Eccentric Fixation With Macular Scotoma

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People with macular scotoma tend to read and visually scan more slowly than others with equivalently reduced visual acuity but intact central fields. We measured fixation eye movements and considered the contribution of fixation variability and centripetal eye drift to poor visual performance. These factors might confound efforts to consistently use an optimum retinal locus outside of the macula. We measured monocular horizontal and vertical eye movements using a search coil eyetracker while subjects with naturally occurring central scotomata or control subjects with simulated scotomata eccentrically fixated a single character that was sized to their visual acuity. Motivated subjects with long-standing stable maculopathies were chosen to estimate attainable performance limits. During attempts to eccentrically fixate, an ubiquitous foveal pursuit or centripetal drift tendency was not found; rather a pattern of drift was idiosyncratic from subject to subject. This finding was confirmed by an analysis of eye drift of 32 eyes with long-standing bilateral macular scotomata. Moreover, the eye drift speeds (15–200 min arc/sec) were too low to be of functional significance. Drift speeds during eccentric fixation with a visible target were not significantly different than those after the target was extinguished; however, drift speeds were greater than during foveal fixation. This suggests that the fovea has a specialized control of slow eye movements. Fixation variability increased with scotoma size for both simulated and real scotomata, with an abrupt rise when scotomata diameters exceeded 20°. A significant minority of subjects (39%) adopted two or more distinct preferred retinal loci (PRL) during fixation. Multiple PRL were also more likely if scotoma size exceeded 20°. Reasonably steady fixation is thus attainable when central scotoma sizes are smaller than approximately 20°. Invest Ophthalmol Vis Sci 29:268–278, 1988

Loss of foveal function occurs within the natural course of various maculopathies, which are currently the leading cause of permanent visual impairment in the United States.1 The reading rates of individuals with central scotomata remain well below the performance of other individuals with equivalent visual acuity but intact central fields.2,3 This finding is not an inevitable consequence of loss in central vision. At least in principle, someone with a central scotoma might adopt an elevated fixation angle that displaces the scotoma so that it does not obscure text and then read at relatively normal speeds, providing that the text is magnified to compensate for visual acuity loss. We suspected that some property of oculomotor control might limit the ability of these subjects to maintain an optimal gaze angle during visual scanning and fixation. The purpose of the present investigation was to describe fixation eye movements associated with central scotomata. We sought characteristics of these eye movements that would further degrade visual acuity or retard word recognition in reading and visual scanning.

In 1962 von Noorden reported that subjects with dense macular scotomata resulting from fundus flavimaculatus were able to maintain eccentric fixation during ophthalmoscopy.4 Voluntary eccentric fixation has also been studied with normally sighted subjects.5,6 In our previous studies we have confirmed that individuals with bilateral maculopathies are able to maintain a target image out of a central scotoma with eccentric fixation and make saccades which move images directly to functioning paramacula.7,8 Moreover, normally sighted subjects with an artificial central scotoma learned to fixate eccentrically within a few trials.7

Although subjects were capable of eccentric fixation, there was reason to suspect that certain characteristics of these fixation eye movements were non-adaptive in the sense that the eye would move quickly to draw the image the subject wanted to see into the blind macula. Normally sighted subjects have exhibited centripetal drift tendencies in complete darkness with more extreme fixation positions9,10 or while eccentrically fixating targets that were below photopic

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elicit pursuit eye movements in the direction of target stabilized on eccentric retina have also been shown to (ie, pursue) a target that is being viewed eccentrically. If positional error (ie, eccentricity of retinal image position) generally elicits pursuit, then one instabilities were associated with eccentric fixation of single visible targets. If so, these instabilities might be of functional significance and reflect inherent properties of oculomotor control.

These prior studies prompted us to examine how eccentric fixation of a single target affected three characteristics of fixation eye movements in patients with maculopathy: average direction of eye drift, eye drift speed and fixation variability. Patients with long-standing bilateral central scotomata resulting from a variety of pathologies were studied. The habitual fixation eye movements during identification of a single character were measured and retinal image position relative to the measured central scotoma was reconstructed.

In addition, we analyzed these same characteristics during monocular eccentric fixation of normally sighted subjects who were required to eccentrically fixate single characters around simulated central scotomata. Performance of normally sighted subjects with simulated scotomata served as a control in several ways: (1) Performance of individuals with diseased retina could be compared to normals with equivalently-sized, simulated scotoma to determine if retinal pathology might have additional effects on eye motion. (2) Neither the fovea nor the visual axis could be identified in eyes with maculopathy, precluding analyses and inter-subject comparisons within a common (oculocentric or egocentric) coordinate system. Such comparisons were possible with normally sighted subjects (eg, Fig. 4). (3) Studies of subjects with normal foveal function permitted identification of a specialized role of the fovea in the maintenance of fixation.

Materials and Methods

Experiment 1: Fixation With Simulated Central Scotoma

Subjects: Prior to any testing, the nature of the procedure, its risks and benefits were explained, and informed consent was obtained. Both eyes of three young (22–25 yr) adult subjects were evaluated with simulated central scotomata. Foveal fixation of five normally sighted subjects was also measured. One subject, RL, had participated in previous eccentric fixation studies. Each subject was tested with correction for myopia of less than 3 diopters but otherwise had normal vision.

Apparatus and procedure: Horizontal and vertical eye movements were measured with the technique of a search coil in magnetic fields. The search coil wire was imbedded in a silicone annulus which adhered concentrically around the cornea. System bandpass was limited by the 200 Hz digital sampling frequency to 0–100 Hz. For eccentric fixation studies, the system had an approximately 40° positional range (±20°) with a resultant noise level of less than 3 minarc rms. The system gain was later increased for foveal fixation studies to reduce the noise level to less than 1.5 minarc rms. This system was used for both experiments 1 and 2.

Monocular fixation eye movements were measured during eccentric fixation while subjects fixated single letters on the rear projection screen in an otherwise completely dark room. Stray light was carefully masked so that only the single letters were visible to the subject throughout the testing period. With a simulated scotoma, the target could be seen only by deviating the eye from a straightforward position (eccentric viewing or fixation) until, at a predefined eccentricity, the shutter would open, revealing a single character seen in a peripheral field. If during fixation the target image entered a predefined area circumscribing the fovea (eg, if the subject attempted to foveate the target), the target was extinguished. The shutter was controlled by a computer (Digital 11-23; Digital Equipment Corp., Maynard, MA) programmed to sample eye and stimulus position and calculate retinal position of the target image. The latency with which the shutter (Uniblitz Model 225L; A. W. Vincent Associates, Inc., Rochester, NY) responded to movement of the target image across the scotoma boundary was a sum of shutter latency (4.2 msec max.), maximum sample interval (5 msec), and the response time of the computer (3 msec), and ranged from 7–12 msec depending on where within an inter-sample interval the target entered or left the scotoma.

Each subject was instructed to move his/her eye in one of eight directions, maintain stable fixation and attempt to keep the target visible at all times. During the first 5 seconds of a fixation trial, each would rotate his/her eye until the target appeared, at which time the eye would settle down near the edge of the criterion eccentricity. The eye and stimulus positions were then digitally stored during the remaining 12 seconds of the fixation trial.

The targets were single stable letters projected centrally onto a rear projection screen 113 cm in front of the subject's eye. Character luminance was 57–64 cd/m² and contrast (L_L – L_D/L_L + L_D) was 99%. The
letter was just resolvable using the predicted acuity for the particular retinal eccentricity being studied\textsuperscript{17-19}, specifically, the overall target size was 5 min-arc at the fovea, and 10.3, 16.7, 20.9 and 27.3 minarc, respectively, at 150, 300, 450 and 600 minarc from the fovea. Measurements during foveal fixation were repeated later with five different subjects after we discovered a need to increase system gain in order to increase the signal to noise ratio.

Eye movements were also measured without a visible target. For several seconds before the trial, the subject fixated either centrally or eccentrically a visible target, which was then turned off at the beginning of the trial.

At least 24 trials were performed per eye: usually six at each scotoma size (in random order) and as many as possible in the dark before time ran out. Each session in experiment 1 was limited to 40 min to prevent discomfort and degrading of visual acuity by the annulus. Several trials with the right eyes of subjects RL and KB were replicated in additional sessions.

**Experiment 2: Fixation With Natural Macular Scotoma**

**Subjects:** Prior to any testing, the nature of the procedure and its risks and benefits were explained, and informed consent was obtained. A total of 39 eyes from 30 subjects with macular degeneration was evaluated. All subjects had open anterior chamber angles, normal intraocular pressures and no signs of anterior segment or peripheral retinal disease. All low vision subjects had macular pathologies that were positively diagnosed by ophthalmoscopy to include fundus flavimaculatus, atrophic age related maculopathy, exudative age related maculopathy or macular holes. Of the 39 eyes, seven were excluded from analysis because either: (1) central field measurements (described below) were not completed; or (2) ring scotoma or central islands of vision within the central scotoma were identified. With the exception of subjects with macular holes, all low vision subjects had bilateral maculopathies for over 2 years and had received rehabilitation services that in most cases included training to develop eccentric fixation.

**Apparatus and procedures:** The same eyetracking system was used for both experiments 1 and 2. Central fields were measured using a 207 cd/m\(^2\) (650 ASB), 4 minarc target that was projected onto a rear projection screen 113 cm from the subject. The background screen illumination was less than 0.02 cd/m\(^2\) (0.07 ASB). The target was projected through horizontally and vertically oriented mirrors that were rotated by General Scanning (Watertown, MA) PD-300 high speed deflectors yoked to the eye position signal through analog circuitry. This image stabilizing system moved the target with the eye, compensating for eye movements while the retinal image position of the target was controlled by the perimetr

Drift Direction

Although we observed that eyes with simulated or pathologically-induced central scotomata drifted centrally from some eccentric fixation positions, the same eye did not consistently drift centrally from other angles. This pattern is typified by the eye movements of a normally sighted subject, KB, while eccentrically fixating around a 20° simulated scotoma. The two panels of Figure 1 illustrate a leftward drift that occurs when the right eye eccentrically fixates to the upper right (Fig. 1a) and to the lower left (Fig. 1b).
In the upper right position the target image tended to drift centrally until the gaze angle became smaller than 600 minarc, at which time the target disappeared into the scotoma. The eye then had to saccade rightward in order to see the target. The result was a low frequency jerk nystagmus with a fast component directed temporally. In the lower left position, however, the target image drifted away from the scotoma (Fig. 1b) and the jerk nystagmus was no longer evident.

A similar jerk nystagmus was illustrated by the records of a 32-year-old female, DL, with bilateral fundus flavimaculatus (Fig. 2). Her preferred fixation placed the scotoma above the target but her eye drifted down so that the retinal image was drifting into the scotoma during this trial. The occasional periodic jerk nystagmus that we observed in eyes with acquired maculopathy could be similarly explained in terms of successive centrally directed drift with corrective saccades.

In most subjects, overall drift tendencies and velocities were obscured by considerable variability in drift direction and velocity and apparently corrective slow eye movements. To extract these often subtle drift tendencies, we developed algorithms for averaging the drift samples over a fixation trial.

*Average drift direction statistic:* First, an algorithm (described below) tagged and eliminated saccades and data within 60 msec of a saccade onset or offset. Then, the direction of resulting slow eye position changes between successive 5 msec samples was computed and tallied onto one of twelve 30° intervals represented by the vectors in the left figure. Vector length is proportional to the relative frequency of each drift direction.

![Fig. 3. Relative frequency distribution of eye drift direction during a single fixation period (left) and a derived resultant vector that represents average drift direction (right). Direction of slow eye movement between successive eye position samples was measured and added to one of twelve 30° intervals represented by the vectors in the left figure. Vector length is proportional to the relative frequency of each drift direction.](https://iovs.arvojournals.org/pdfaccess.ashx?url=/data/journals/iovs/933369/ on 10/11/2018)
scotoma
perimeter

SUBJECT RN
LEFT EYE
VECTOR LENGTH
0 100%
% of total fixation time

RIGHT EYE

Fig. 4. Eye drift direction and consistency associated with various eccentric eye positions adopted by normally sighted subjects around simulated scotomata. The concentric circles indicate the criterion eccentricity of each fixation position (150, 300, 450, 600 minarc). A character positioned at the center was visible only if the subject maintained an eye position greater than the criterion eccentricity. The origin of each vector indicates the modal eye position during a fixation trial. The vector angle is toward the average eye drift direction and length is inversely related to variability of drift direction (see Fig. 3). Dashed lines indicate eye drift in complete darkness.

vals yielding 12 sections (see Fig. 3). The relative number of tallies, represented by vector length, is proportional to the percentage of time the eye spent drifting in that direction. All of the vectors in the histogram were oriented around a single point representing the modal eye position during eccentric fixation. Note that the vector attributes are independent of eye speed (which is considered below).

If the eye moved in a truly random manner, or if corrective eye drifts consistently cancelled an opposing drift, the eye would theoretically drift in opposing directions with equal frequency. If all 12 vectors were added tip-to-tail, the resultant vector should have a magnitude of zero. If the magnitude is not zero, this would indicate an average drift in a particular direction. The angle of this resultant vector (Fig. 3) would be an average direction of drift, with its magnitude inversely related to the variability of drift direction. This vector addition was calculated for each trial yielding one final drift vector, and results using this method of analysis were consistent with overall drift tendencies if any were apparent on the stripcharts.

The resultant drift vectors were compiled across all fixation positions in Figure 4 to characterize overall drift tendencies for each eye of the normally sighted subjects with simulated scotomata. Quite clearly, the eyes do exhibit a predominant drift direction at each position, but in none of the eyes was average drift direction centripetal from all fixation positions. In general, each eye tended to drift in a similar direction for most gaze angles; these patterns were somewhat symmetric between the right and left eyes of each subject, but idiosyncratic from subject to subject. It should be noted that the significant shifts in drift direction seen in the lower left quadrant of KB's right eye reliably recurred on different days. Although eye drift during eccentric fixation without a visible target (dashed lines in Fig. 4) was usually in the same direction as with a visible target, there are several instances where the directions were quite different (RL's right eye), indicating that eye drift direction was under retinal control rather than simply the result of subjects attempting to maintain a desired eye position as they did in the dark. Again, a general centripetal eye drift was not apparent in any of the subjects while they were maintaining eccentric fixation in complete darkness.

Of particular interest are the "null" positions where shorter vectors cluster, indicating an eye position field where drift is random. Null regions are evident in the upper left quadrant of subject RN's left eye and the left movement field of the right eye. In subject RN's data, longer vectors tended to point to a null movement field, indicating drift toward the null fields.

We could not summarize measurements across subjects with naturally occurring macular scotomata since without a definable visual axis, we could not superimpose findings on a common coordinate system as we did with normal observers (Fig. 4). By assuming that the scotoma contained the fovea, however, we could rule out general centripetal drift or foveal pursuit tendencies in eyes with maculopathy. Time usually limited our measurements of fixation eye movements to the preferred fixation positions, usually within the same quadrant. However, by assuming that the scotoma was approximately centered on the macula, we categorized drift directions in different retinal quadrants (for examples see Fig. 5). We considered a total of 62 fixation positions (28 eyes)
that were distributed in all quadrants with from nine to 20 observations in each quadrant. In six eyes with fixations in all quadrants, at least one vector pointed away from the scotoma. In 42% of the fixation positions compiled across eyes, the drift vector was pointed away from the scotoma and the presumed location of the fovea and primary position. Although we cannot, of course, rule out the possibility that some people might exhibit centripetal drift tendencies from all fixation positions, we can conclude that general centripetal drift is not the rule.

All three of the normally sighted subjects exhibited some overall nasal component to drift; however, in 54% of eyes with maculopathy, the drift vector tilted temporally. Therefore, there were no general nasal/temporal drift tendencies observed across eyes with macular scotomata.

**Speed of Eye Drift**

*Average drift speed statistic:* First, saccades were tagged if the eye speed exceeded 10 deg/sec (12 min-arc/20 msec) or eye acceleration exceeded 300 deg/sec². Data within 60 msec of a saccade tag were excluded from subsequent analysis. Next, eye velocity was computed over successive 120 msec epochs of data using a “sliding window” program similar to that described by Collewijn, Martins and Steinman. Linear regression of horizontal and vertical eye position over 24 samples (120 msec) yielded respective velocity estimates. An eye speed estimate, the resultant of these two vectors, was assigned to the sample number in the center of this epoch, the epoch slid one sample, and the analysis was repeated until the end of the 12-second fixation interval. This procedure was necessary to isolate the low frequency (0–5 Hz), slow (under 10 deg/sec) component of fixation eye motion from higher frequency noise, eye tremor, and saccades.

For each trial, a distribution of eye drift speeds was computed. A logarithmic transformation of speed produced a unimodal symmetrical distribution of drift speeds (Fig. 6). Statistical summaries were therefore performed with log transformed data. Across all fixation positions, the geometric mean drift speeds when normally sighted subjects eccentrically fixated around simulated scotomata ranged from 13 to 55 minarc/sec. Individual geometric mean drift speeds were 22 (RL), 25 (KB) and 26 (RN) minarc/sec. In complete darkness, geometric mean drift speeds were...
Fig. 6. The relative frequency distributions of eye drift speed that occurred during five fixation intervals. Each distribution was based on 2376 samples of horizontal and vertical eye position minus samples that occurred within 60 msec of saccades. Each fixation interval was selected from a different subject (SW—normal foveal fixation, RV, DM, SS—juvenile macular degeneration, IK—macular hole). Distributions were selected to represent different mean drift speeds.

23 (RL), 38 (KB) and 24 (RN) minarc/sec. There was no reliable difference between eye drift during eccentric fixation of a visible target and maintenance of eccentric eye positions in complete darkness (Fig. 7, top panel). Foveal fixation, however, resulted in reliably lower mean drift speeds (9.7 minarc/sec). Indeed, none of the drift speeds observed with simulated scotoma, real scotoma, nor in complete darkness fell within the expected 0.95 confidence interval around mean foveal drift speeds (Fig. 7, bottom panel).

When drift in the dark and with a visible light (Fig. 7, top) were pooled, the regression equation was $Y = 0.08(\pm0.03)X + 1.02(\pm0.12)$. The correlation was marginally significant ($P < 0.05$). In our visual inspection of the data we also observed that the speed did show a slight decrease if the eye was oriented in the direction indicated by the average drift vectors. The position of lowest speed was usually very close to the drift “null regions” if they could be identified.

Most subjects with macular pathology exhibited drift speeds that fell within expected normal limits for a given eccentricity of fixation (Fig. 7, bottom). There were exceptions, however. Patients with larger central scotomata were more likely to exhibit abnormally high drift speeds. Age and visual acuity cannot explain this observation since many of these patients (with juvenile macular degeneration in Fig. 7) were within 10 years of age of our normally sighted subjects, and targets were scaled to the reduced visual acuity. Increased drift speeds were most likely secondary to extramacular retinal damage resulting from the pathologies.

Variability of Eye Position

Subjects with a macular scotoma usually used one preferred area on the retina when attempting to resolve target detail. Some subjects’ fixations were found consistently to involve two or more fixation positions. That is, the target image moved among retinal loci during a fixation trial (Fig. 5). Most subjects confined the target image to relatively small regions for most of the fixation period (eg, Fig. 5). These regions, or Preferred Retinal Loci (PRL), were defined as $3^\circ \times 3^\circ$ areas that contained the center of the target image for over 20% of the fixation interval. In most subjects only one PRL was identifiable by the above criteria. Within a single 12-second trial, 21% of the eyes with measured central scotomata positioned the target image in two or more PRL that were centered over $4^\circ$ apart (subjects VK, JS, FB, VY in Fig. 5). Across trials, 39% of the eyes exhibited multiple PRL. The subject with the highest fixation variability moved the target image over multiple scattered retinal areas (VY in Fig. 5). This subject, a 40-year-old male, had bilateral macular scotomata (juvenile macular degeneration) that had been stable for over 10 years. His fixation stability, therefore, could not be attributed to incomplete adaptation.

Fixation variability was also measured within a $200' \times 200'$ range of eye position where the eye spent...
the most time, that is, the most strongly preferred retinal locus. Variability was derived from two-dimensional histograms representing fixation dwell times. Each of the 2400 stored eye positions was assigned to an appropriate cell in a $40 \times 40$ matrix over a $200' \times 200'$ range of eye position (thus, each cell represents 25 minarc$^2$). The relative time the eye position spent in each cell was computed. Starting with the cell with the highest relative frequency, the routine added up in descending order the area of these cells until a total area was computed in which the eye spent 68% of the total time. This area characterized variability of eye position. This measure of fixation variability would increase as a multiple of the number of fixation positions over $25'$ apart where the eye spent a significant amount of time. Unlike parametric statistics such as the bivariate contour ellipse, this measure is not affected by the distance between fixation positions nor does it require assumptions about underlying distributions.

With normal eyes and simulated scotomata, the variability of eye position ranged from 625 to 3800 minarc, increasing reliably ($P < 0.01$) with eccentricity (Fig. 8). Fixation variability without a visible target did not reliably differ from fixation variability while subjects eccentrically fixated a visible target.

In eyes with naturally occurring scotomata, fixation variability increased with the size of the central scotoma. With scotoma sizes greater than $20^\circ$ average diameter, there appears to be a sharp increase in fixation variability. Likewise, 60% of eyes with a scotoma in excess of $20^\circ$ exhibited multiple PRL (as defined above), whereas multiple PRL were observed in only 14% of the eyes with a smaller scotoma.

* Parametric bivariate statistics such as the bivariate contour ellipse (BCE) were not used to characterize variability for two reasons. First, the distribution of eye position as illustrated in Figure 5 was not always unimodal, which violates an assumption underlying the estimation of the area of the ellipse. Second, the area estimates are affected by distance between fixation positions and by transient extreme shifts in eye position. In cases where the distributions were unimodal, both the parametric and our non-parametric statistics yielded similar estimates. In cases where subjects alternated between two distinct, distant positions but otherwise were quite consistent, the BCE generated considerably higher estimates of fixation variability than our estimates.
Discussion

Fixation and Visual Function

In our examination of fixation eye movements, we considered aspects that might degrade visual function. Excessive retinal image speed could not only degrade visual acuity, but also necessitate corrective eye movements. The resultant nystagmus would retard efforts to quickly scan a visual scene or printed page. Centripetal eye movements (drifts or saccades) or a tendency to centrally fixate would result in variations in the visual acuity of someone with maculopathy, as would excessive fixation variability.

A low frequency jerk nystagmus evident in some subjects with either real or simulated scotomata apparently reflected a sequence of drift from more to less sensitive retina, followed by corrective saccades. The drift speed, however, was unlikely to require the execution of a functionally significant number of corrective saccades that otherwise might retard reading and visual search. To illustrate, the subject with the highest recorded average drift speed (186 minarc/sec) would fixate a target at his acuity limit that subtended 137 minarc. During a typical fixation duration of 300 msec, the target, or at least some portion of it, would remain within the initial retinal locus throughout the fixation period, thereby eliminating a need for corrective eye movements. Corrective saccades might, however, emerge during lengthy fixation.

When they attempted to fixate a target eccentrically and subsequently maintain the eccentric eye position in complete darkness, our subjects exhibited drift directions that were consistent over time but were otherwise idiosyncratic across individuals. Our data are not, however, inconsistent with another systematic attempt to study drift in the dark. Becker and Klein examined drift direction and velocity after saccades to various eccentric eye positions in complete darkness. They found eye drift that might have appeared centripetal from extreme fixation angles actually was part of an overall tendency to drift toward a “null,” most stable position that was approximately 10° from the primary position. Skavensky and Steinman observed centripetal drift toward a straightforward position in one subject while their other subject exhibited downward drift. Drift toward a null position was observed with one of our subjects and might have been evident in the drift patterns of other subjects if we had explored a still greater range of eccentric fixation angles.

In general, with normal observers and artificial scotomata, eye drift speed and direction varied little with eccentricity of eye position or retinal image position. There was not even a reliable difference between fixation with and without a visible target. However, eye drift speeds were significantly lower during foveal fixation. These differences in drift speed cannot be attributed to differences in visual acuity since the target sizes matched the acuity of a retinal locus. These findings suggest a specialized role of the fovea in the control of slow eye movements.

In our subjects, the observed drift speeds of less than 2 deg/sec were not sufficiently high to degrade visual acuity. The 1 deg/sec retinal image motion that was commonly observed among our subjects with macular scotomata has been shown to degrade high spatial frequency (15 cycles per degree) contrast sensitivity (and presumably normal grating acuity). However, our subjects with fundus flavimaculatus and age related maculopathy had visual acuities equivalent to 1–6 cycles/deg, a range where retinal image motion of less than 2 deg/sec has minimal effects on contrast sensitivity and little effect on visual acuity. Rather, low speeds of 0.5 to 2 deg/sec significantly enhance low spatial frequency contrast sensitivity (below 1 cycle/deg). However, the normal course of saccades during typical visual scanning would likely produce sufficient retinal image motion for optimum low spatial frequency contrast sensitivity. Therefore, more stable prolonged fixation might prove quite useful to the perimetrist but otherwise would have little effect on the day-to-day visual function of someone with a macular scotoma.

The aspect of fixation most likely to create functional problems might be characterized by fixation variability. Considerable fixation variability reflects failure to use functioning retina or the patch of retina best suited for a particular visual task.

Our observation of fixation variability with real and simulated scotoma resulted in estimates of fixation variability that were somewhat greater than previously reported by Sansbury et al. Their estimates would fall on the lower limit of our range of scores. The difference is likely due to our requirement that subjects fixate eccentrically. In the Sansbury et al experiment subjects maintained primary position at the approximate center of a symmetrical array of lights. Timberlake et al reported fixation eye movements while subjects with macular scotoma fixated a single target. Their findings with three subjects were within our predicted range for their scotoma size.

Even with our higher estimates of fixation variability observed with scotomata less than 20° average diameter, the target image was maintained within an area less than 10,000 minarc for 67% of the fixation period. If this area were circular, its diameter would be less than 2°. Our results suggest that this degree of fixation control is within the capabilities of subjects with scotomata restricted to 20° average diameter. Larger central scotomata, however, were associated...
with a sharp increase in fixation variability, possibly indicative of a breakdown in fixation control. Since the target size was scaled in accordance with an individual subject’s best visual acuity, this increase in fixation variability with scotoma size cannot be attributed to a loss in retinal position information. Increased variability is more likely to result from increased drift speed or repetitive scanning-type patterns such as those observed in two subjects. Subjects with these larger scotomata also revealed the most severe deficiencies in reading rate and accuracy.8

In summary, eye drift and associated nystagmus during fixation were not functionally significant. Subjects with recent loss in central function or with scotomata in excess of 20° average diameter might not be expected to use a smaller area of optimally functioning retina with consistency; however, our more experienced subjects have demonstrated that more consistent eccentric fixation could apparently be learned even with large scotomata. The possibility remains that other aspects of oculomotor control such as saccade accuracy might be irreversibly disrupted by a central scotoma and that these latter oculomotor problems limit reading and visual search. Another possibility is that reading rate is limited by the pattern or word recognition capabilities of peripheral retina.

Phenomenology of Eccentric Fixation

In von Noorden’s pioneering studies of eccentric fixation with a macular scotoma,4 he suggested that with time and practice, a new “retinomotor” center would develop outside of the macular scotoma. The emergence of this preferred fixation locus is identifiable during Visuoscope ophthalmoscopy,28 where a target is focused on retina and thus can be fixed during ophthalmoscopy. A more recent report of the fixation eye movements of three subjects with macular scotomata27 has confirmed these earlier observations that the well-adapted subject consistently uses a single, strongly preferred area for fixation outside of the central scotoma. Such a finding suggests that fixation eye movements might be modified along an “offset” dimension. Changing offset would shift the “retinomotor center” to a better functioning eccentric position. If fixation were indeed a “reflex” that nulled the difference between target image position and a retinomotor zero point, the distribution of retinal image position would always be unimodal as long as it were on functioning retina.

We have found that in subjects with bilateral macular scotoma for over 2 years, in some cases over 10 years, the distribution of retinal image position was not always unimodal. Although most subjects did use a single retinal area for fixation, a significant number of subjects consistently used more than one retinal area. Saccades directed images to these areas repeatedly within a trial and across trials, and the fixation areas were non-overlapping and several degrees apart. Multiple PRL were observed even though our procedure encouraged subjects to use a single PRL. Our task encouraged subjects to use the area of best visual acuity. Moreover, the target was rather predictably within about 5° of a straightforward position, permitting adoption of a consistent eye position during our testing session.

We have been impressed by the idiosyncratic nature of eccentric fixation across subjects, a finding which suggests that the eye movement control underlying “fixation” is capable of extensive plasticity in that fixation variability and the number and location of PRL may, hypothetically, change to optimize some aspect of visual function (eg, visual acuity or the size of the right visual field). The fixation eye movements during face recognition, reading, scanning a room for a desk or steadily fixating an object for maximum resolution of detail might involve positioning targets of interest in rather different retinal regions that might be better suited to the task at hand. In some individuals, this process might lead to the development of multiple, task-specific PRL.

Conclusions

We have sought to define performance limits by selecting highly cooperative subjects with relatively long-standing maculopathies. We found that with scotomata diameters less than 20°, fixation eye movements were unlikely to interfere with word or character recognition: (1) eye drift speed was not sufficient to degrade visual acuity; (2) general centripetal eye drift or foveal pursuit was not observed; and (3) saccades maintained the image on functioning retina. However, subjects all reported that their adaptation was lengthy, arduous and possibly incomplete7 when large saccades were required. Care must be taken not to generalize our findings to patients with recent vision loss and less reliable eccentric fixation when they are encountered in the low vision clinic. The apparent plasticity of eye control during fixation suggests a role of patient education and training to facilitate rehabilitation of visual performance following loss of central vision. Our findings suggest that a high level of fixation control is possible.

Key words: macular disease, fovea, eye movements, low vision, visual fields
References