Fixation Characteristics in Macular Disease

Relationship Between Saccadic Frequency, Sequencing, and Reading Rate

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The relationship between reading rate and saccadic frequency in patients with macular degeneration was studied to determine if this simple measure of eye movements would be helpful in explaining the reduction in reading rates. Nineteen subjects and five controls were tested for visual acuity, reading rate, and saccadic frequency for intended stationary, simple left-to-right, and sequencing step tasks. Eye movements were recorded using an electro-oculography technique. Absolute eye position was not known. The results demonstrated that, using a 2° threshold for a stationary target, patients refixated a mean of 42.7 times per min, and controls refixed 0.00 times per min. For a two-letter left-to-right task, patients averaged 3.57 times more saccades than an ideal response, and controls had 1.14 times more saccades than ideal (P < 0.01). For a five-letter left-to-right sequencing task, patients refixated a mean of 2.10 times more than ideal, and controls refixated 1.15 times more than ideal (P < 0.05). Regression analysis demonstrated that sequencing task scores of saccadic frequency and visual acuity were the best predictors of reading rate (r² = 0.705). These results indicate that higher saccadic frequencies are associated with lower reading rates and that there appears to be a relationship between the sequencing of visual information and reading rate. Invest Ophthalmol Vis Sci 32:567-574, 1991

A corollary to the loss of central visual acuity in patients with macular disease is the reduction of reading rate.1-6 The poor reading rates are seen even when text material is greatly magnified.1 Loss of reading accuracy occurs to a lesser extent and is primarily found in patients with central scotomas greater than 20° in diameter.2 Patients with relative scotomas or small absolute scotomas usually can read at acceptable rates with tolerable levels of magnification and appropriate instruction on the use of magnifying devices. However, a substantial portion of patients with absolute macular scotomas do not achieve acceptable reading rates.

Abnormalities in eye movement control have been described in patients with macular scotomas2-6 and in normal subjects with simulated scotomas.7-8 Rayner and Betera7 showed a relationship between the number of centrally masked characters in a reading task and reading rate in normal subjects. Additionally, they demonstrated a positive relationship between character mask size and the number of fixations made during a reading task.

Whittaker et al3 and Cummings et al2 also demonstrated abnormal eye movements in scanning and reading tasks and suggested there is an important relationship between reading, eye movement control, and scotoma size in patients with macular scotomas. However, the nature of eye movement control problems and the relationship between these control problems and reading in the presence of macular scotomas is poorly understood. Stimulated by experiments in which normally sighted subjects with artificial scotomas demonstrated an increase in the number of refixations made during a reading task, we recorded saccadic frequencies during several eye movement experiments, using normally sighted subjects and patients with macular scotomas, and investigated the relationship between saccadic frequency and reading rates in these subjects.

Materials and Methods

Nineteen patients with bilateral age-related macular degeneration ranging in age from 56-84 years (mean, 71 years) were recruited randomly from the Low Vision Service at the UIC Eye Center, University of Illinois at Chicago. Entrance criteria for patients included: (1) ages between 50-85 years, inclusive; (2) duration of vision loss in the second involved eye of 6 months or longer; (3) absence of clinically significant cataract; (4) absence of neurologic disease...
or other ocular disease; and (5) willingness to participate in the study and give an informed consent. Five age-matched control subjects were recruited from the UIC Eye Center’s general eye clinic for the purpose of distinguishing normal from abnormal responses. These subjects (mean age, 59 years; range, 53–66 years) were without clinically significant cataract, were free of other ocular or neurologic disease, and were willing to participate.

Baseline tests on each patient and control included: (1) best distance spectacle-corrected visual acuity (VA) in units of log minimum angle of resolution (log MAR); (2) near visual acuity at 40 cm corrected with appropriate distance lenses and a +2.50 reading lens; (3) threshold continuous-text reading resolution level; and (4) reading rate with text 0.2 log MAR larger than the threshold resolution level.

Threshold continuous text levels were determined using a distance lens correction plus a +2.50 reading aid in a trial frame reading Sloan text cards at 40 cm. Threshold was defined as that size at which the patient could identify words accurately enough to determine the content of each sentence. Reading rate was defined as scanning rate multiplied by percent of words read correctly as described by Legge and colleagues. Short passages reprinted from a local newspaper at 98% contrast, 0.2 log MAR larger than the threshold text level, were used to determine reading rates for patients and controls.

The better-seeing eye of patients and a randomly selected eye from controls were used for eye movement recordings. An electro-oculogram (EOG)/saccadic velocity recording instrument (Visulab, model 510L; Life-Tech, Houston, TX) was used to measure horizontal eye movements from the test eye. The high and low band pass of this system was 0.016 Hz and 16 Hz, respectively. The low-frequency cutoff for this instrument was greater than zero, and therefore a true DC position was not recorded. There was some low-frequency drift present. Gold scalp electrodes were placed on the skin adjacent to the medial and lateral canthi of the test eye. A reference ground electrode was placed on the forehead. Simultaneous eye position and saccadic velocity recordings were made. The saccadic velocity trajectories were useful with this system in separating saccades from noise, blinks, and other muscle-induced electrical activity. The low-frequency cutoff limited the sensitivity levels used and the duration of each test run. At sensitivity levels permitting 20–30-sec sampling of eye movements, the resolution for detecting saccades was 1°.

Instrument calibration for normal subjects consisted of measuring pen deflection (DC potentials) for known saccade trajectory amplitudes. These included 1, 2, 5, 10, and 20° presented randomly. Calibration for patients consisted of the same format, but because of the reduced or absent foveal function, the premise of the patient foveating a target could not be used as a reference in the calibration procedure. Therefore, calibration—or more appropriately, relative calibration—consisted of measuring the relative consistency of pen deflection for an intended saccade amplitude and assessing proportional changes in saccade amplitude. If a patient had x mm of pen deflection for a 10° separation of targets, then 2x mm of pen deflection would be expected for a 20° target separation in the calibration procedure. Frequently, estimates were made for calibration because of unsteady fixation characteristics. This form of calibration gives relative information only, since absolute eye position is not known with an EOG system. Because detection of saccades was the measurement sought, neither true eye position nor absolute saccade amplitude was necessary. The threshold of detection was important, and this was determined during the calibration trials. Based on experience, 1° saccades could be detected in most patients but not consistently, presumably due to patients being unable to discriminate the target separation. We therefore used a 2° threshold since reliable responses were detected more easily, and the separation from background noise was achieved readily.

Three experiments were done. In the first, the participants were positioned 40 cm from a single-letter target 0.1 log MAR larger than their near visual acuity. After a calibration routine, they were asked to fixate the letter for three 20-sec recordings. In the second experiment, subjects were asked to fixate alternately two letters of the same size separated by 20° (10° degrees each from the midline). For the third experiment, subjects were asked to fixate sequentially five letters separated by 5° (20° between the midpoint of the first and last letters) in a staircase fashion. When the fifth letter of the row was reached, subjects were asked to return to the first letter and begin the sequencing again. Three 30-sec observations per subject were obtained.

Results

The mean log MAR VA for patients was 1.03 (standard deviation [SD], 0.289) for patients and for controls, 0.06 (SD, 0.09). The mean reading rates in words per minute were 30.4 (SD, 30.9) and 155 (SD, 43) for patients and controls, respectively. The mean VA and reading rates were clinically and statistically different between the controls and patients (P < 0.001, by t-test).

Single-Letter Target

For the single-target experiment, some patients had spontaneous eye movements in the form of small
square-wave jerk saccades. Recordings for all of the controls (Fig. 1) and 5 of the 19 patients (Fig. 2) are presented as representative examples for the single-target experiment. Patients 4 and 5 had saccadic activity. The remaining three patients shown, and none of the controls, had saccadic eye movements above threshold values. Patient 1 appeared to have small square-wave jerks, but these were below threshold values. To quantify the results, the number of refixation saccades were summed for the three 20-sec trials, yielding a ratio of refixations/min (r/m). The mean r/m for patients was 42.7 (SD, 46.8). Comparing controls with this mean, one sample analysis showed that \( P < 0.05 \). The 95% confidence limits were 20.4 and 63.6 for the patients.

**Two-Letter Target**

The two-letter target experiment presented a simple trajectory task of moving back and forth between two known, fixed points. Control subjects demonstrated typical square-wave-like tracings with little undershooting or overshooting (Fig. 3). Patients, however, presented a much more varied picture (Fig. 4). Patients 2 and 3 from our sample had normal or near-normal saccadic responses with some hypometric saccades being evident. For patients 1 and 4 small-amplitude square-wave saccades of approximately 2–5° were found overlaid on the task-related activity. Patient 5 showed a different type of response, typified by strings of hypometric saccades 2–5° in amplitude, when traveling between targets. This was more commonly seen when the subject was moving left to right.

If the number of detected saccades counted for the three observation periods is divided by the number of expected (ideal) saccades, a ratio can be derived which reflects the number of refixations recorded per refixations expected (f/x2). For controls this mean refixation ratio was 1.14 (SD, 0.13). Patients had a higher saccadic frequency than control subjects and had a mean refixation ratio of 3.57 (SD, 1.98). The two estimates are statistically significantly different \( (P < 0.05, \text{by t-test adjusted for unequal variances}) \). Additionally, the total number of forward and backward saccades above the ideal for patients were 3.48 (SD, 2.04) and 3.68 (SD, 2.10), respectively. These were not statistically significantly different \( (P > 0.05, \text{by t-test}) \).

**Five-Letter Target**

The five-letter experiment was more complex than the two-letter task and required sequencing of left-to-right saccades. With a return saccade to the far left target, the task rudimentarily resembled reading. Variations in eye movements were seen even among controls for this task. Single-step hypometric saccades, and occasionally hypermetric saccades, were
Fig. 3. Control subjects. EOG eye movement tracings for the two-letter target. Prominent square-shape waves are typical of these normal tracings. Minimal undershooting is seen. The spikes found in the tracings for C5 are artifacts produced by blinking.

Fig. 4. Patients. EOG eye movement tracings for five of 19 patients for the two-letter, left-right task. More small-amplitude, square-wave activity is found superimposed on the large square-shaped waves than seen with control subjects. P2 and P3 demonstrate essentially normal tracings. P4 shows considerable undershooting of the intended targets. Eight of the 19 patients had some hypometric saccadic activity greater than 2° in amplitude, and 9 (47%) patients showed some small square-wave jerk saccadic activity overlaid on the intended task. Eight patients showed both hypometric and small square-wave jerk saccades.

If the same quantitative method to determine the \( f/x_2 \) ratio is applied to the responses to the five-letter target, a refixation ratio for the five-letter task (\( f/x_5 \)) can be found. The mean \( f/x_5 \) for controls was 1.15 (SD, 0.14) and was 2.10 (SD, 0.76) for patients. The two estimates were statistically significantly different \( (P < 0.05, \text{by t-test adjusted for unequal variances}) \). The mean number of forward and backward saccades for patients above the expected (ideal) were 1.89 (SD, 0.80) and 2.99 (SD, 1.54), respectively. These values indicate a higher frequency of regression saccades than forward saccades above the ideal, and they were statistically significantly different \( (P = 0.01, \text{by t-test}) \).

When patients in whom the majority of their abnormal or unanticipated saccades are square-wave jerks are compared with those with primarily hypometric normal pattern but skipped over intended targets. Eighteen of the 19 (95%) patients had some hypometric saccadic activity greater than 2° in amplitude, and 9 (47%) patients showed some small square-wave jerk saccadic activity overlaid on the intended task. Eight patients showed both hypometric and small square-wave jerk saccades.

The mean \( f/x_2 \) for controls was 1.15 (SD, 0.14) and was 2.10 (SD, 0.76) for patients. The two estimates were statistically significantly different \( (P < 0.05, \text{by t-test adjusted for unequal variances}) \). The mean number of forward and backward saccades for patients above the expected (ideal) were 1.89 (SD, 0.80) and 2.99 (SD, 1.54), respectively. These values indicate a higher frequency of regression saccades than forward saccades above the ideal, and they were statistically significantly different \( (P = 0.01, \text{by t-test}) \).
saccades, the mean number of forward saccades were not statistically significantly different. This was also true for backward saccades.

Pearson correlation coefficients revealed a positive relationship between VA and $f/x_5$ ($r = 0.633$), VA and $r/m$ ($r = 0.532$), and VA and $f/x_2$ ($r = 0.671$) for patients, indicating an association between higher saccadic frequencies and poorer levels of distance visual acuity. The VA and log reading rate were negatively correlated ($r = -0.715$), indicating an association of poor vision with poor reading speed. The VA for control subjects was significantly correlated with $f/x_5$ and log reading rate ($r = 0.884$ and $r = 0.742$, respectively). Control $r/m$ and $f/x_2$ scores were not correlated with VA, but control $f/x_5$ scores were correlated with reading rates ($r = 0.672$). Log reading rates for patients were highly correlated with $f/x_5$ scores ($r = -0.795$), indicating a strong association between saccadic frequency in a sequencing task and patient reading rates. All of the preceding correlations were statistically significantly greater than zero ($P < 0.05$, by t-test). A weaker relationship was found between reading rate and saccadic frequency in non-sequencing tasks ($r/m$, $r = -0.496$; $f/x_2$, $r = -0.497$; $0.05 < P < 0.1$). The $r/m$ and $f/x_2$ scores were highly correlated among patients ($r = 0.833$), suggesting that these two tasks may test the same function.

Multiple-regression analysis using the log reading rate as the dependent variable demonstrated that log $f/x_5$ and VA were significant variables in predicting reading rates, accounting for 70% of the variance ($r^2 = 0.705$) jointly. The VA contributed 5% to the variance.

Discussion

Reading is a complex process requiring visual resolution of text, reasonably stable retinal images, saccadic accuracy, word encoding, lexical accessing, and short- and long-term memory. In the presence of a macular scotoma, the peripheral retina necessarily becomes the site of visual information uptake in the reading process. Spatial and temporal resolution of reading material viewed with eccentric retinal loci have been shown to be sufficient for reasonable reading rates to be achieved.

Legge et al showed resolution of text material with eccentric viewing by subjects with macular scotomas and noted that unmanageably large levels of magnification were commonly required for reasonable reading speeds to be achieved. Turano and Rubin demonstrated the potential of the peripheral retina for reading using rapid serial visual presentation in the presumed absence of eye movements. In their study, normal subjects were able to achieve reading rates of 500–1000 words/min when using central fixation and in excess of 100 words/min using an area of retina located 10° from the fovea.
A decrease in fixation stability, an increase in inaccurate saccades, and a higher frequency of saccades occur in normal subjects tested with artificial scotomas. These subjects had abnormal fixation stability with scotomas as small as $1^\circ$ in diameter. Timberlake et al. showed that patients with much larger macular scotomas have less fixation instability than normal subjects tested with artificial scotomas, suggesting that a learning process exists for reestablishment of fixation control.

Whittaker et al. found less than normal fixation stability in well-motivated patients with long-standing maculopathies; this instability increased with scotoma size. This increase in fixation instability was most noted with scotoma diameters greater than $20^\circ$. Eye-drift speeds were also found to be higher for both nonfoveating normal subjects and patients with macular scotomas. The direction of these drifts were reasonably consistent for particular patients but idiosyncratic across their patient group. Although corrective saccades were common in their sample, they believed that drift velocities during fixation periods were not sufficient to degrade acuity and were not responsible for this action except for long fixations (greater than 300 msec). Corrective saccades were more likely to be made to improve position relative to better functioning retina.

Our study demonstrated a decrease in fixation stability in steady-state ($f/m$) and under intentional movement conditions ($f/x_2, f/x_5$) in patients. Control subjects did not show fixational instability as defined by our threshold values. Individuals with macular scotomas who had a predominance of hypometric saccades during intended movement were more able to maintain steady fixation while observing a stationary target than those with re fixation saccades resembling small square-wave jerks. It would appear that control of eye position even for simple stationary tasks may be abnormal in some patients with macular scotomas.

Most studies found that patients prefer to use a single eccentric locus for fixation, although some patients will use more than one preferred retinal locus. Whether this is task specific has not been determined.

Several authors have commented on the frequent need for corrective eye movements during a scanning or reading task in the presence of macular scotomas. Hypometric saccades, hypermetric saccades, and nystagmoid eye movements have been found during these corrective eye movements. Similar types of eye movements have also been shown in patients with homonymous hemianopias, which split fixation, and in cases of strabismic amblyopia.

During intended saccadic activity, the amplitude of eye movements demonstrated by our patients was impressive even though the number of saccades made to reach an intended target may have been large. Our testing method does not allow us to determine absolutely whether a patient used a single preferred retinal locus or several. However, we postulate that those persons with a pattern of frequent regression refixations (backward saccades) may use more than a single eccentric retinal locus for fixation, whereas those with multiple undershooting characteristics may use one locus most of the time. The rationale for this hypothesis lies in the relative consistency in the size and character of the saccades found in those patients with predominately hypometric saccades versus those with small square-wave jerk saccades. Patients with a series of small saccades linked together tended to show this pattern regardless of the nature of the intended task, suggesting a strategy of a predetermined saccade amplitude. This could be dictated by a prescribed pulse of nonvisually or partially visually determined amplitude leading to the perceived march across a field of letters. Another possibility is that patients may want to keep the intended target in the same hemisphere or within a small area of the retina in an attempt to minimize placement errors of sequential saccades.

Those patients with square-wave jerk saccades suggest that hopping back and forth between two or more fixation loci is another strategy to seek targets. These individuals tend not to maintain steady fixation while observing a single stationary target. These square-wave jerks tended to be 2–20° in amplitude, with a gaze duration between 250–350 msec. The intergaze intervals varied extensively with the shortest interval being 300 msec and the longest being many seconds. The square-wave jerks could represent cerebral or cerebellar abnormalities rather than responses to the central scotomas. Two of our patients with a pronounced tendency toward this type of saccadic activity underwent neuro-ophthalmologic examination to exclude cerebral or cerebellar lesions. No abnormalities were found.

Our control population did not have recordable square-wave activity. The small number of controls and the slightly younger mean age of this group does not exclude a higher level neurologic deficit as a possible cause for these wave forms being found in our patients, however. An analysis of those with predominantly square-wave jerk saccades compared with those with hypometric saccades showed no significant difference in reading speeds, $f/x_2$ ratios, or $f/x_5$ ratios ($P > 0.05$, by t-test).

The higher number of unexpected backward saccades than forward saccades found with the five-letter task ($f/x_5$) was interesting and puzzling. There were
four times as many intended forward saccades in the five-letter task as backward saccades, yet unexpected backward saccades outnumbered forward saccades 1.53:1. We anticipated more unexpected forward saccades on the basis of chance alone. Interestingly, the relative number of forward and backward saccades for patients with predominantly square-wave jerk saccades and those with mostly hypometric saccades were not significantly different. Taking the ratio of forward-to-backward saccades for the two intended movement conditions \( f/x \) and \( f/x \) did not show a consistent difference among subjects by predominant saccadic wave forms recorded. However, for the steady-state task, there was a trend for patients with square-wave jerks in the other experiments \( f/x \) to refixate more often than those without such saccades (mean, 76.2 r/m and 27.2 r/m, respectively, by t-test, \( P = 0.08 \)). The low significance of these values may represent an artifact from the low statistical power of our calculations.

One patient's pattern of skipping targets in the five-letter sequencing task presumably represents a scotoma placement pattern error suggestive of an overshoot without a compensatory regression sac-
ccade. This type of error is likely to affect reading accuracy and, secondarily, reading speed. This pa-
tient had the most normal-looking eye movement pattern but read only 19 words/min.

The frequency of saccadic activity was greatest when the reading-like task \( f/x \) was done, implying that it may be more difficult for persons with macular scotomas to perform a sequencing task than simple left-to-right tasks or steady-state tasks. Sequencing tasks simulating reading more closely correlated with true reading rates than did nonsequencing tasks (Fig. 7). For patients with central vision loss, saccadic accuracy—defined as the eye reaching its intended target in one fast eye movement—appears to be relatively poor. This poor accuracy leads to a corre-
sponding increase in saccadic frequency in order for the intended target in a sequencing task to be reached. The greater number of saccades results, in part, in slow reading speeds. The high correlation be-
tween saccadic frequency in sequencing tasks and the reading rate evident in our results suggests that the characteristic eye movements typically adopted in re-
sponse to the loss of macular function result in poor reading rates. Whether these naturally occurring ad-
aptations are the most productive and efficient re-
 mains to be defined.

Key words: macular degeneration, low vision, eye move-
ments, reading speed

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Fig. 7. Reading vs. saccadic frequency \( f/x \). \( f/x \) is the saccadic frequency ratio of the actual number of saccades divided by ideal or expected number of saccades for the five-letter sequencing experi-
ment. The plot demonstrates a strong correlation between reading rate and saccadic frequency for a sequencing task. The ellipse en-
closes the 95% confidence region.


