate that with a small field of view where peripheral vision is limited, observers can perceive heading accurately. This is due to the fact that the flow pattern is highly redundant, with each motion vector providing an additional estimate of the heading, yet vectors nearer to the FOE give more reliable estimates because they are less affected by noise.

In the current study, we investigated whether the above findings can be extrapolated to patients with retinitis pigmentosa (RP). RP is an inherited disease of the retina in which light-detecting cells degenerate. The loss of function of the rod photoreceptor cells precedes the loss of cone vision and first diminishes a patient's ability to see in the dark (night blindness); with time, it also diminishes peripheral vision and constricts the visual field. Patients with RP usually lose almost all of their peripheral vision, but central vision may remain intact and functions almost normally. Although patients with RP have been reported to have impaired

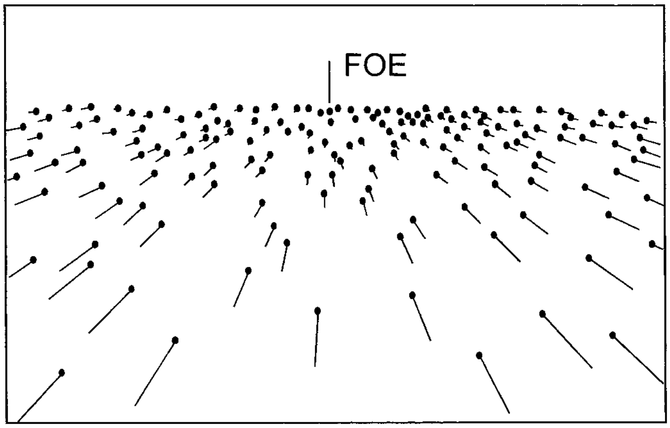
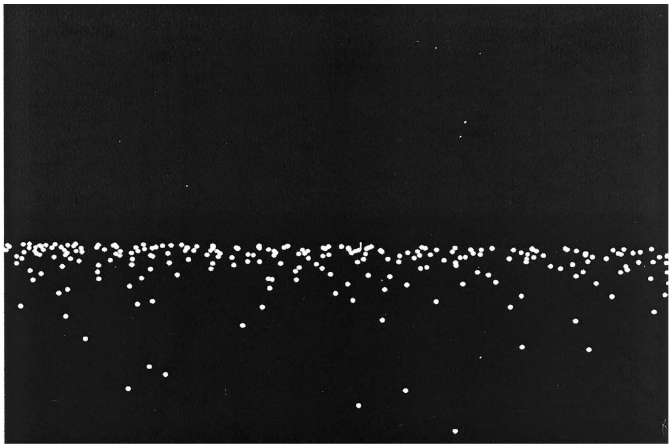


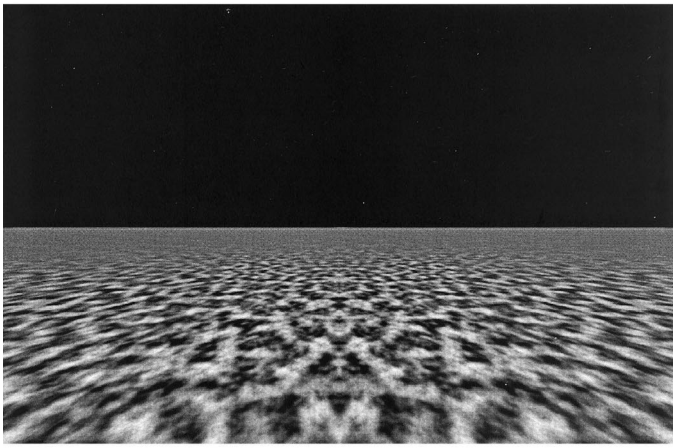
FIGURE 1.
Retinal velocity field for walking over a ground plane. Each vector represents the flow vector of an element in the scene. An observer is walking toward the vertical line without eye, head, or body rotation. The focus of expansion (FOE) indicates the heading.

mobility,[12, 13] it is still not clear how their constricted visual field affects their mobility. It could be that they cannot perceive their heading accurately or that they cannot see obstacles in their path and spend more time scanning for them. There are two limitations in interpreting previous studies to mean that RP patients are able to perceive heading from optic flow. First, the display used in those studies was a three-dimensional random-dot cloud, which is rarely experienced in daily life. More importantly, the studies tested normally sighted observers with temporary, simulated visual field defects in the display, whereas RP patients have permanent, naturally restricted visual fields on their retina. These two groups could have different strategies to determine heading, thus the findings from normally sighted subjects cannot be extrapolated to RP patients.

We examined whether RP patients with <10° visual field can perceive heading from optic flow and, if so, how fast they can gather sufficient information for heading perception. We tested two display conditions with an increasing degree of naturalness. The *random-dot ground* (Fig. 2a) was more natural than the random-dot cloud used in previous research. The dots were uniformly distributed on a ground plane, and their distances were continuously varied. The *textured ground* (Fig. 2b) was mapped with a multiscale grass-like texture so it resembled a meadow. The textured ground contains dense motion parallax information. In a previous study, Li and Warren[14] found that heading perception with simulated eye rotation was better on the textured ground than on the random-dot ground for normally sighted observers. In the current study, we found that with active scanning eye movements, RP patients can perceive heading from optic flow, and their performance on the random-dot ground is comparable to that on the textured ground. Furthermore, increasing display duration from 0.5 s to 1 s improves patients' heading performance, but giving them more time (3 s) to gather more visual information does not consistently further improve their performance. This suggests that the patients might be able to find the FOE in the flow in about 1 s despite their small visual field.



(a)



(b)

FIGURE 2.
Display conditions in the experiments. a: Random-dot ground. b: Textured ground.

METHODS
Patients

Four male RP patients, BM, GW, RS, and HA (51 to 65 years old) were recruited from the New England Eye Center (Boston, MA). Before the commencement of the study, we measured their left and right eye visual field separately using the Bausch & Lomb Auto-Plot perimeter. The Auto-Plot perimeter is a mechanical kinetic perimeter that allows examination of the central 50° (diameter) of the visual field. The perimeter projected small circular spots of light onto a screen 1 m away from the patient's viewing point. While the patient was asked to maintain a steady gaze on a bright red spot at the center of the screen, a white spot (6-mm diameter) was introduced and moved on the screen. The patient was asked to orally report when the target appeared in their visual field. This process was repeated several times until the shape of the patient's visual field was identified. Measurements were taken in a dimly lit room (0.21 ft-c: Minolta Illuminance meter TL-1), with a screen luminance of 0.021 cd/m^2 (Minolta LS 110 spot photometer). Fig. 3 depicts the measured visual field for each of the four patients. Among them, BM and GW had a slightly larger than 5° binocular visual field, and RS and HA had approximately a 10° visual field. All four patients had normal or corrected-to-normal vision and walked effectively with the aid of a long cane.

Displays

Displays simulated the flow field of an observer walking over a ground at a speed of 2 m/s. The heading direction was selected randomly along the horizontal axis at 11 positions with respect to the center of the screen (0, ±2°, ±4°, ±6°, ±8°, or ± 10°). Positive values were to the right and negative values to the left of the center of the screen. They were crossed with two display conditions: (1) Random-dot ground—700 green dots were distributed on the ground plane (50 m wide × 20 m deep) with a mean density of 0.7 dots/m^2. The background was black. One dot was positioned in each cell (1.43 m × 1 m) of a rectangular grid, with its position randomly jittered from the center of the cell on each trial. Each dot consisted of a 2 × 2 cluster of pixels, and an anti-aliasing routine was used so that the centroid of the cluster moved smoothly over time. (2) Textured ground—the ground plane was

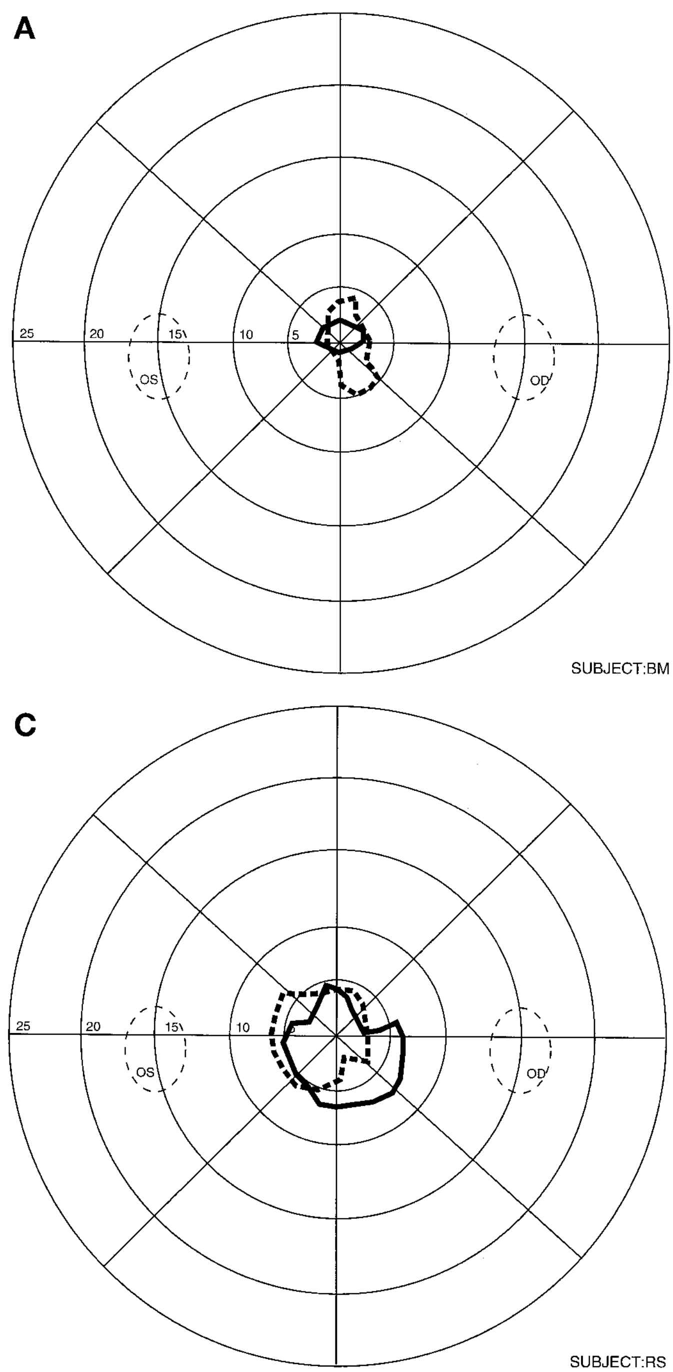


FIGURE 3.
Visual field plot for each of the four patients. Solid line indicates the measured visual field of the right eye; dashed line indicates the measured visual field of the left eye.

texture-mapped with a multiscale green texture composed of a filtered noise pattern with a power spectrum of $1/f^2$, where f is spatial frequency, for the range of frequencies from eight to 32 cycles per image. The background was again black.

The displays were generated on a Silicon Graphics Crimson Reality Engine at a frame rate of 30 Hz and were rear-projected on a large screen (112° horizontal × 95° vertical) with an Electrohome Marquee 8500 Ultra graphics projector with a 60-Hz refresh rate. Subjects viewed the screen binocularly from a chin rest at a distance of 1 m, positioned at the vertical midline of the screen. Simulated eye height above the ground plane was 1.1 m, the same as the height of the chin rest. The edges of the screen were in the periphery against a black background in a dark room, minimizing the possibility that they might provide a stationary frame of reference.

Procedure

On each trial, the first frame appeared for 1 s to allow observers to pay attention, followed by motion. The duration of motion was 3 s in experiment 1 and was varied from 0.5 to 1 s in experiment 2. The motion then stopped, the last frame remained visible, and a blue probe line (9.1° tall) appeared at the center of the screen at a simulated distance of 10 m. The azimuth position of the probe could be adjusted using a computer mouse. Subjects were instructed to place the probe in their perceived heading direction. The deviation angle between the simulated heading and their perceived heading (heading error) was measured to determine the subject's accuracy. The probe and the last frame remained visible until they clicked a mouse button to go to the next trial. To ensure that subjects understood the task and the response device, they received a set of practice trials before each condition. No feedback was provided on any trial. An experimental session typically lasted about 1.5 h.

EXPERIMENT 1: FULL-FIELD VS. APERTURE VIEWING

The purpose of this experiment was to compare the accuracy of RP patients and control subjects in perceiving heading from optic flow. The RP patients in this study all had severely restricted visual fields (<10°) and thus could not see the global motion in the flow to find the FOE for heading perception. However, they could perform scanning eye movements or extrapolate the local motion in a visible patch of flow to locate the FOE. We tested two viewing conditions. In the full-field viewing condition, patients viewed the display with free fixation so that they could actively scan the flow pattern to locate the FOE. In the aperture viewing condition, patients viewed the display through a computed aperture that was stationary on the screen, with a fixation point at its center (Fig. 4). The size of the aperture (5° or 10°) approximately matched the patient's visual field to ensure that the patient only saw the part of the display near the fixation point. If patients indeed use eye movements to locate the FOE in the flow to determine heading, we expected that heading judgments would not be affected much by the position of the simulated heading on screen in the full-field condition but would be in the aperture condition. If patients do not need to see the FOE but can extrapolate local motion in the flow to find heading, we expected comparable heading performance in the full-field and in the aperture conditions.

Methods

Subjects. Four RP patients and four age-matched normally sighted subjects participated in the present experiment. They all had normal or corrected-to-normal visual acuity (20/30 or better).

Displays. Both the random-dot and the textured ground displays were tested. The duration of display motion was 3 s.

Viewing Conditions. The two display types were crossed with two viewing conditions: (1) full-field viewing condition—no fixation point appeared during the course of the trial, and subjects viewed the whole display (112° horizontal × 95° vertical) with free fixation; (2) aperture viewing condition—a fixation point appeared at the center of a computer-generated aperture through which subjects viewed the display (Fig. 4). The aperture was fixed at the center of the screen, and its size was either 5° or 10° in diameter, approximately matching the size of the visual field of the patient being tested.

Procedure. Each patient and each age-matched control subject viewed the two types of displays in both the full-field and the aperture conditions in a counterbalanced order. In the aperture condition, two of the control subjects viewed the display with a 5° aperture and the other two with a 10° aperture. Each subject received 110 trials in each of the viewing conditions (10 at each simulated heading). Trials were blocked by display condition and viewing condition, randomized within blocks.

Results

Mean constant heading error is plotted as a function of the simulated heading in Fig. 5. A flat function indicates that heading judgments were unaffected by the position of the heading on the screen, whereas a positive slope indicates that the perceived heading overshot the simulated heading (toward the edge of the screen), and a negative slope indicates that it undershot (toward the center

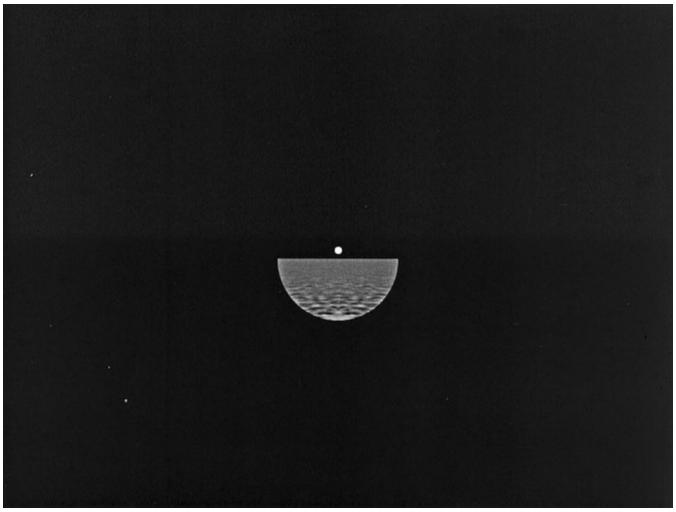


FIGURE 4.
The aperture viewing condition with the textured ground display. The white dot at the center is the fixation point.

of the screen). A negative slope of 1 indicates that the subject could not judge heading at all and always put the probe at the position of the fixation point at the center of the screen. Fig. 5 a and b shows the mean heading errors of the RP patients with 5° and 10° visual field, respectively. For patient BM, a multivariate regression analysis revealed that the slope for the textured display (−0.13) was not statistically different from that for the random-dot display (−0.06) in the full-field condition ($t_{36} = 1.97$, NS), but the slope for the random-dot display (−0.71) was shallower than that for the textured display (−0.86) in the aperture condition ($t_{36} = -3.95$, $p < 0.01$). Overall, the slopes in the full-field condition were significantly shallower than those in the aperture condition ($t_{40} = -20.23$, $p < 0.001$). The same pattern of results was found with patient GW. The slopes for the textured and the random-dot display were 0.1 and −0.04 ($t_{36} = -1.65$, NS) in the full-field condition but were −0.78 and −0.48 ($t_{36} = 3.66$, $p < 0.01$) in the aperture condition ($t_{40} = -9.51$, $p < 0.001$). For patient RS, the multivariate regression analysis showed again that the slopes in the full-field condition (−0.40 and −0.397) were significantly shallower than those in the aperture condition (−0.64 and −0.63) ($t_{40} = -9.8$, $p < 0.001$), but the slope for the texture display was not different from that for the random-dot display in either the full-field ($t_{36} = 0.06$, NS) or the aperture ($t_{36} = 0.27$, NS) condition. For patient HA, the slopes for the textured and the random dot displays (−0.23 and −0.07) in the full-field condition were again not different from each other ($t_{36} = 1.45$, NS) and were shallower than those in the aperture condition ($t_{40} = 8.10$, $p <$ 001). However, in contrast to the other three patients, the slopes in the aperture condition were positive, showing that HA overshot the actual heading, and the slope for the texture display (0.41) was

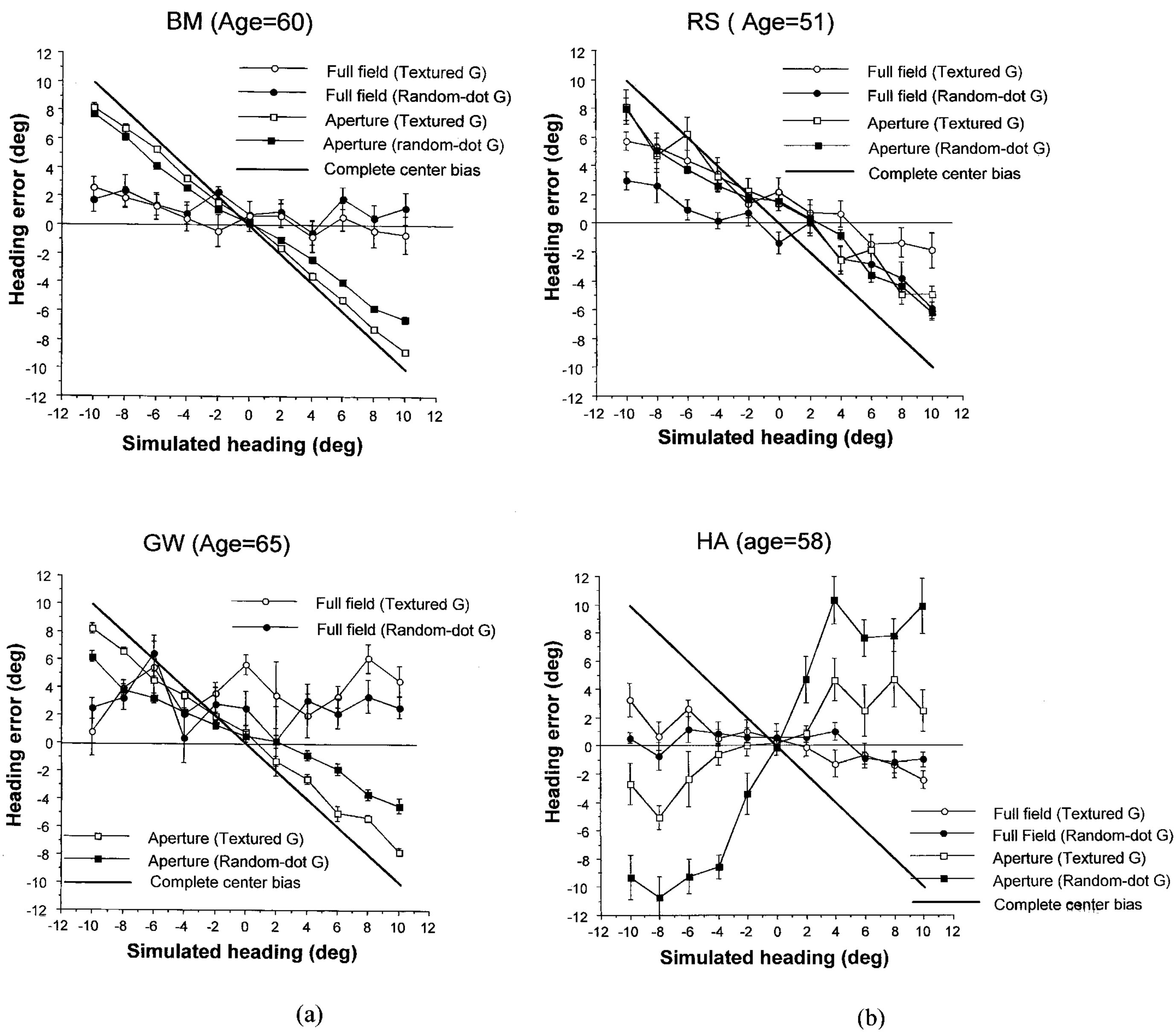
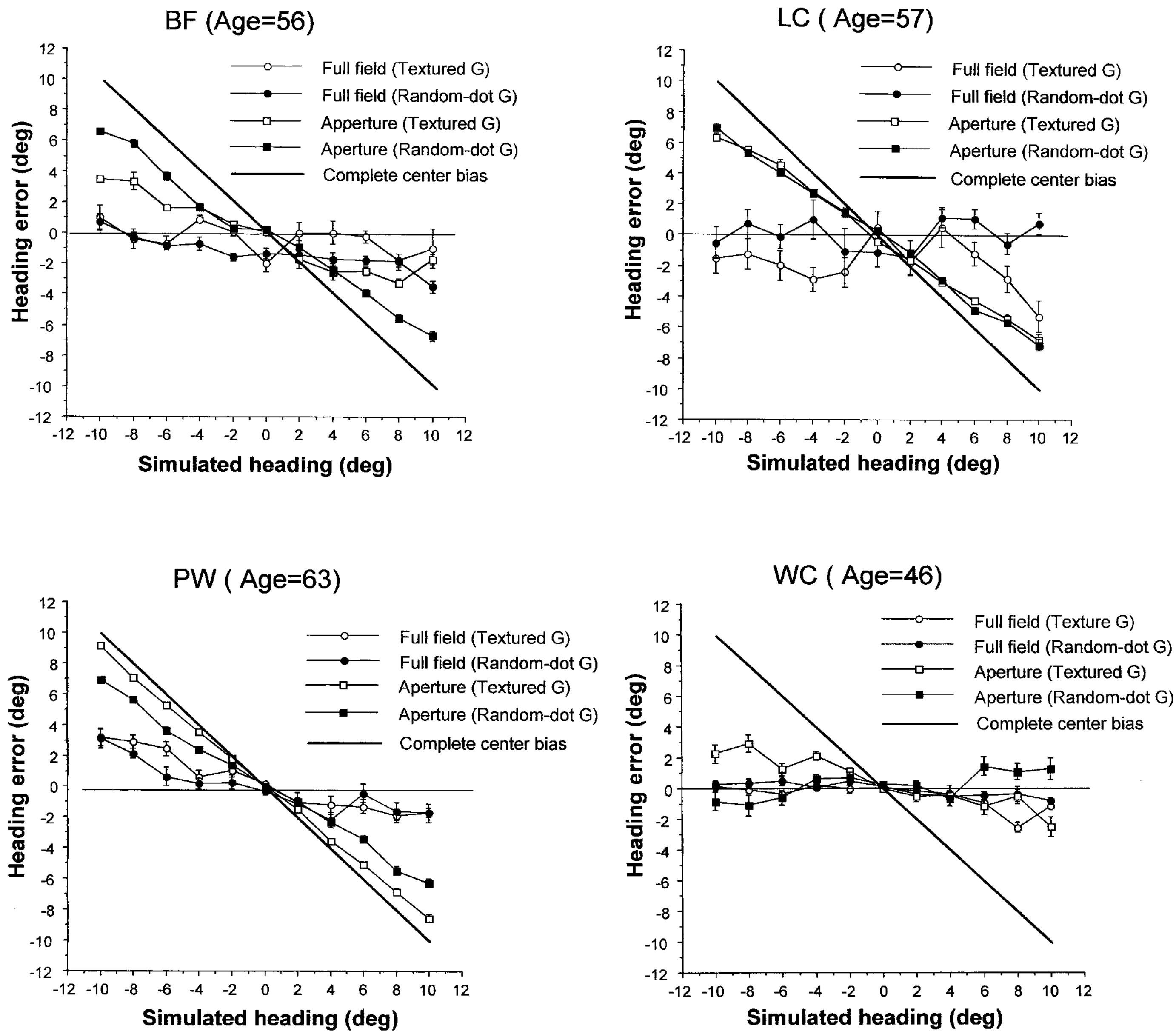


FIGURE 5.

Mean heading error as a function of the position of the simulated heading on the screen in experiment 1. a: Two RP patients (BM and GW) with approximate 5° visual field. b: Two RP patients (RS and HA) with approximate 10° visual field. c: Two age-matched control subjects (BF and PW) in 5° aperture condition. d: Two age-matched control subjects (LC and WC) in 10° aperture condition.



(c) (d)

FIGURE 5.
Continued.

shallower than that for the random-dot display (1.21) ($t_{36} = 7.09$, $p < 0.01$).

In summary, for all patients, slopes were shallower in the full-field condition than in the aperture condition, indicating a better heading performance with full-field free-fixation viewing. In the full-field condition, there was no indication that performance on the textured ground display was better than that on the random-dot display. In the aperture condition, there were mixed results about performance on the random-dot ground and on the textured ground. In the aperture viewing condition, all patients except HA displayed steep negative slopes, indicating large heading errors toward the fixation point. HA, on the other hand, displayed a large positive slope and thus appeared to use a different strategy to judge heading, which we will discuss later.

A similar pattern of results was found for the age-matched control subjects, as shown in Fig. 5 c and d. Except for WC, all age-matched control subjects displayed significantly shallower slopes in the full-field condition than in the aperture condition, with magnitudes comparable to those of the RP patients. For BF, the slopes for the textured and the random-dot displays, respectively, were −0.07 and −0.14 in the full-field condition and −0.33 and −0.64 in the aperture condition ($t_{40} = -7.66$, $p < 0.001$); for PW, the slopes were −0.28 and −0.22 in the full-field condition and −0.87 and −0.65 in the aperture condition ($t_{40} = -14.82$, $p < 0.001$); and for LC, they were −0.07 and 0.02 in the full-field condition and −0.69 and −0.71 in the aperture condition ($t_{40} = -11.98$, $p < 0.001$). WC displayed similar slopes (−0.09 and −0.06) for the textured and the random-dot displays in the full-field conditions (t_{36} = 0.77, NS); however, he had a slight negative slope for the textured display (−0.23) but a slight positive slope (0.10) for the random-dot ground display in the aperture condition (t_{36} = 9.22, $p < 0.001$).

Discussion

In the full-field viewing condition, the RP patients appeared to be able to perceive heading despite their small visual field, with performance comparable to that of the age-matched control subjects. In the aperture viewing condition, three of four RP patients displayed large negative slopes, indicating that they could not judge heading accurately and placed the probe near the fixation point at the center of the screen regardless of the position of the simulated heading on the screen. The patients with a 10° visual field did not show much improvement over those with a 5° visual field in this condition.

Patient HA displayed positive slopes in the aperture condition, indicating an increasing and constant bias toward the edge of the screen. During debriefing, HA reported that when he could not see the FOE, he tried to triangulate the visible flow vectors to locate the FOE to determine heading because the FOE is the common point of intersection of all flow vectors. As Koenderink and van Doorn[6] pointed out, there is noise in extracting the direction of local velocity vectors. Because this noise (direction error) increases as the flow pattern is sampled farther from the FOE, it introduces an increasing triangulation error that overshoots the FOE[15] (Fig. 6), accounting for HA's positive slopes in the aperture condition. The textured display provides a greater number of visible flow vectors than the random-dot display, thus the estimate of the common point of intersection is less likely to be affected by noise, accounting for HA's better performance with the textured display in the aperture condition.

Similar to the RP patients, three of the age-matched control subjects displayed strong center bias in the aperture condition and better heading performance in the full-field condition. WC (viewed 10° aperture) appeared to be able to judge heading well in both conditions. It is still unclear whether increasing the size of the aperture (from 5° to 10°) improves heading judgments for age-matched control subjects. We propose that the normal control subjects and RP patients behave alike in perceiving heading from optic flow. The inability of both normal control subjects and RP patients to judge heading in the aperture condition is due to the fact that active eye movements could not be executed to scan the full flow pattern, unlike in the full-field viewing condition. This suggests that observers need to sample from several positions in the flow field to be able to accurately perceive heading.

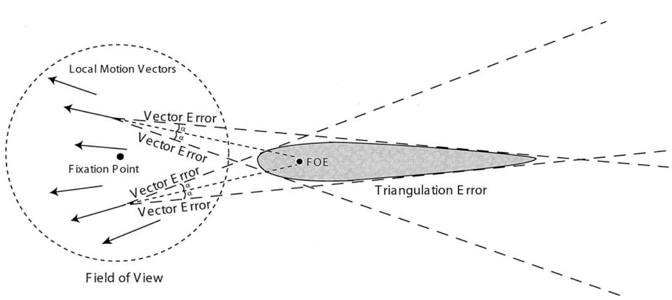


FIGURE 6.
A diagram illustrating the cause for the positive slope in heading estimation when the field of view does not include the FOE (adapted from Bardy et al.[15]). The dotted circle indicates the field of view of the observer. Estimating the position of the FOE requires estimating the intersection point of at least two local motion vectors seen within that field. Error in estimating the motion vectors (α), symmetrical about the actual direction of the local motion vectors, lead to a triangulation error (indicated by the asymmetrical ellipse). The asymmetry in shape of the ellipse results in the estimated FOE usually being farther away from the fixation point than the actual FOE. That direction will result in a positive slope of the heading curve.

EXPERIMENT 2: VARYING DISPLAY DURATION

Several research studies have reported that normally sighted observers can gather sufficient information from optic flow for heading perception in ≤0.5 s.[10, 16, 17] In the experiment by Cornelissen and van den Dobbelsteen,[10] normally sighted observers with simulated field constriction took longer to locate the FOE in the flow, and their reaction time varied inversely with the size of the simulated field of view. In particular, when the speed of the simulated motion in the display was 1 m/s, it took about 0.85 s for the observers with a 5° simulated field of view to respond and about 0.71 s for observers with an 8° field of view to respond. Furthermore, Cornelissen et al.[18] reported that in a letter search task, observers with simulated field constriction had increased fixation duration, thereby needing more time to scan the visual environment. Cornelissen et al.[18] concluded that compensating for a field defect by making eye movements is possible, but at the cost of an increased search time. To investigate whether this applies to RP patients with a natural visual field defect, we manipulated the display duration in the full-field viewing condition. We presented the display motion for three different durations (0.5, 0.75, and 1 s) and compared the patients' performance to that of the full-field condition in experiment 1 (display duration 3 s). If the patients have prolonged search time, heading errors should increase with the decrease in display duration.

Method

Subjects. The same four RP patients from experiment 1 participated in this experiment.

Displays. Both random-dot and textured ground displays were tested.

Display Duration Conditions. The two types of displays were crossed with three display durations: 0.5, 0.75, and 1 s. In each trial, the first frame appeared for 1 s, followed by motion for the specified duration. Subjects viewed the whole display (112° horizontal × 95° vertical) with free fixation.

Procedure. Each patient viewed the two types of displays in three duration conditions in a counterbalanced order. Each patient received 110 trials in each duration condition (10 at each heading direction). Trials were blocked by display type and display duration, randomized within blocks.

Results

In experiment 1, we observed that the increased naturalness in the display (textured vs. random-dot ground) did not influence heading judgments in the full-field condition. Thus, we collapsed patients' heading performance data over display types. A multivariate analysis on the performance data of the four patients showed that the mean slopes for the 0.5-, 0.75-, and 1-s display duration conditions were −0.36, −0.32, and −0.21, respectively. Although the slopes in the 0.5-s duration condition were not different from those in the 0.75-s condition ($t_{168} = 0.75$, NS) and the slopes in the 0.75-s condition were not different from those in the 1-s condition ($t = 1.89$, NS), the slopes in the 0.5-s condition were significantly steeper than those in the 1-s condition ($t_{84} = 2.81$, $p < 0.01$), indicating an improvement in heading performance when the display duration increased from 0.5 s to 1 s. We then compared the slopes in the 1-s duration condition with those in the full-field condition of experiment 1 that had a 3-s display duration. We found that the slopes in the 1-s duration condition (−0.21) were not different from those in the 3-s duration condition in experiment 1 (−0.16) ($t_{168} = 1.0$, NS), indicating that increasing display duration from 1 s to 3 s might not help to further improve patients' heading performance. Patients' slope data for the four display durations appear in Fig. 7.

The analysis of each patient's slope data showed that the four patients displayed different pattern of performance improvement over display duration increase. Whereas BM and HA showed a saturated heading performance at the display duration of 1 s, GW showed an improvement in heading judgment only when the display duration was increased from 1 s to 3 s ($t_{36} = 2.24$, $p < 0.03$), indicating that it might take GW longer to find the FOE. On the other hand, patient RS, who displayed large heading errors (high slopes) with the full-field condition in experiment 1, did not show any improvement in heading performance at any display duration tested, indicating that he might be using a different strategy to perceive heading from the flow.

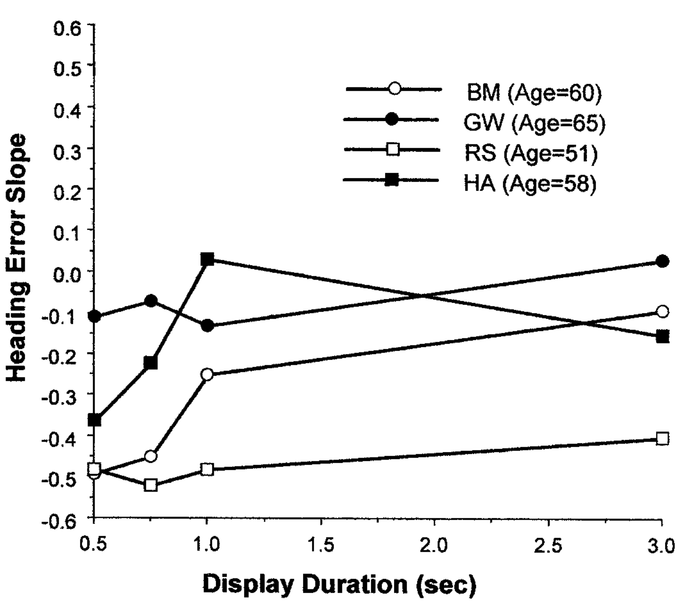


FIGURE 7.
Heading error slopes as a function of display duration.

Discussion

In accordance with the findings of Cornelissen and van den Dobbelsteen[10] on the increased heading perception time of normally sighted observers with simulated field constriction, we found that RP patients' heading performance improved when the display duration was increased from 0.5 s to 1 s. This improvement suggests that RP patients continue to gather information from optic flow up to at least 1 s for accurate heading perception. It is possible that RP patients have developed compensatory strategies to reduce the influence of a permanent field defect. One such strategy could be to use active scanning eye movements to search the flow pattern and locate the FOE. Due to their constricted visual field, RP patients might need more time to scan than normally sighted observers do. The mean saccadic latencies for RP patients are about 200 ms, so their relatively accurate heading performance at 1-s display duration implies that they are able to find the FOE within 5 saccades. In contrast, previous studies reported that normally sighted observers can locate the FOE in the flow field in only 2 saccades on average.[17] However, given the specific task and displays we used and relatively old age of patients in the experiment, it might be too early to conclude that RP patients take more time than age-matched normally sighted observers to perceive heading from optic flow. Furthermore, the individual differences in patients' heading performance suggest that not all patients may use the same strategy (e.g., locate the FOE) to gather information from the flow for heading perception.

CONCLUSIONS

We draw several conclusions from the present experiments. First, age-matched normal control subjects and RP patients behave alike in perceiving heading from optic flow. The relatively accurate heading judgments in the full-field viewing condition suggest that observers need to sample several positions in the flow field to be able to determine heading accurately, and RP patients are able to use active scanning eye movements to compensate for their visual field loss. Second, RP patients' relatively stable performance at 1-s display duration suggests that they might be able to gather sufficient optic flow information for accurate heading perception in about 5 saccades.

To our knowledge, this is the first study that has examined heading perception of RP patients. The question remains whether our results can predict the effects of field constriction on RP patients' real-world mobility problems. Many real-world locomotion tasks, such as running, biking, or driving involve keeping track of heading direction, and our results suggest that RP patients can do this successfully when there are no other distracting visual tasks. It is possible that due to their constricted visual field, RP patients might not be able to detect potential obstacles on their path and thus trip and fall more frequently than normally sighted people do. Indeed, some of our RP patients report that they have little difficulty in moving around in their home, where they know the exact positions of the furniture. However, if someone in their family moves a chair to a new position, they are likely to collide with it.

The source of poor mobility behavior might also lie in cognitive processes. Even though RP patients can use active scanning eye movements to compensate for visual field loss, the information they obtain in each scan is piecemeal and may not overlap with that from the next scan due to the constricted visual field. Consequently, when they try to use piecemeal information from a series of eye scans to determine the layout of the surrounding environment, the relative positions of objects could be distorted. This distortion can lead to difficulty in plotting a route to a goal or remembering their path sufficiently well to return home. Such issues regarding the causes of poor mobility in RP patients call for further investigation.

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REFERENCES

1. Gibson JJ. Perception of the Visual World. Boston: Houghton Mifflin, 1950.
2. Gibson JJ. The Senses Considered as Perceptual Systems. Boston: Houghton Mifflin, 1966.
3. Warren WH Jr, Morris MW, Kalish M. Perception of translational heading from optical flow. J Exp Psychol Hum Percept Perform 1988;14:646–60.
4. Warren WH Jr, Blackwell AW, Morris MW. Age differences in perceiving the direction of self-motion from optical flow. J Gerontol 1989;44:147–53.
5. Warren WH Jr, Blackwell AW, Kurtz KJ, Hatsopoulos NG, Kalish ML. On the sufficiency of the velocity field for perception of heading. Biol Cybern 1991;65:311–20.
6. Koenderink JJ, van Doorn AJ. Facts on optic flow. Biol Cybern 1987;56:247–54.
7. te Pas SF, Kappers AM, Koenderink JJ. Detection of the sign of expansion as a function of field size and eccentricity. Percept Psychophys 1996;58:401–8.
8. Warren WH, Kurtz KJ. The role of central and peripheral vision in perceiving the direction of self-motion. Percept Psychophys 1992;51:443–54.
9. Crowell JA, Banks MS. Perceiving heading with different retinal regions and types of optic flow. Percept Psychophys 1993;53:325–37.
10. Cornelissen FW, van den Dobbelsteen JJ. Heading detection with simulated visual field defects. Vis Impair Res 1999;1:71–84.
11. Vishton PM, Cutting JE. Wayfinding, displacements, and mental maps: velocity fields are not typically used to determine one's aimpoint. J Exp Psychol Hum Percept Perform 1995;21:978–95.
12. Lovie-Kitchin J, Mainstone J, Robinson J, Brown B. What areas of the visual field are important for mobility in low vision patients? Clin Vis Sci 1990;5:249–63.
13. Marron JA, Bailey IL. Visual factors and orientation-mobility performance. Am J Optom Physiol Opt 1982;59:413–26.
14. Li L, Warren WH Jr. Perception of heading during rotation: sufficiency of dense motion parallax and reference objects. Vision Res 2000;40:3873–94.
15. Bardy BG, Warren WH Jr, Kay BA. The role of central and peripheral vision in postural control during walking. Percept Psychophys 1999;61:1356–68.
16. Crowell JA, Royden CS, Banks MS, Swenson KH, Sekuler AB. Optic flow and heading judgments. Investigat Ophthalmol Vis Sci 1990;31(Suppl):522.
17. Hooge IT, Beintema JA, van den Berg AV. Visual search of heading direction. Exp Brain Res 1999;129:615–28.
18. Cornelissen FW, Brenner E, Kooijman AC. Visual search with simulated field defects. Investigat Ophthalmol Vis Sci 1998;39:S164.

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