Eye Movements of Patients with Tunnel Vision While Walking

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PURPOSE. To determine how severe peripheral field loss (PFL) affects the dispersion of eye movements relative to the head in patients walking in real environments. This information should help to define the visual field and clearance requirements for head-mounted mobility visual aids.

METHODS. Eye positions relative to the head were recorded in five patients with retinitis pigmentosa who had less than 15° of visual field and in three normally sighted people, each walking in varied environments for more than 30 minutes. The eye-position recorder was made portable by modifying a head-mounted system (ISCAN, Burlington, MA). Custom data processing was implemented, to reject unreliable data. Sample standard deviations of eye position (dispersion) were compared across subject groups and environments.

RESULTS. The patients with PFL exhibited narrower horizontal eye-position dispersions than did the normally sighted subjects (9.4° vs. 14.2°, $P < 0.0001$), and the vertical dispersions of patients with PFL were smaller when they were walking indoors than when walking outdoors (8.2° vs. 10.3°; $P = 0.048$).

CONCLUSIONS. When walking, the patients with PFL did not increase their scanning eye movements to compensate for missing peripheral vision information. Their horizontal scanning was actually reduced, possibly because of lack of peripheral stimulation. The results suggest that a field of view as wide as 40° may be needed for closed (immersive) head-mounted mobility aids, whereas a much narrower display, perhaps as narrow as 20°, may be sufficient with an open design. (*Invest Ophthalmol Vis Sci.* 2006;47:5295–5302) DOI:10.1167/iovs.05-1043

T unnel vision, or severe peripheral visual field constriction, impairs mobility by causing difficulties in navigation and orientation and a reduced ability to spot obstacles. In most jurisdictions, patients are considered legally blind if their residual visual field is less than 20° along the horizontal meridian. Diseases such as retinitis pigmentosa (RP), choroideremia, and advanced glaucoma can cause this type of peripheral field loss (PFL).[1-3] Approximately 2% of adults older than 40 have glau-coma.[1] An estimated 0.020% to 0.035% of individuals have RP.[1,4]

Many patients with severe PFL retain good visual acuity until an advanced stage of the disease; therefore, the main difficulty for these patients is gathering sufficient information about the environment for effective orientation and navigation.[5] A wider range of scanning eye positions in patients with PFL than in normally sighted people is presumed necessary both horizontally (to avoid lateral obstacles or detect objects approaching from the side) and vertically, particularly in the downward direction (following paths or traversing uneven terrain, curbs, and stairs). Patients are frequently trained to scan the environment systematically and quickly, to gain the information necessary for navigation, in the hope that the resultant increased *dynamic field of view* will compensate to some extent for the reduced *static visual field*.[5] To our knowledge, it has not been demonstrated that larger scanning amplitudes are actually performed after such training or by such patients. Scanning can be achieved through eye movements alone or through a combination of eye and head movements. Eye movements are faster than head rotation and therefore may be more efficient. Thus, one might expect a wider dispersion of eye movements with severe PFL.

Turano et al.[6] measured the direction of gaze (affected by both eye and head movements) of patients with severe PFL (due to RP) while walking for approximately 1 minute. The scanning strategies of the patients with PFL differed from those of the normally sighted subjects: the mean angular area scanned by the gaze point was approximately 10 deg^2 in the normally sighted group, but it was about three times larger in the patients with PFL. Turano et al.[6] did not report which part of the increased gaze-point scanning was achieved through eye movements and which part through head movements. Knowledge of that division may help in designing and improving scanning training of patients with severe PFL.

In addition to the recommended increased scanning, several optical (minifying) visual aids have been proposed for rehabilitation of patients with severe PFL.[7] Minifying aids for navigation include handheld divergent lenses[8] and reversed spectacle-mounted telescopes.[9-12] The loss of resolution inherent in minification and the interaction of the dynamic field of the patients with the field viewed through the aid have been cited as reasons for rejection of these aids.[5,13] To overcome these limitations, we have proposed and implemented video-based augmented-viewing systems using see-through, head-mounted displays (HMDs).[14-16] Superimposing a low-resolution minified contour image over the residual visual field enables access to the wider field provided by the minification, while maintaining the full resolution of the natural view available through the display. The field of view through a mobility visual aid for a person with PFL should accommodate not only the patient's residual visual field, but also the dynamic field that the patient typically would access. Otherwise, the mobility aid may restrict the effectiveness of the patient's eye-scanning movements. In designing an HMD, achieving a large field of view is a major challenge. Thus, a good design has the smallest display field that satisfies the functional needs of a person with severe PFL. The field of the HMD can be scanned only with eye

movements, whereas the environment seen through the display may be scanned with both eye and head movements.

The purpose of this study was to measure the dispersion of eye positions in patients with severe PFL during independent mobility. We measured eye positions in patients walking for a long period (half an hour) in unfamiliar indoor and outdoor environments, including the many different visual tasks that such mobility entails. Eye movements were measured with reference to the head.

MATERIALS AND METHODS

The study was conducted in accordance with the tenets of the Declaration of Helsinki.

Subjects

Five patients with severe PFL due to RP were recruited, and three normally sighted people served as the control group. The inclusion criteria for patients were less than 20° total extent of residual horizontal and vertical visual field in both eyes, visual acuity with refractive correction of better than 20/50, and good independent mobility skills. Subjects' characteristics are summarized in Table 1.

Vision Measures

The monocular visual field extent in both eyes was measured by using a perimeter (AutoPlot; Bausch & Lomb, Rochester, NY), in a dim room with a 6-mm white-light target on a white board at a distance of 1 m. Monocular visual acuity was measured in both eyes (B-VAT II SG; Mentor O&O, Norwell, MA).

Eye-Tracking Equipment

A modified head-mounted eye-tracking setup was used (ISCAN with an RK426-PC board; ISCAN, Inc., Burlington, MA). An infrared (IR) video camera recorded eye pupil position relative to the head-mounted camera, while a second camera recorded the scene. The scene camera, approximately optically conjugated with the eye pupil, was used only for calibration purposes and to determine the walking environment in each segment during analysis. The video signals from the pupil and scene cameras were recorded with two small digital camcorders (ZR10; Canon, Lake Success, NY) that served as video cassette recorders (VCRs). Subjects carried the camcorders, the batteries, and the camera driver in a small shoulder bag.

In normal use, the ISCAN's pupil camera directly feeds the RK426-PC computer board (ISCAN), which performs a dark-pupil–tracking algorithm. In the current study, after the walking session, the recorded video was fed into the board. Each video field was sampled into 512 (horizontal; H) × 256 (vertical; V) pixels every 16.7 ms and was processed to estimate pupil center position (h, v), pupil diameter, and corneal reflection location.

To keep the *ISCAN* stable on the head during walking, we replaced the original headband with an adjustable head mount from an indirect ophthalmoscope. In addition, some subjects wore a silicone swimming cap under the head-mounted apparatus, to provide improved friction and stability.[17] This system interfered minimally with the normal view of the subjects, enabling use of habitual eye and head scanning, and could be worn without discomfort for extended periods while walking.

Eye-Movement Recording Procedure

The subjects each walked independently for more than 30 minutes in total, using their normal visual refractive correction and long canes. They performed free eye (and head) movements during their navigation and received no instructions other than to walk normally to various points along a route. Only walking directions to the next point were given. The environments were not controlled for either the number of pedestrians crossing or of obstacles. Subjects were not assisted; they located and opened doors, pressed elevator buttons, and so forth. The route was similar, but not identical, for all subjects because of the effects of weather, sun position, and building and sidewalk construction. The route included segments in unfamiliar indoor environments (including stairs, ramps, closed doors, elevators, and parking garage, in either a hospital or government office building) and city streets (including traffic, pedestrian crossings, and naturally occurring obstacles). Subjects spent several minutes in each environment (9 minutes on average). Because walking speed was not dictated, and the route was not exactly the same for all subjects (as explained above), the length of time for each subject in each environment varied (see Table 2 for data on recording duration). Due to recording artifacts, data from most segments were not processed in their entirety.

We tried to avoid bright sunny spots that would cause extended corneal reflections and result in failed detection of pupil position. Light blockers, such as sunglasses and tinted visors, were ineffective, and some patients rejected them. Therefore, cloudy days and late afternoons were preferred for outdoor walking. When the sun caused difficulties with eye tracking on a scheduled walk, the route was redirected where possible under arcades (covered passageways) in the shade of buildings, resulting in an outdoor environment that had some of the characteristics of the indoor environments. These segments were named "arcades" and were scored separately. After the whole recording session, subjects were debriefed about the strategies they generally followed when walking and navigating through environments similar to the ones in the study.

Each time a subject entered a new segment of the route, angular calibration recordings were made, so that any shifts of the headgear could be determined. We used a 3 × 3 grid of nine fixation targets (spanning approximately 18°) on a frame mounted with a lightweight boom (32 cm) on a portable bite bar with a customized dental imprint that assured stable and repeatable positioning. Eye positions were recorded with subjects fixating monocularly for a few seconds on each of nine fixation targets.

A calibration procedure was performed in the laboratory to determine the angle equivalence $(\alpha^*, \beta^*)_{m=1\ldots9}$ of the nine calibration

TABLE 1. Subjects' Characteristics

Subject	Field	VA (OD; OS)	Age (y)	Rx Correction	Mobility Aid
1_RP	10°	20/30; 20/30	66	Yes	Long cane
2_RP	12°	20/20; 20/20	59	Yes	Long cane
3_RP	15°	20/30; 20/30	76	No	Long cane
4_RP	7°	20/30; 20/50	34	No	Long cane, occasional
5_RP	11°	20/20; 20/40	54	No	None
1_NS	No visual loss	20/20; 20/20	73	Yes	None
2_NS	No visual loss	20/20; 20/20	64	Yes	None
3_NS	No visual loss	20/25; 20/30	66	Yes	None

RP denotes a patient with PFL; NS, a normally sighted subject; field, the binocular field horizontal diameter derived from two monocular field measurements; VA, visual acuity for each eye; Rx Correction, use of corrective lenses.

TABLE 2. Eye Position Dispersion for Each Subject and Data for Each Segment

Subject	Environment	S_H (deg)	S_V (deg)	Time (min)	Valid Samples (%)
Controls					
1_NS	Indoor	16.16	8.10	5.01	91
	Indoor	14.39	9.99	5.74	88
	Outdoor	13.84	9.97	7.93	87
	Indoor	14.74	9.44	5.73	86
	Outdoor	8.95	10.73	8.45	84
2_NS	Indoor	14.08	13.41	5.69	90
	Outdoor	12.73	6.96	6.80	89
	Indoor	14.34	5.93	6.27	92
	Outdoor	13.84	8.33	9.66	86
	Indoor	13.23	7.99	1.99	90
3_NS	Arcade	18.58	11.68	13.81	26
	Outdoor	16.50	11.07	11.10	29
PFL patients					
1_RP	Arcade	9.44	7.27	26.50	74
2_RP	Outdoor	8.71	10.31	5.05	91
	Indoor	8.24	5.84	3.61	92
	Indoor	8.68	8.16	4.88	96
	Arcade	8.56	10.99	18.37	60
	Arcade	8.72	11.05	22.24	41
3_RP	Arcade	10.38	9.73	14.21	70
	Outdoor	10.33	11.16	13.82	11
	Outdoor	7.71	5.91	5.50	8
	Indoor	10.70	4.98	3.84	58
4_RP	Indoor	9.28	7.96	13.52	88
	Indoor	8.48	9.91	5.22	89
	Outdoor	9.65	10.41	10.96	48
5_RP	Indoor	12.73	8.71	10.69	71
	Outdoor	10.66	10.35	10.17	47
	Indoor	11.86	9.26	2.63	73

Dispersion data: horizontal (S_H) and vertical (S_V). Segment data: environment, recording time, and percentage of useful samples. NS, control subjects; RP, patients with RP.

targets for each subject (described in the Data Processing section). We used either a picture of the calibration frame taken with the scene camera including known angular calibration markers or a perimeter monocular measurement of the subtended angle for each fixation point.

Data Processing

The first stage in data processing was to exclude erroneous data. The dark-pupil tracker sometimes failed to deal either with bright sunlight reflections off the cornea or when a large part of the image was as dark as the pupil. In addition, blinks, sudden illumination changes, and shadows could cause the instantaneous estimates of pupil position to be inaccurate. However, with the appropriate settings, the ISCAN was able to provide acceptable tracking for most of the frames.

We developed an automatic algorithm to discard erroneous frames, allowing the processing of large amounts of data with minimal operator intervention. First, we imposed limits on the acceptable horizontal and vertical position coordinates of the pupil center. The operator set these limits after reviewing the recorded video. Second, unreasonable pupil diameters were used, to detect erroneous eye-position data. Because the normal pupil dimensions changed along the walking route due to the variations in illumination, we imposed an adaptive rather than a fixed restriction on the pupil diameter. Figure 1 shows an actual plot of this adaptive pupil diameter selection. For each frame we calculated a running-average pupil diameter based on a temporal window of 1000 frames (16.67 seconds) centered on the evaluated frame. We rejected those frame data in which the pupil diameter was outside a range of ±200 ISCAN units from the average pupil diameter.

Additional corrections were also applied:

1. A slight bias or offset (arbitrarily selected up to 75 units) from the average signal toward the larger pupil diameters was intro-

duced. This adjustment compensated for the fact that small pupil diameters were more frequent in the unreliable frames. Therefore, the running-average diameter was, in these cases, smaller than the expected mean pupil diameter in the reliable frames.

2. We also imposed a minimum for the running-average pupil diameter (100 units) to reject those segments in which most of the frames were not useful (associated with very small pupil diameter estimates). The percentage of valid data obtained after all these procedures is reported in Table 2.

After eliminating erroneous data, valid data were converted from raw ISCAN units to angular eye rotations. The raw units (h, v) used internally by *ISCAN* for pupil position form a 5120×2560 matrix representing subpixel resolution. Each pixel of the eye camera corresponds to approximately 48 μm at the pupil plane (10 horizontal and 5 vertical *ISCAN* units). To convert the pupil pixel coordinates (h, v) into angular horizontal and vertical rotation of the eye (α, β), expressed in degrees, we arbitrarily used a quadratic polynomial expression

$$\begin{pmatrix} \alpha \\ \beta \end{pmatrix} = \sum_{i=0}^{2} \sum_{j=0}^{i} \begin{pmatrix} a \\ b \end{pmatrix}_{ij} h^j v^{i-j}, \qquad (1)$$

where $(a,b)_{ij}$ are the five pairs of polynomial coefficients obtained from the nine-point calibration grid.

To derive the conversion coefficients the angular coordinates $(\alpha^*, \beta^*)_m$ of the m-th calibration grid point (computed from the known grid size and distance from the observer measured in the laboratory calibration procedure) was fitted to the averaged pupil position
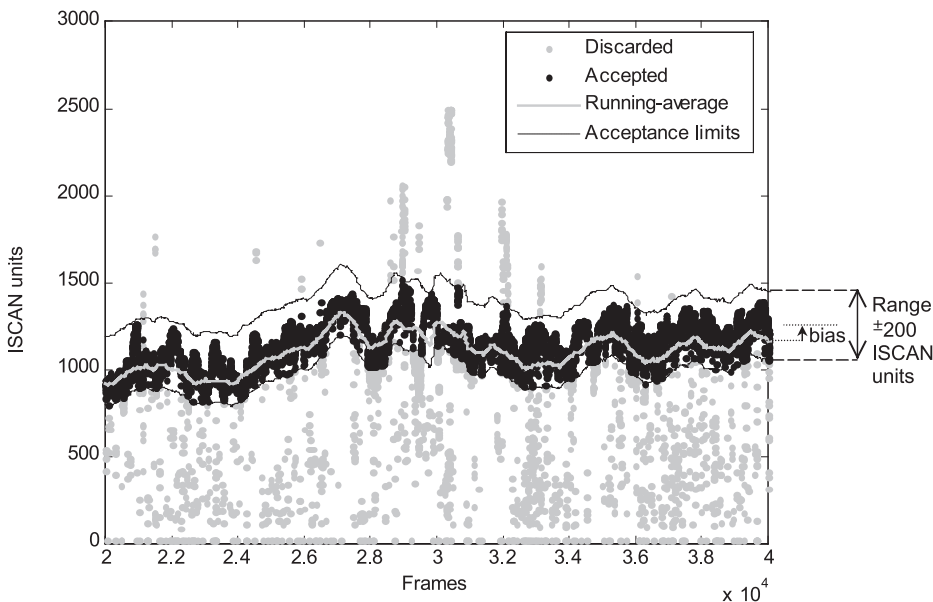
FIGURE 1. Frame rejection criteria based on pupil diameter. The graphic illustrates the pupil diameters obtained from the ISCAN in each frame during a time segment of approximately 5.5 minutes (each dot represents one data point). *Gray trace*: running-average pupil diameter; *black dashed lines, right*: allowed pupil diameter range (88% accepted frames). The acceptance band is set by the window size (in this case ±200 ISCAN units) centered on the bias-corrected running average.

(b_m, v_m) measured during fixation on each of the calibration targets. Using a least-squares algorithm for bidimensional second-order polynomial fitting in commercial software (MatLab; The MathWorks, Natick, MA), we obtained the coefficients $(a,b)_{ij}$:

$$\begin{pmatrix} \alpha^* \\ \beta^* \end{pmatrix}_{m=1\ldots9} = \sum_{i=0}^{2}\sum_{j=0}^{i}\begin{pmatrix} a \\ b \end{pmatrix}_{ij} b_m^j v_m^{i-j}, \qquad (2)$$

Characterization of Angular Eye-Position Dispersion

The entire recorded video from each subject was divided into segments corresponding to walks in specific environments. Each segment was preceded by a calibration recording and was assigned to one of three environment classes: indoors, outdoors, or arcades, based on the images provided from the scene camera in the post-processing. We characterized the eye position dispersion for each segment using the sample horizontal and vertical standard deviations (S_H, S_V referred to as dispersions) of the angular eye positions (α,β). Dispersion provides a measure of the range of eye movements during walking and thus provides a guide to the size of the field of view of a head-mounted device that might be useful as an aid for a person with severe PFL.

Statistical Analyses

To determine whether normal distributions could be assumed, Lilliefors two-sided normality tests were performed on the distributions of eye position (α, β), and the distributions of angular dispersion (S_H, S_V) of each group (normally sighted and PFL) in each environment, for horizontal and vertical components separately. The hypothesis of normality was rejected for all the eye-position distributions. Nevertheless, the dispersions, computed as standard deviations, are mathematically defined for any distribution. Because one sample of angular dispersions failed the normality test, we used a Wilcoxon two-sided rank sum test for all comparisons of the dispersions between groups and environments. All the analyses were performed in commercial software (Statistics Toolbox, ver. 5.0.1 of MatLab R14SP1; The MathWorks Inc., Natick, MA).

RESULTS

Figure 2 shows examples of bidimensional histograms of vertical and horizontal eye positions for one normally sighted subject and one patient with RP and PFL, for the indoor and outdoor segments. Data were binned in squares of 2° × 2°. The ordinates indicate the percentage of valid frames for which the eye was within each bin area. These histograms were selected because they present a smooth bell shape. The horizontal extent of the eye position dispersion for the patient with PFL is noticeably narrower than that for the normally sighted subject. When walking outdoors, the patient with PFL scanned over a larger vertical range than when indoors. The other histograms (not included) showed the same general patterns of eye-position dispersions; however, some were not as smooth as the ones presented in Figure 2.

Table 2 lists the results for each subject and segment chronologically, excluding the calibration segments and totally rejected segments. Valid Samples % specifies the percentage of accepted video frames in the segment with respect to the total number of frames of the recorded segment. This percentage provides an indication of the quality of the eye-tracking in that segment. As can be seen, many of the segments yielded approximately 90% valid data. The segments where the percent valid data was much lower were usually associated with bright outdoor weather conditions' impeding the recording.

Figure 3 shows a scatterplot representation of horizontal (S_H) and vertical (S_V) dispersions, where each point represents the collapsed data for all segments of each subject within each environment. In general, in the PFL patient segments, the horizontal eye position dispersion was narrower than in normally sighted subjects. It is also apparent that in the patients with PFL the vertical dispersion outdoors was larger than the vertical dispersion indoors.

In Figure 4, box plots show the horizontal (S_H) and vertical (S_V) dispersions obtained in the segments (as reported in Table 2), across groups (normally sighted and PFL) and for the relevant environments (indoors, outdoors, and total accumulation of segments including arcades). We excluded segments categorized as arcades from the comparisons, because we considered them to be weather-forced situations that did not exactly match either of the other conditions. Wilcoxon two-sided rank sum testing for identical populations revealed no significant differences ($P > 0.2$) between indoor and outdoor dispersions in normally sighted subjects, or the indoor and outdoor horizontal component for patients with PFL, and so we have presented only the collapsed totals for those conditions.
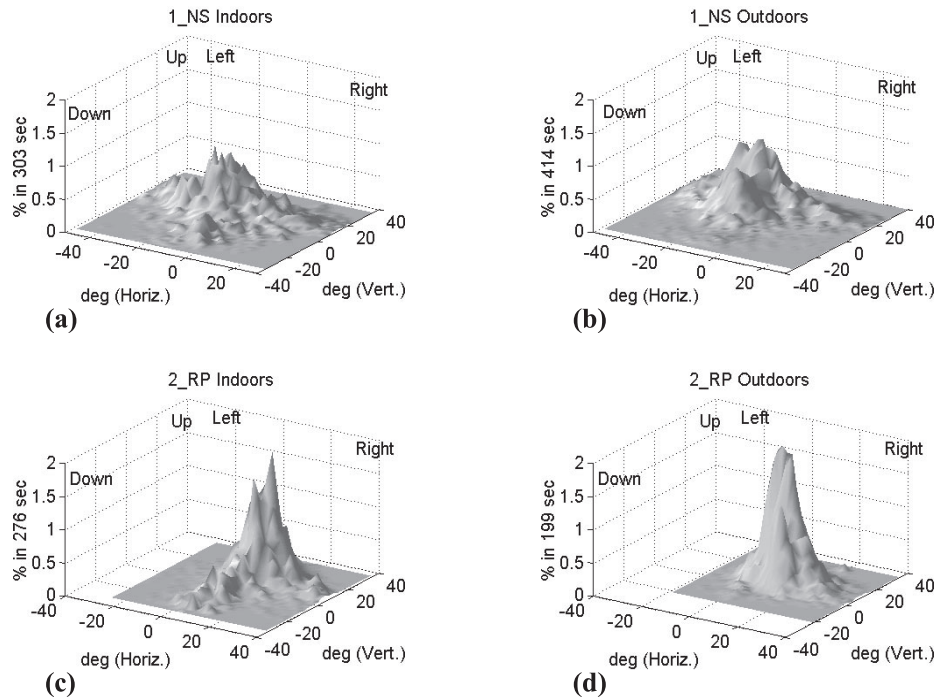
FIGURE 2. Examples of bidimensional histograms of vertical and horizontal eye position in two subjects and two conditions: (**a**) normally sighted subject (1_NS) indoors and (**b**) outdoors; (**c**) PFL (2_RP) indoors, and (**d**) outdoors. Note the change in pattern for the PFL patient between the two environments. Ordinate: percentage of valid frames for which the eye was within each bin area. The spatial position on the abscissas is relative to the central fixation point on the portable calibration grid.

Normally sighted subjects demonstrated a wider horizontal than vertical dispersion ($P = 0.0003$). However, in patients with PFL, vertical and horizontal dispersions were similar. Furthermore, both were equivalent to the normally sighted subjects' vertical dispersion. Patients with PFL demonstrated a narrower horizontal dispersion of eye positions compared with the normally sighted subjects. This was true for all environmental conditions ($P < 0.0001$). Although we expected to find a difference between groups, this result was the opposite of our expectation. Within the PFL group, we did not find any

correlation between the residual horizontal visual field extent and eye-position dispersion.

As shown in Figure 3, patients with PFL behaved slightly differently outdoors and indoors. Patients increased their vertical scanning dispersion while walking outdoors ($P = 0.048$) compared with walking indoors, as we would expect from their need to monitor obstacles or irregularities at ground level. We evaluated whether the increase in vertical dispersion when outdoors occurred mainly toward the lower field. Of the three subjects who performed both indoor and outdoor walks, two had a slight expansion of the distribution downward (as shown in the example in Fig. 2d), but the main effect was an overall (symmetric) increase in vertical dispersion.
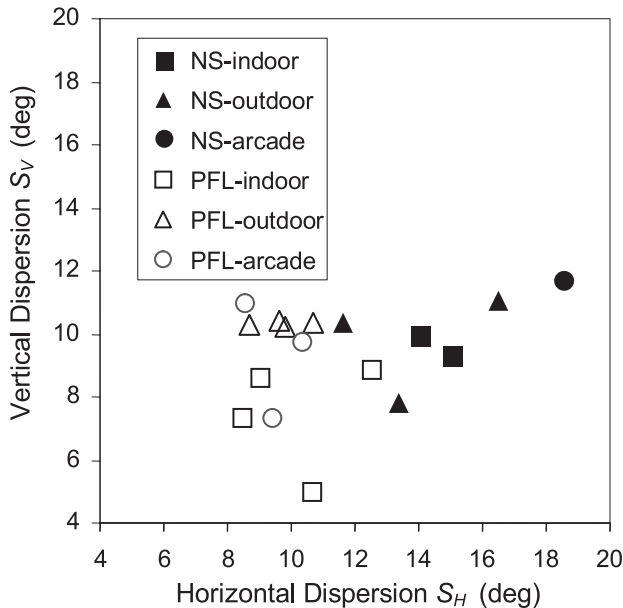

FIGURE 3. Horizontal and vertical eye position dispersions (standard deviations) in normally sighted subjects (NS) and patients with PFL. Each symbol corresponds to the data for a subject in a particular environment (indoors, outdoors, or arcades) collapsed over all segments.
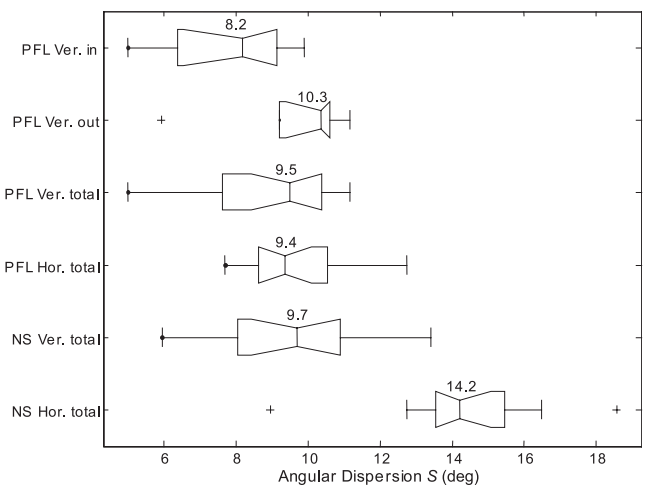

FIGURE 4. Box plots of angular eye position dispersion in normally sighted subjects (NS) and patients with PFL. Data are segmented by environmental condition: indoors (in), outdoors (out) and overall (total of in and out); and by dispersion component: vertical (Ver.) and horizontal (Hor.). Values for the sample *Boxes:* medians and quartiles; *whiskers:* remainder of the sample (unless there are outliers). +, outliers, values >1.5 times the interquartile range away from the top or bottom of the box.

DISCUSSION

Because we are developing field expansion devices based on HMDs, we measured the dispersion of eye movements relative to the head. We believe that this measure could help us define the necessary field of view to be used in such displays. A wide field of view is one of the most difficult parameters to achieve in HMD design and is usually associated with loss of resolution.[18] We also hoped to gain a better understanding of the variables that affect eye movements in the face of the challenges imposed by severe PFL (tunnel vision) when walking.

Our findings in normally sighted subjects (dispersion of 9.7° vertically and 14.2° horizontally) are comparable with the findings in a previous study conducted under similar conditions.[19] Bahill et al.[19] used electro-oculography (EOG) and reported only the distribution of saccade amplitude during extended walking on a college campus. They found that most saccades measured less than 15°. In the patients with PFL, we found dispersions of 9.5° in the vertical direction and 9.4° for the horizontal (approximately two thirds that of the normally sighted). Despite the small sample size, the difference in horizontal dispersion between patients with PFL and normally sighted subjects was found to be statistically significant.

Other studies of the effects of restricted visual fields on eye movements have been performed in different contexts. The recording methodology used by Turano et al.[6] was similar to ours, but they measured only a few seconds of indoor walking and analyzed mainly gaze position, identifying objects that were fixated. Other studies focused on gaze movements (meaning compound eye+head position) during search tasks on displays, either by normally sighted people with simulated PFL,[20] or by patients with PFL using an augmented-viewing device.[16]

The implication from our results is that head-mounted mobility visual aids for severe PFL may be effective, even with a relatively narrow field of view. A field of view covering four times the dispersion found would keep approximately 96% of fixations inside the active area of the visual aid, if eye fixations are assumed to be normally distributed. Consequently, desirable fields would be approximately 40° × 40°. On the one hand, immersive HMDs prevent any vision outside the active display area and may indeed require a field of view that wide. The required field may be even wider if the full extent of the residual field is to be within the display all the time. On the other hand, an open display design permits natural viewing outside the active area of the display. Therefore, to provide augmented visual information, the field of view of an HMD, to be implemented in a mobility visual aid for PFL, need not be more than double the eye position dispersion found in the PFL group. Hence, displays that subtend approximately 20° both horizontally and vertically may be sufficient. Such a display assures that, most of the time (approximately 64%), the line of sight of users with PFL will be within the active display field, providing useful information. Manufacturers of HMD-based magnifying low-vision aids generally seek wider fields of view. However, displays with a narrower field of view available at a lower price would make potential aids for PFL more affordable. Smaller displays should help patients with PFL locate their targets of interest within the display itself, since, in most cases, they would not have to scan the active area. With a smaller display, the patients would have less trouble identifying their own gaze location within the display. This self-localization helps them to achieve a quicker correspondence with the target location in the real environment. Luo and Peli[16] proposed the inclusion of guide grids in the active area of an HMD to help patients locate the center of the display. A similar difficulty in self-locating within a display field was noted for

simulated PFL in a visual search experiment with targets presented on computer monitors.[20]

We found a relative change in the vertical scan dispersion between indoor and outdoor environments for all patients with PFL. This behavior is probably associated with differences in the navigation and obstacle-avoidance demands of the two environments. On the one hand, a patient walking indoors might expect to find an even floor, with little concern for low-lying obstacles or abrupt changes in elevation. On the other hand, walking outdoors entails increased concern for ground-level obstacles (e.g., uneven pavement and curbs) and head-level obstacles (e.g., low tree branches). This would require less attention to the ground and a consequent reduction in the vertical dispersion indoors. Most of our patients with PFL used long canes to monitor the ground for obstacles and uneven pavement. One would expect that a patient who does not use a long cane might exhibit an even wider dispersion of vertical eye movements in outdoor mobility than we have found. Indoor mobility comes with an increased need to locate orientation features such as doors and hallways, as shown by Turano et al.[6] However, the horizontal angular span of such features is limited by the structure of the corridors. While outdoors, objects located at more distant lateral locations are used mostly for navigation rather than safe mobility (obstacle avoidance) and they can usually be spotted from a farther distance where their angular span is limited. Yet, the normally sighted subjects exhibited horizontal dispersions that were wider than their vertical dispersions. Possible reasons for this are discussed in the following text. These differences suggest that while a display with wider horizontal than vertical field (landscape mode) may be better for normally sighted users, a square or even a portrait mode display with wider vertical span may be more useful for patients with PFL, especially outdoors. For two of the three PFL subjects, who completed indoor and outdoor walks with a long cane, we found a trend toward an expansion of the vertical dispersion downward when outdoors (although the main effect was a symmetrical expansion). Patients who do not use long canes may tend to scan even more downward vertically. Thus, we suggest that an asymmetric setting of the display relative to the camera, using more of the display to cover the lower than upper field, may also be beneficial.[6]

The limited size of the display field of view does not imply that patients with PFL never use larger eye movements. In fact, we have found that they do perform occasional large scanning eye movements. Therefore, such visual aids should neither restrict nor block normal eye movements, nor restrict the dynamic visual field.[5] Moreover, since the severely restricted visual field of patients with PFL can be fully blocked by a small obstruction, the design of such displays and their field of fixation[21,22] should avoid even small peripheral obstructions (5–10°); therefore, immersive HMDs should be avoided for mobility applications. The term "clearance" of a visual aid, defined as the overall unblocked visual field, was adopted to indicate the field of view that allows unrestricted eye scanning by the user, both inside and outside the active display area of the visual aid.[15] As an example, some studies reported that patients with PFL found the field of the multivision night-vision goggles restrictive, even though they had a relatively wide display field of 32° × 24°.[23–25] The concept of clearance suggests that a narrow display is more likely to be useful if it is embedded within a clear carrier lens, which is one of the implementations we have proposed[15] and implemented.[16] Clearance of an HMD is not dissimilar to the peripheral field that is available to spectacle wearers outside of the rim of the frame, providing a non–optically corrected, yet important, area of visual field.

A plausible explanation for our main finding of reduced horizontal eye position dispersions in patients with severe PFL is that head movements play an important role in scanning. This must be confirmed in future studies recording eye and head movements under similar conditions. Patients with PFL may have a better sense of direction when they use their body heading as their main reference. Some of the subjects reported such a strategy when debriefed. They reported selecting a reference or landmark directly ahead in the direction in which they were walking and trying to keep that landmark in view, only briefly shifting their gaze to scan the path between them and the landmark or to check for likely sources of hazards. They indicated that it was quite difficult to recover their landmark if their gaze had been shifted away by scanning eye movements. By comparison, scanning with head movements seemed to facilitate recovery of the primary position of gaze and facilitate regaining of the landmark.

Patients with PFL may use a wider scanning strategy in some situations, although on average they show a reduced dispersion of eye position while walking. A wide scanning strategy may be used at a critical street crossing or when searching for a misplaced object. Such situations may be observed more readily by rehabilitation personnel, which may explain the clinical impression of increased scanning by these patients.

For normally sighted observers, saccades are usually aimed at some peripheral visual target. It is possible that the patient with PFL would not make eye movements aimed anywhere outside of the field, because of the lack of peripheral stimulation and therefore would have a restricted range of eye movements—a possibility that may be the main reason for our finding. This concept of saccade inhibition is implicit in the results of Luo and Peli.[16] They showed that patients with PFL have a reduced search time and an increased directness of the gaze path to a target placed outside the visual field, when using either auditory clues or an augmented-viewing aid. The augmented-viewing aid and auditory cues provided the missing peripheral information necessary to induce larger gaze movements toward the target stimulus. Cornelissen et al.[20] also speculated about the effect of PFL in limiting the ability to program efficient eye movements. Furthermore, there is evidence from reading eye movements in patients with hemianopia, that the lack of peripheral stimulation reduces saccade length; right hemianopes generally make smaller-amplitude saccades to the right along a line than do the normally sighted, and left hemianopes make many small-amplitude leftward saccades when returning to the beginning of the next line rather than the single large leftward return sweep saccade made by normally sighted readers.[26,27] A possibly related effect was described by Hassan et al.,[28] who showed that a moderate reduction in the visual field due to glaucoma had an impact on head-movement patterns while crossing streets; the patients with glaucoma did not exhibit head movements consistent with maximizing safety. The authors hypothesized that this result could be due to the dynamic nature and complexity of the street-crossing task. However, it is possible instead to advance an explanation based on the lack of visual stimulation from the peripheral field. Important objects such as oncoming cars were not noted and therefore did not induce shifting of the gaze to the blind field.

Thus, we believe that the absence of visual stimulation is probably the main cause of our primary finding of reduced horizontal ocular scanning in people with severe PFL. If this were the case, we might expect to find that horizontal dispersion would decrease as field size decreased; however, we did not find such a correlation, presumably because the sample size and range of visual field sizes examined were too limited. On the other hand, the strategy reported by patients of using proprioceptively cued head movements to restore context

would also account for the narrower eye movement dispersion found and are not necessarily related to field size.

References

1. Robinson B, Acorn CJ, Millar CC, Lyle WM. The prevalence of selected ocular diseases and conditions. *Optom Vis Sci*. 1997;74:79–91.
2. Turano KA, Rubin GS, Quigley HA. Mobility performance in glaucoma. *Invest Ophthalmol Vis Sci*. 1999;40:2803–2809.
3. Turano KA, Geruschat DR, Stahl JW, Massof RW. Perceived visual ability for independent mobility in persons with retinitis pigmentosa. *Invest Ophthalmol Vis Sci*. 1999;40:865–877.
4. Pagon RA. Retinitis pigmentosa. *Surv Ophthalmol*. 1988;33:137–177.
5. Dickinson C. *Low Vision: Principles and Practice*. Oxford, UK: Butterworth-Heinemann; 1998.
6. Turano KA, Geruschat DR, Baker FH, Stahl JW, Shapiro MD. Direction of gaze while walking a simple route: persons with normal vision and persons with retinitis pigmentosa. *Optom Vis Sci*. 2001;78:657–666.
7. Cohen JM. An overview of enhancement techniques for peripheral field loss. *J Am Optom Assoc*. 1993;64:60–70.
8. Kozlowski JM, Mainster MA, Avila MP. Negative-lens field expander for patients with concentric field constriction. *Arch Ophthalmol*. 1984;102:1182–1184.
9. Kennedy WL, Rosten JG, Young LM, Ciuffreda KJ, Levin MI. A field expander for patients with retinitis pigmentosa: a clinical study. *Am J Optom Physiol Opt*. 1977;54:744–755.
10. Krefman RA. Reversed telescopes on visual efficiency scores in field-restricted patients. *Am J Optom Physiol Opt*. 1981;58:159–162.
11. Hoeft WW, Feinbloom W, Brilliant R, et al. Amorphic lenses: a mobility aid for patients with retinitis pigmentosa. *Am J Optom Physiol Opt*. 1985;62:142–148.
12. Vargas-Martin F. Survey of a free cost viewfinder for visual field expansion. In: Jones S, Rubin G, Hamlin D, eds. *Vision 2005: held between 4 and 7 April 2005 in London, UK*. Amsterdam: Elsevier; 2005;1282:1080–1084.
13. Fasce F, Bettin P, Lucà G, Brancato R. Effects of minification on visual performance in advance glaucoma. In: Stuen C, Arditi A, Horowitz A, Lang MA, Rosenthal B, Seidman K, eds. *Vision Rehabilitation: Assessment, Intervention and Outcomes*. Lisse, The Netherlands: Swets & Zeitlinger; 2000;177–179.
14. Peli E. Augmented vision for central scotoma and peripheral field loss. In: Stuen C, Arditi A, Horowitz A, Lang MA, Rosenthal B, Seidman K, eds. *Vision Rehabilitation: Assessment, Intervention and Outcomes*. Lisse, The Netherlands: Swets & Zeitlinger; 2000;70–74.
15. Vargas-Martin F, Peli E. Augmented-view for restricted visual field: multiple device implementations. *Optom Vis Sci*. 2002;79:715–723.
16. Luo G, Peli E. Use of an augmented-vision device for visual search by patients with tunnel vision. *Invest Ophthalmol Vis Sci*. 2006;47:4152–4159.
17. Turano KA, Geruschat DR, Baker FH. Oculomotor strategies for the direction of gaze tested with a real-world activity. *Vision Res*. 2003;43:333–346.
18. Piantanida T, Bowman DK, Larimer J, Gille J, Reed C. Studies of the field of view/resolution trade-off in virtual-reality systems. In: Rogowitz BE, ed. *Human Vision, Visual Processing and Digital Display III/Depth Perception and Sensory Integration for Complex Visual Environments*. San Jose, CA: The International Society for Optical Engineering (SPIE); 1992:448–456.
19. Bahill AT, Adler D, Stark L. Most naturally occurring human saccades have magnitudes of 15 degrees or less. *Invest Ophthalmol*. 1975;14:468–469.

20. Cornelissen FW, Bruin KJ, Kooijman AC. The influence of artificial scotomas on eye movements during visual search. *Optom Vis Sci*. 2005;82:27–35.

21. Woods RL, Fetchenheuer I, Vargas-Martin F, Peli E. The impact of non-immersive head-mounted displays (HMD) on the visual field. *J Soc Inform Display*. 2003;11:191–198.

22. Bailey IL. Critical view of an ocular telephoto system. *CLAO J*. 1987;13:217–221.

23. Spandau UH, Wechsler S, Blankenagel A. Testing night vision goggles in a dark outside environment. *Optom Vis Sci*. 2002;79:39–45.

24. Hartong DT, Jorritsma FF, Neve JJ, Melis-Dankers BJ, Kooijman AC. Improved mobility and independence of night-blind people using night-vision goggles. *Invest Ophthalmol Vis Sci*. 2004;45:1725–1731.

25. Zebehazy K, Zimmerman G, Bowers A, Peli E. Establishing the reliability of mobility measures to assess the effectiveness of night vision devices: results of a pilot study. *J Vis Impair Blind*. 2005; 99:663–670.

26. Zihl J. Visual scanning behavior in patients with homonymous hemianopia. *Neuropsychologia*. 1995;33:287–303.

27. Trauzettel-Klosinski S, Brendler K. Eye movements in reading with hemianopic field defects: the significance of clinical parameters. *Graefes Arch Clin Exp Ophthalmol*. 1998;236:91–102.

28. Hassan SE, Geruschat DR, Turano KA. Head movements while crossing streets: effect of vision impairment. *Optom Vis Sci*. 2005; 82:18–26.