1040-5488/04/8103-0205/0 VOL. 81, NO. 3, PP. 205–213
OPTOMETRY AND VISION SCIENCE

ORIGINAL ARTICLE

Preferred Retinal Locus and Reading Rate with Four Dynamic Text Presentation Formats

ALEX R. BOWERS, PhD, MCOptom, RUSSELL L. WOODS, PhD, MCOptom, FAAO, and ELI PELI, MSc, OD, FAAO

The Schepens Eye Research Institute and Harvard Medical School, Boston, Massachusetts

ABSTRACT: *Background.* Electronic display devices hold the potential to improve access to written material by people with low vision. For those with central field loss, the optimal form of electronic text presentation may vary according to the location of the preferred retinal locus, but this has never been investigated. In this study, we examined the relationship between preferred retinal locus location and reading rate for four electronic display formats (rapid serial visual presentation, horizontal scroll, vertical scroll, and page). *Methods.* Short sentences were presented in each format to 35 low-vision (most with central field loss) and 14 age-matched control subjects. Subjects read aloud to determine maximum oral reading rate and read silently to determine preferred silent reading rate. *Results.* With the exception of page format, maximum oral reading rates were faster than silent preferred reading rates for both groups of subjects. For the low-vision group, there was no significant difference in maximum oral reading rates between the four display formats; and when reading at a preferred silent rate, page format was faster than the other three formats. Though page format was read more quickly, half of the low-vision subjects preferred the horizontal-scroll format. Contrary to our predictions, there was no significant effect of preferred retinal locus location (vertical vs. lateral) on reading rate and no significant interaction between preferred retinal locus location and display format. *Conclusions.* The differences between maximum oral and preferred silent reading rates and the lack of a relationship between reading rates and preferred display format reinforce the importance of patient preference in the evaluation and selection of a device or display format during rehabilitation. (Optom Vis Sci 2004;81:205–213)

Key Words: reading, low vision, preferred retinal locus, central visual field loss, electronic displays

Many people with visual impairment (low vision), especially those with central field loss (CFL), read at reduced rates, even with magnification that compensates for their reduced visual acuity.[1–3] The CFL typically comprises a relative or absolute scotoma that may obscure part or all of a word that is imaged on the fovea (central fixation), thus contributing to the reading difficulties of those with CFL.[4] One adaptive strategy commonly used by the CFL reader is to view eccentrically using an extrafoveal location, known as the preferred retinal locus (PRL). In this manner, the scotoma may be shifted away from the fixated word so that it is no longer obscured. Many patients with CFL naturally adopt a PRL, which is typically located close to the edge of the central scotoma (macular lesion) that can be used for fixation and more complex tasks such as pursuit and reading.[4–8] Here, we state the position of the PRL with respect to the central scotoma in visual space. Clinical studies consistently report that PRL's are found in all locations[a] (directions) around the scotoma, including some positions that seem to be less than optimal for reading (e.g., PRL directly to the left or right of the scotoma). Simulations of CFL suggest that PRL location is a significant factor determining reading rate and that CFL patients possibly do not choose the best PRL location for reading when using conventional text displays (i.e., stationary text in page format).[11–13]

With the rapid development of computer-based display technologies, there is the potential to manipulate many aspects of the presentation of text including magnification, text layout, contrast, color, and mode of text presentation (stationary or dynamic). People with different PRL locations may benefit from different forms of text presentation that reduce the problems associated with eye movement control (e.g., difficulties with consistently placing the object of regard onto the PRL) and are customized to suit their preferred PRL location. A number of hardware (e.g., Horizon, Mentor O&O, Norwell, MA) and software (e.g., Zoomtext, AiSquared, Manchester Center, VT; LP-Windows, Visionware Software, Brookline, MA) products have been developed to take advantage of these possibilities, but the potential interaction

[a] Lateral PRL (left more common than right) is more common than vertical PRL (below much more common than above) among people with CFL.[4, 9, 10]

between PRL location and display format has not been investigated.

In this study, we examined the relationship between PRL location and reading rate in a group of CFL readers for four electronic display formats to determine whether there were any beneficial interactions between PRL location and display format that could be used to customize electronic text presentation to suit the PRL location of the CFL reader. In particular, we were interested in examining whether horizontally scrolling text would be beneficial for patients with vertical PRL's (above or below the scotoma) and whether vertically scrolling text would be beneficial for patients with lateral PRL's (to the left or right of the scotoma) (see below). For comparison purposes, we also investigated the relationship between PRL location and reading rate for two other electronic display formats: rapid serial visual presentation (RSVP), for which we expected there to be no effect of PRL location, and the commonly used page format (a simulation of a page with lines of stationary text). Page format was the electronic display presentation that was most similar to conventional text; therefore, any effect of PRL location was expected to be similar to that which would occur during reading of conventional page displays. RSVP was included because of interest in using this as a display format for those with CFL due to the potential to increase reading rates through the reduction in between-word and between-line eye movements.[14–19]

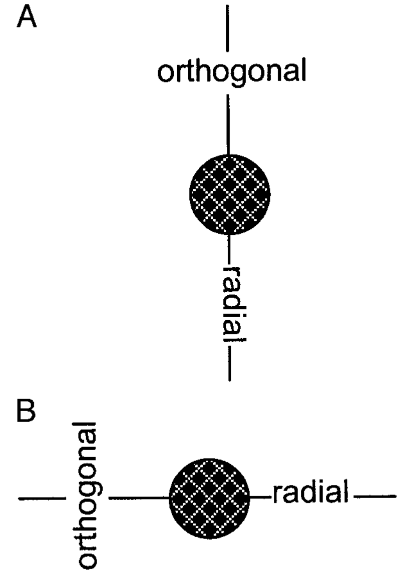

FIGURE 1.

Theoretical considerations concerning the effect of central vision loss on reading and eye movements. Schematic illustration of orthogonal and radial directions relative to the line connecting the preferred retinal locus (PRL) and fovea for (A) a vertical PRL (above or below the scotoma) and (B) a lateral PRL (to the right or left of the scotoma). The hatched area represents the central scotoma (over the fovea). Saccadic eye movements are controlled more easily when directed orthogonal to a line connecting the PRL and fovea,[20] and orthogonal aligned text should be read more easily than radial text.[21]

Horizontal and Vertical Scroll: Relation to PRL Location

Based on an analysis of eye movements, Peli[20] suggested that the optimal text presentation format for people with CFL would allow saccadic eye movements during reading that were orthogonal (perpendicular) to a line connecting the fovea with the PRL, saccadic eye movements along the radial line being more difficult (Fig. 1). Evidence from studies of spatial vision[21] suggests that there is an asymmetry of crowding between radial and orthogonal directions such that text presented orthogonal to the line connecting the fovea with the PRL should be read more easily than radial text. Thus, based on eye movement control and spatial vision, the optimal text presentation format may depend on the PRL. With a vertical PRL, it may be easier to read (conventional) horizontally aligned text than vertically aligned text, whereas the opposite may be true for a lateral PRL. In these examples, optimal eye movements are consistent with optimal spatial arrangement of the text.

Text scrolled horizontally across the screen (similar to ticker tape) is a display format[22, 23] (Fig. 2) that produces faster reading rates for visually impaired readers than using a conventional page format.[23] The ability to read horizontally scrolled text may be influenced by the subject's PRL. Because patients with a vertical PRL viewing this dynamic format would require orthogonal eye movements, the horizontal-scroll format may be beneficial to these patients. However, people with a lateral PRL may not benefit from the horizontal-scroll format because radial eye movements would be required. Also, eye movements would move text into the scotoma, and the radial arrangement of the text would be expected to create more crowding[21] for patients with a lateral PRL. Burns et al.[24] tested an alternative dynamic display format in which text scrolls vertically one word at a time (similar to movie credits) (Fig.

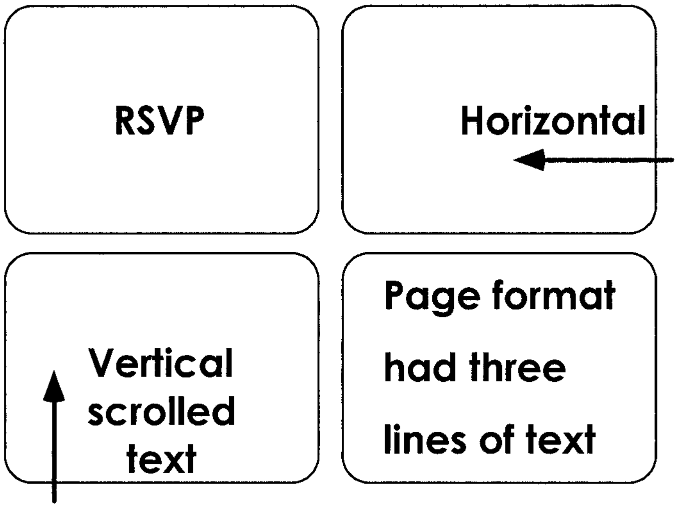

FIGURE 2.

A schematic illustration of the four text presentation formats used in this study. Both rapid serial visual presentation (RSVP) and page formats changed the displayed text, one word or word group at a time, until the end of the sentence. Text scrolled across the screen for both horizontal scroll and vertical scroll. As indicated by the arrows, horizontal-scroll text started at the right edge and moved left, and vertical-scroll text started at the lower edge and moved up.

2). Vertically scrolled text was read more quickly than RSVP by their visually impaired readers, but more slowly by normally sighted readers. Again, the ability to read vertically scrolling text may be influenced by the subject's PRL. Patients with a vertical PRL may find this format less useful because the required eye movements would be radial (and for an above PRL,[b] the words would emerge from the scotoma). Patients with a lateral PRL would require orthogonal eye movements, suggesting that the vertical-scroll format may be beneficial to these people, but the radial arrangement of the text may negate the benefits of the text motion relative to the PRL. It is uncertain which of these factors (orthogonal eye movements or radially aligned text) might have the greater influence on reading rate for those with a lateral PRL. Table 1 summarizes the eye movement direction and text alignment resulting from horizontal-scroll and vertical-scroll formats for patients with vertical and lateral PRL's.

We predicted that people with a vertical PRL would read faster with the horizontal-scroll format than the Vertical-scroll and page formats. The converse prediction that people with a lateral PRL would read faster with the vertical-scroll format than the horizontal-scroll and page formats is uncertain due to the conflict between the orthogonal eye movements and the radially aligned text.

Table 1.
Summary of eye movement direction and text alignment, relative to a line connecting the PRL and fovea (Figure 1), for those with vertical and lateral PRL's reading horizontal-scroll and vertical-scroll formats (Figure 2)[ab]

PRL Location	Display Format	
	Vertical Scroll	Horizontal Scroll
Vertical	Eye movements radial Text alignment orthogonal	Eye movements orthogonal Text alignment orthogonal
Lateral	Eye movements orthogonal Text alignment radial	Eye movements radial Text alignment radial

[a] Theoretical considerations suggest that the optimal display format, to maximize reading rate, should utilize orthogonally aligned text and enable orthogonal eye movements.
[b] PRL, preferred retinal locus

Maximum Oral Reading Rate and Preferred Silent Reading Rate

Maximum oral reading rate, the most common experimental measure of reading performance, is unlikely to be the preferred silent reading rate that a person would habitually adopt when reading in a "real-world" setting. Although rauding rates (reading to comprehend the complete thought contained in each sentence[25]) have been shown to correlate with maximum oral reading rates,[1, 23, 25, 26] no one has yet shown how preferred silent reading rates relate to maximum oral reading rates for dynamic text display formats. Preferred silent reading rates are likely to be slower than maximum oral reading rates, but the ratio of the two may differ depending on display format. This would make it impossible to predict the preferred silent reading rate for one display format from the maximum reading rate measured with another display format. Hence, we measured both maximum oral and preferred silent reading rates for all four dynamic display formats. Also, we asked which of the four text presentation formats was preferred, in the expectation that the preference would relate to differences in reading rate. The eventual goal of this research program is to be able to determine the optimal method(s) of text presentation on electronic displays for people with specific vision impairments.

METHODS
Subjects

Patients with low vision (visual acuity 20/70 or worse and CFL) were recruited from an ophthalmology practice, Schepens Retina Associates, Boston, MA. Seven of the 42 subjects were unable to complete all aspects of the study due to time limitations or fatigue and were excluded from data analyses. The average age of the remaining 35 patients (whose data were included in the analyses reported here) was 70 years (median, 74; range, 34 to 87), and the average visual acuity was 20/150 (0.87 logMAR) (median, 20/130; range, 20/70 to 20/600). The median duration of the visual impairment was 13 years (range, 0.5 to 37). Six low-vision subjects used closed-circuit television magnifiers, and two reported using screen enlargement software on a computer.

The low-vision subjects were categorized on the basis of their central visual field and the location of any monocular PRL. Both CFL and PRL were defined using scanning laser ophthalmoscopic (SLO) evaluation, clinical Autoplot testing, or a modified Welsh-Allyn direct ophthalmoscope (with a large visuoscopy fixation target). Indication of dense scotoma in the central 5° was considered a CFL. Four low-vision subjects with visual acuity in the range 20/70 to 20/125 did not have a dense scotoma (only relative field loss) in the central 5° and were therefore categorized as "no CFL"; nevertheless, these four subjects were included in the low-vision group for data analyses because they did have mild CFL (i.e., a relative scotoma). For most patients, the PRL was determined by SLO.[27] In line with the binary classification underlying our hypotheses, CFL subjects were categorized by PRL location into two main groups: vertical PRL (PRL above or below scotoma) and lateral PRL (PRL to the right or left of the scotoma). In addition, subjects who did not fall within either of these two groups were classified either as central PRL (PRL within the central scotoma) or other PRL (Table 2). When the monocular PRL's were different, the PRL used for categorization was the PRL of the eye with better visual acuity. The vertical-PRL and lateral-PRL groups were similar in terms of visual acuity and age (unpaired t-test, $p > 0.7$) (Table 2). Documented PRL information was not available for three subjects, but visual acuity, diagnosis, and fundus photographs supported their classification as CFL.

An age-matched control group of 14 subjects with visual acuity of 20/40 or better and no CFL in at least one eye also participated in the study. The average age of these 14 subjects was 69 years (median, 69; range, 40 to 84), and the average visual acuity was 20/25 (0.09 logarithm of the minimum angle of resolution) (median, 20/25; range 20/16 to 20/40). Only four control subjects had no known ocular disease, although most of those with ocular disease (eight) had one "healthy" eye without retinal disease. This reflects recruitment mainly from an ophthalmological practice and the categorization based on single-letter visual acuity (Mentor B-VAT II, Mentor O&O) determined using their habitual spectacle correction. Of the two control subjects who did have ocular disease in both eyes, one had a peripheral retinal hole in the eye

[b] An above PRL is uncommon.[4]

Table 2.
Classification by PRL location for low-vision subjects with central field loss (N = 31)[a,b]

PRL Group	No.[c]	Age (yr) Mean ± SD	VA (logMAR) Mean ± SD
Central (PRL within scotoma)	4	73 ± 10	0.85 ± 0.29
Vertical	14 (1 above, 13 below)	71 ± 11	0.86 ± 0.18
Lateral	9 (5 right, 4 left)	71 ± 16	0.90 ± 0.29
Other	1 (above and right)	81	0.60

[a] PRL location is given with respect to the central scotoma in the visual field.
[b] PRL, preferred retinal locus; VA, visual acuity; logMAR, logarithm of the minimum angle of resolution.
[c] PRL data not available for three subjects.

with better acuity, and the other had vasculitis. Of the eight control subjects with one healthy eye, six had a large difference in visual acuity between the two eyes and were essentially monocular (using the healthy eye, which was free from CFL), and the remaining two had more similar acuity in the two eyes, with both eyes free from CFL. All subjects were native English speakers and had attended high school. There were almost equal numbers of male and female subjects in each group. None of the subjects had any prior experience of reading RSVP or scrolling text displays. All subjects provided informed consent in accordance with the institutional review board approval.

Apparatus and Materials

A modified Horizon LV Magnifier (Mentor O&O) was used for text presentation and data collection. White text was presented on a black background (contrast 96%) using a 27-inch Sony color television monitor. Average luminance across the background was 4.4 ± 2.7 cd/m^2. All text was a proportionally spaced, bold, san-serifed, bitstream font. A lowercase letter x measured 5.4 cm by 3.7 cm. To maintain a text window that had a constant number of visible characters (window size), altering subject viewing distance (as described below) varied the visual angle subtended by the text (magnification). Consequently, a lowercase x subtended between 1.8° by 1.2° and 8.4° by 5.7°.

Four modes of text presentation (display format) were available: (1) RSVP, (2) horizontal-scroll, (3) vertical-scroll, and (4) page. These are schematically illustrated in Fig. 2. The limitations imposed by the monitor on RSVP and horizontal-scroll formats and the methods used to tackle the limitations of the apparatus have been described in detail previously.[15, 16] For the text size used, monitor width limited the maximum word size to 11 to 13 characters of this proportional font. All words could be displayed completely in one line. For RSVP, all words were presented in the middle of the monitor (centered). Using this 30 frames/s, interlaced monitor, the minimum duration of each word was 17 ms (one field). Maximum presentation rate was restricted to 1200 words per minute (wpm).[28] This did not restrict any subject because the fastest recorded reading rate was 513 wpm. Horizontal-scroll text emerged from the center of the right monitor edge and moved leftwards as a horizontal line of characters and words. The proportional font varied the gap between words from 2.5 to 3.5 cm depending on the surrounding characters. Speed of movement (words per minute) was determined from the number of pixels and words in the sentence. Where precise movement could not be achieved for a given speed, the movement of one or more fields within a group of fields was altered to give the correct average speed of movement over that series of fields. For example, moving 9, 9, 9, and 10 pixels on successive fields gave a motion equivalent to 9.25 pixels per field (555 pixels/s). Using this approach, apparent smooth motion was achieved except at the slowest text speeds (<20 wpm). At these very slow presentation rates, the low-vision readers did not detect the jumpiness apparent to a normally sighted observer. Vertical-scroll text emerged from the center of the lower monitor edge one word at a time and moved upwards.[24] The lower edge of each line was 12 cm below the preceding line, leaving a gap of between 6.8 and 4.9 cm between characters on subsequent lines (this varied due to differences in letter height and whether characters were capitalized). Apparently smooth movement was obtained in a manner similar to that used for the horizontal-scroll text. Page format presented as many words as could fit on three lines of text (constrained by the character-spaces-per-line limitation and the between-line spacing) for a period determined by the number of words and the display rate in words per minute. For example, a page of text would be visible for 3 s if there were five words in that page presented at 100 wpm. A typical sentence was displayed on two or three pages.

The corpus of short (MNRead) sentences developed by Legge et al.[23] was augmented to create a total of 400 sentences. Each of the sentence presentations had 55 characters (including spaces) comprising 9 to 14 words and no internal punctuation. All sentences were preceded by a string of five capital character X's. This was provided to give subjects a temporal and spatial cue for the commencement of the sentence and its position on the screen. Sentences were randomly assigned to 20 groups of 20 sentences. Each subject was allocated a different sequence of the 20 groups. No subject read the same sentence twice.

Design and Procedures

In a room with low ambient illumination (median 75 lux), each subject sat in a comfortable chair at a distance from the television monitor that ensured that the text subtended a visual angle that was at least 4×, and typically 6×, the acuity threshold of the better eye. Whittaker and Lovie-Kitchen[2] reported that an acuity reserve of 3× was sufficient for maximum oral reading rates of simple sentences, although Fine and Peli[16] found that this might not be sufficient for the horizontal-scroll and RSVP presentations. The viewing distance for subjects in the control group was 7 feet, an acuity reserve of about 10× for a subject with 20/40. This large acuity reserve was due to the size of the room limiting the maximum viewing distance. All subjects wore a recent spectacle correction appropriate for the viewing distance when required and viewed the television monitor binocularly. No telescopic devices were used.

Subjects read the sentences aloud (maximum oral) or silently (preferred silent). The order of the reading condition was alternated for successive subjects. All display formats with the first reading condition (e.g., maximum oral) were completed before starting the four display formats with the second reading condition (e.g., preferred silent). Display format order was randomized for each subject for the first reading condition; the same order was then used for the second condition. To measure the maximum oral reading rate, a simple staircase procedure was adopted. "Incorrect" was defined as two or more errors in a sentence. Text speed was increased or decreased accordingly by predetermined step sizes. With successive reversals (i.e., change from correct to incorrect or vice versa), the step size was reduced. Threshold reading rate was defined as one step slower than the text speed at which two consecutive sentences were marked as incorrect once the smallest step size had been reached. For low-vision subjects, the first text speed was 40 wpm and the smallest step size (i.e., the step size at the end of the staircase) was 5 wpm, whereas for control subjects, these were 160 wpm and 10 wpm, respectively. Preferred reading rate was determined in a similar manner, except that the subjects read silently, and text speed was altered according to the response to the question "If you were using this device to read for your own pleasure, would you have liked the presentation rate to be faster or slower than that of the last sentence?" Display speeds were altered based on the subject's response to the question, using the same staircase procedure. Subjects were given minimal practice with each display format before data collection commenced. Comprehension was not assessed formally, but subjects were reminded frequently that they must read the sentences for understanding. Occasionally the experimenter asked a question about sentence content, but more frequently subjects commented on the sentences. At the end of the reading trials, subjects were asked to indicate which of the four display formats they preferred.

Data Analysis

Data were analyzed using SPSS statistical software (version 10 for windows). Because the reading rate measures were approximately normally distributed, repeated-measures analyses of variance was used for initial data analyses. Specific hypotheses formulated in the introduction were evaluated using simple contrasts. Pairwise comparisons with Bonferroni correction and t-tests were used for *post hoc* evaluation of differences between groups and conditions. A probability level of <0.05 was considered statistically significant for all analyses.

Statistical analyses were performed using data from the 35 low-vision subjects who completed all aspects of the study and the 14 control subjects. For the analyses where the low-vision subjects were subdivided by PRL location, only the low-vision subjects with documented PRL's were included (Table 2). Of the 14 subjects in the control group, five had visual acuities worse than 20/25. The main results were unchanged when we repeated reading rate analyses with control group inclusion limited to visual acuity of 20/25 or better.

RESULTS

As expected, on average, the control group read faster than the low-vision group (overall mean reading rate across all display formats: control group, 271 ± 95 wpm; low-vision group, 88 ± 61 wpm; $F_{1,47} = 95$; $p < 0.001$), and maximum oral reading rates were faster than preferred silent reading rates (overall mean reading rate for all subjects across all display formats: maximum oral, 155 ± 118 wpm; preferred silent, 126 ± 101 wpm; $F_{1,47} = 29$; $p < 0.001$). Overall, RSVP was the fastest display format ($F_{3,141} = 22$; $p < 0.001$). However, there were significant interactions between groups, reading condition, and display format that were of interest. As shown in Fig. 3A, for the control group, maximum oral reading rate with RSVP (377 ± 117 wpm) was faster ($p < 0.004$) than the other three display formats (average, 269 ± 70 wpm). However, when control subjects read at their preferred silent reading rate, page and RSVP formats were faster than horizontal scroll and vertical scroll ($p < 0.05$). For all display formats for the control

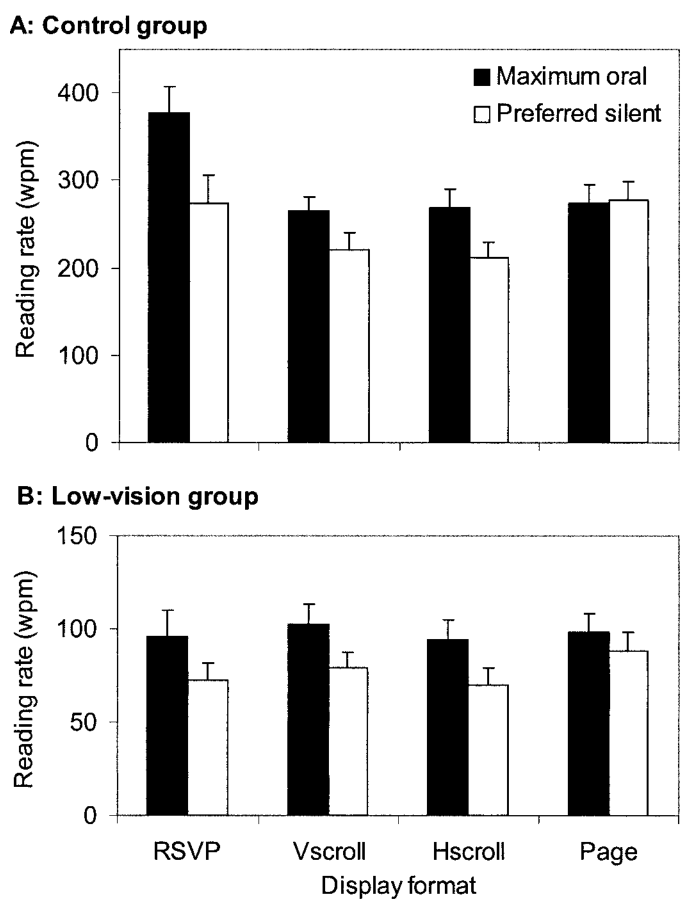

FIGURE 3.

Mean reading rates of (A) the control group (N = 14) and (B) the low-vision group (N = 35). Note the difference in scale on the y axis between control and low-vision groups. Error bars represent SEM. RSVP, rapid serial visual presentation; Vscroll, vertical-scroll text that started at the lower edge and moved up; Hscroll, horizontal-scroll text that started at the right edge and moved left (Fig. 2); wpm, words per minute.

group, maximum oral reading rate was correlated with preferred silent reading rate ($r > 0.63$; $p < 0.01$). The ratio of preferred silent to maximum oral reading rates for page format (103%) was significantly higher ($p = 0.003$) than for the other three display formats (RSVP 74%, vertical scroll 84%, and horizontal scroll 81%).

As can be seen in Fig. 3B, maximum oral reading rates of the low-vision group were not significantly different for the four display formats (average, 98 ± 67 wpm).[c] Contrary to Rubin and Turano,[14] RSVP did not provide faster reading than a page format; and contrary to Burns et al.,[24] vertical scroll was not faster than RSVP. Our result is similar to Fine and Peli,[15, 16] who found that RSVP was read at the same speed as horizontal scroll (except at very large acuity reserves of 8 to 10 times threshold[16]). On average, preferred silent reading rates were slower than maximum oral reading rates ($F_{1,34} = 19$; $p < 0.001$). For preferred silent reading rates, page format (88 ± 60 wpm) was read at a faster speed than the other three display formats (average, 74 ± 52 wpm); page format was significantly faster than horizontal scroll and RSVP ($p < 0.03$). Maximum oral reading rate was highly correlated with preferred silent reading rate ($r > 0.79$; $p < 0.001$). The ratio of preferred silent to maximum oral reading rates for the page format (92%) was higher, although not significantly higher, than the other three display formats (RSVP 87%, vertical scroll 85%, and horizontal scroll 79%).

Our review of the literature—eye movement control and relative text orientation—suggested that reading rates with different text presentations might be influenced by the location of the PRL. We predicted that the vertical-PRL group would read faster with the horizontal-scroll format than with the vertical-scroll and page formats. Contrary to our prediction, reading by the vertical-PRL group with horizontal scroll was slightly slower than with the vertical-scroll format (contrast $F_1 = 5.5$; $p = 0.04$) (Fig. 4) and the page format (contrast $F_1 = 5.7$; $p = 0.03$) (Fig. 4). Due to the conflict between orthogonal eye movements and radially aligned text, the converse prediction that the lateral-PRL group would read faster with the vertical-scroll format than the horizontal-scroll and page formats was uncertain. Overall, the reading rate of the lateral-PRL group for the vertical-scroll format was not significantly different from the reading rate achieved with the horizontal-scroll and page formats (contrasts $F_1 < 2.8$; $p > 0.1$) (Fig. 4). The lack of strong effects of PRL location on reading rates with the different display formats was confirmed by a repeated-measures analyses of variance that considered PRL location (vertical, lateral, or central), reading condition, and display format. Overall, there was no significant effect of PRL group ($F_{2,24} = 0.9$; $p = 0.4$) and no significant interactions between PRL group and the other factors ($p > 0.2$).

Visual comparison of Fig. 4 A and B gives the impression that the difference in maximum oral and preferred silent reading rates was greater for the lateral-PRL group than the vertical-PRL group, especially for the horizontal-scroll and vertical-scroll formats. Indeed, the average ratio of preferred silent to maximum oral reading rates across the four display formats was 94% for the vertical-PRL group compared with 79% for the lateral-PRL group. However this between-groups difference was not significant (analyses of variance $F_{1,20} = 2.2$; $p = 0.16$), and there was no significant interaction between display format and PRL group for the ratio of preferred silent to maximum oral reading rates. Our between-groups comparison is limited by sample size. Only eight subjects were included in the lateral group for this analysis because one subject (subject 29) could not read with the RSVP format (reading rate, 0 wpm), therefore the preferred silent to maximum oral reading rate ratio could not be calculated for the RSVP condition for this subject. With eight subjects, we could only expect to detect an absolute difference between the preferred silent to maximum oral reading rate ratios for the two groups of >31% ($\alpha = 0.05$, $\beta = 0.20$). The difference in preferred silent to maximum oral reading rate ratios approached this value for the horizontal-scroll (95% and 68% for vertical-PRL and lateral-PRL groups, respectively) and the vertical-scroll (98% and 68% for vertical-PRL and lateral-PRL groups, respectively) formats.

Given that, in general, the preferred silent reading rate using the page format was fastest, it seems reasonable to expect that this would be the preferred display format. Of the 31 subjects with low vision who expressed a preference (four reported no preference), 15 preferred the horizontal-scroll format, six preferred the vertical-

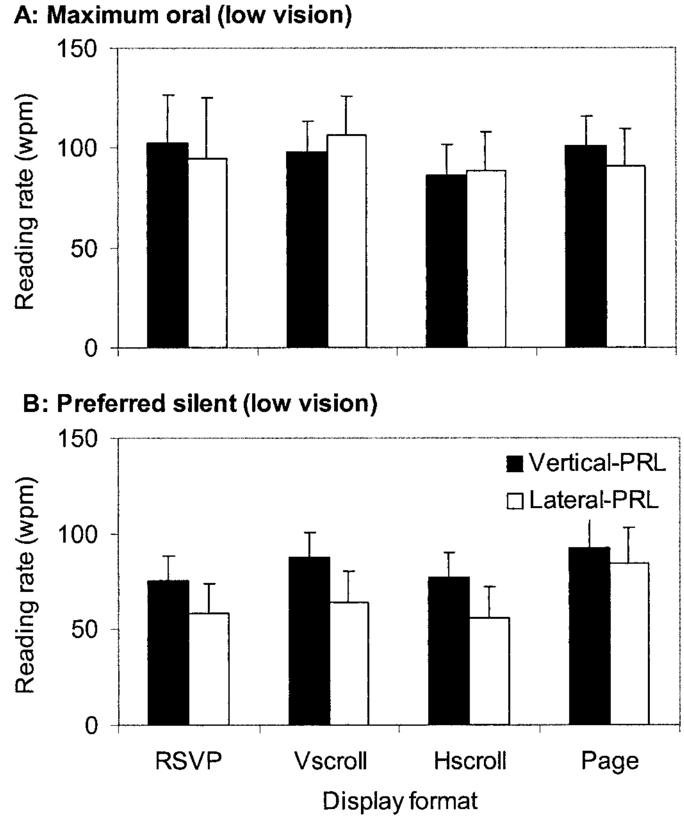

FIGURE 4.
There was no significant difference between the vertical preferred retinal locus (PRL) (N = 14) and lateral-PRL (N = 9) groups of central field loss subjects in (A) the maximum oral reading rate or (B) the preferred silent reading rate. Error bars represent SEM. RSVP, rapid serial visual presentation; Vscroll, vertical-scroll text that started at the lower edge and moved up; Hscroll, horizontal-scroll text that started at the right edge and moved left (Fig. 2); wpm, words per minute.

[c] For the low-vision group, with a sample size of 35 subjects, we could only expect to detect a difference in maximum oral reading rates of greater than about 19 wpm ($\alpha = 0.05$, $\beta = 0.20$).

scroll format, and six preferred the page format, whereas only four preferred RSVP. The stated preference was not related to differences in reading rate with the different formats or to the PRL.

Learning Effects and Reliability

Each subject's reading rate for each display format and reading condition was measured once only in the main experiment. A limited assessment of learning effects and intrasubject reliability was therefore carried out. Two subjects (one with normal acuity [20/16, no ocular pathology] and one with low vision [20/400, CFL and a below PRL]) returned for a total of five sessions each within a period of 2 weeks. Each session was identical to that described above. No subject read the same sentence twice. At each session, the order of reading conditions was alternated. The order of the display format at each session was approximately randomized, with an allocation such that no display format had the same order position (e.g., third) more than twice. Sequential sessions were evaluated for improvements with time (i.e., a learning effect). When no learning effects are apparent, the variance of the five measurements may be used as a measure of reliability.

Maximum oral reading rate of the normal-acuity subject did not vary across the five sessions, but the preferred silent reading rate increased, on average from 197 $\pm$ 22 wpm to 237 $\pm$ 21 wpm (paired t-test, $p = 0.002$). Reading rates of the low-vision subject did not vary systematically across the sessions. Both of these subjects used electronic displays regularly in their jobs. The variance of the reading rate estimates was similar for the normal-acuity and the low-vision subjects, with the standard deviation of the five estimates (i.e., of the five sessions) ranging between 19 and 60 wpm. This within-subject variance is similar to the between-subject variance in the main study.

DISCUSSION

Contrary to our predictions, we found no overall significant effect of PRL location on sentence reading rate for the four electronic display formats investigated in this study. Patients with vertical PRL's did not read more quickly with the horizontal-scroll than the vertical-scroll format. Fletcher et al.[29] also reported for a group of 99 subjects with macular scotoma that PRL location was not a statistically significant factor determining maximum oral reading rate on single sentences presented in a "page" format (MN-Read acuity chart). By comparison, studies that have used simulated scotomas in normally sighted subjects show clear effects of PRL location on reading rate, with a right PRL enabling faster reading than a left PRL[11, 12] and a below PRL enabling faster reading than a left PRL.[13] Similar trends (not statistically significant) in reading rates across PRL subgroups are also evident in clinical studies.[10, 29]

A variety of factors may account for this difference in the strength of the relationship between reading rate and PRL location in simulated scotoma and real scotoma studies. Large between- and within-subject variances (and small sample size,[d] e.g., Sunness et al.[10]) limit the power of statistical analyses in clinical (real scotoma) studies; however, the degree of between-subject variance is reduced by the use of simulated scotomas. Typically, artificial scotomas are unilateral and, at best, provide only a limited simulation of a real scotoma in as much as they create absolute defects with well-demarcated edges, whereas many real scotomas are bilateral and contain areas of relative loss with diffuse borders. Equally, simulated scotoma studies do not replicate the sensory adaptations that may occur over time in CFL readers with a real scotoma, and the PRL on the compromised retina of a CFL reader may behave differently to a PRL in the same location on healthy retina in an artificial scotoma study.[29] In real scotoma studies, PRL location is usually measured monocularly (as in this study) viewing a simple target, whereas reading (a complex task that involves planned eye movements along extended targets) is often performed binocularly. Therefore, the PRL used for fixation may be different to the PRL used for reading, however Trauzettel-Klosinski and Tornow[8] confirmed that 89% of their subjects with CFL used the same PRL when fixating a 1° cross and when reading continuous text in a SLO (monocular viewing). The monocular and binocular PRL are not necessarily the same.[30] Therefore, the recorded PRL may not be the PRL used for reading, possibly making categorization incorrect. Fletcher et al.[29] used subjects in whom the monocular PRL's were in a similar location relative to the macular scotoma in both eyes; therefore, it is likely that the binocular PRL was similar to the monocular PRL, but they still did not find a significant effect of PRL location on reading rate.

As suggested above, it is possible that the recorded PRL might not be the PRL used when reading. Although the majority of people with CFL use a single PRL, there are reports of the use of multiple PRL's, dependent on the size, nature (single letter or word), and luminance of the stimulus.[5, 8–10, 31–34] Some of these reports[31, 33, 34] are case reports of a small number of subjects ($\leq$5 subjects); whereas in larger-scale studies, multiple PRL's are found to be relatively uncommon (e.g., observed in about 10% of patients for studies with sample sizes of 35[10] and 288 subjects[32]). Although the majority of PRL's were determined with the SLO in our study, some were determined by alternative methods (clinical visual fields assessment and direct ophthalmoscopy). However, previous studies have shown relatively good correspondence between PRL's determined by SLO and clinical visual fields assessment using tangent-screen methods[27] and Tuebingen manual perimetry.[8] The possibility of the PRL varying with stimulus and task conditions is a potential limitation of our study; we suggest, however, that it is a relatively infrequent occurrence and is unlikely to have had any significant impact on the findings. Many of the reports of multiple PRL's relate to "ring" scotomas where there is a small area with high spatial resolution remaining within the center of the scotomatous area that may be used to identify small targets or single letters, whereas an alternative PRL with a wider functional area, but lower resolution, outside of the scotoma might be used to view larger targets or read words.[8, 9, 33, 34] In our study, subjects exhibiting multiple PRL's of this type would have been classified as central PRL (PRL within the central scotoma) and would have had no impact on analyses based on the binary vertical- vs. lateral-PRL categorization because these analyses included only subjects classified as having vertical or lateral PRL's.

We compared maximum oral reading rates with the silent reading rates that subjects preferred for reading with each of the four

[d] We did not have sufficient subject numbers to perform PRL subgroup analyses to compare reading rates for right, left, below, and above PRL's).

electronic display formats. It is likely that the preferred rate that we measured is representative of the reading rate that a CFL patient might adopt when first being trained to use a novel electronic text display format. The difference between the self-selected silent preferred rate and the maximum oral rate (achieved during forced experimental conditions) gives an indication of the potential for improvement through training. In general, preferred silent reading rate was a relatively high proportion of maximum oral reading rate. Both control and low-vision subjects had preferred silent reading rates that were very close to maximum oral reading rates for the page format (103% and 92%, respectively), probably because this was the most familiar of the display formats and no training would be required to achieve maximum speeds. The proportional difference between the two rates was greater for the other three display formats, but was still above about 79%, indicating that the limited amount of practice achieved within the one experimental session was sufficient for most subjects to select preferred silent reading rates that were fairly close to maximum oral rates.[e] Because the majority of our low-vision subjects had little or no experience with using electronic displays and were naïve to the dynamic display formats used in the study, this suggests that CFL patients would not need extensive training to achieve maximum reading rates with these display formats. Aquilante and Yager (personal communication, 2003) found little evidence of within-session practice effects for naïve CFL subjects and normally sighted subjects reading electronic displays with RSVP, page, and horizontal-scroll formats.

We have only limited information (one normal acuity and one low-vision subject) about how the maximum oral and preferred silent rates might improve with practice over a number of sessions; however, we suspect that the preferred silent reading rates of our low-vision subjects were close to those that would be achieved with more experience with electronic displays. Aquilante and Yager (personal communication, 2003) found that RSVP reading rates of CFL subjects did not change during five sessions. In this study, we measured preferred silent reading rates for short sentences with display rate controlled by the experimenter. It is possible that preferred silent reading rates might be different for extended passages because additional time may be required to integrate information within the text across multiple sentences.[35–37] Equally, more training might be required to read longer passages (greater practice effects), especially if the display speed is controlled by the subject, in a situation more representative of real-world reading.

The RSVP display format did not result in faster reading than the other display formats; in particular, the preferred silent RSVP rate was significantly slower than the preferred silent page display rate. Given that reading text in RSVP format theoretically requires fewer eye movements than the other display formats, it is possible that our RSVP display was less than optimal. In this study, the RSVP text was presented at a constant rate; however, there is accumulating evidence[18, 19] that RSVP with a variable presentation rate, where word duration varies according to word length, enables faster reading rates for subjects with CFL. In moving toward the goal of providing experimental electronic display situations that are representative of real-world reading, both preferred silent (rather than maximum oral) reading rates and subject control of display speed need to be considered. Arditi[18] demonstrated that when slow readers with low vision were allowed to control word presentation rate for RSVP display, reading rates were on average 47% faster than for conventional RSVP with constant word duration. Further investigation is required to understand the impact of user-controlled presentation rates on reading performance for a range of electronic display formats.

Although the low-vision group read the page format more quickly at the preferred silent rate than the other display formats, the majority of subjects (15 of the 31 who expressed a preference) preferred the horizontal-scroll format (for our single-sentence displays). Only four subjects preferred the RSVP format. There was no obvious link between the display format preference and reading rate or PRL. Similarly, Harland et al.[17] found, for reading of short passages, that horizontal scroll was preferred to RSVP, and their user-controlled page format (using a closed-circuit television) was approximately equally as popular as horizontal scroll. It is possible that the display format preference would vary with experience or when reading extended passages, but this was not investigated here.

In summary, reading rate was influenced by the display format in both control and low-vision groups, but the effects were different for the two groups. Therefore, reading rates with dynamic displays of people with low vision could not be predicted from the reading rates of control subjects. We found no significant effect of PRL location (vertical vs. lateral) on reading rate for the reading of simple sentences and no significant interaction between PRL location and display format; however, more research is required to determine whether a stronger relationship might exist when the reading task is more challenging. The differences between maximum oral and preferred silent reading rates and the lack of a relationship between reading rates and preferred display format reinforce the importance of patient preference in the evaluation and selection of a device or display format during rehabilitation.

ACKNOWLEDGMENTS

Supported, in part, by National Eye Institute, National Institutes of Health grant EY10285. Beth O'Brien and Lee Zimmerman provided the additional MNRead formatted sentences.

We thank Clement L. Trempe, Franz van der Velde, Catherine W. Burns, Angela T. Labianca, and Aaron M. Soschin for their contributions to the study. In particular, we thank Elisabeth M. Fine for her input on study design and her comments on early drafts of this manuscript.

Submitted February 14, 2003; accepted October 6, 2003.

REFERENCES

1. Legge GE, Rubin GS, Pelli DG, Schleske MM. Psychophysics of reading. II: low vision. Vision Res 1985;25:253–65.
2. Whittaker SG, Lovie-Kitchin J. Visual requirements for reading. Optom Vis Sci 1993;70:54–65.
3. Bullimore MA, Bailey IL. Reading and eye movements in age-related maculopathy. Optom Vis Sci 1995;72:125–38.
4. Fletcher DC, Schuchard RA. Preferred retinal loci relationship to macular scotomas in a low-vision population. Ophthalmology 1997;104:632–8.
5. Cummings RW, Whittaker SG, Watson GR, Budd JM. Scanning characters and reading with a central scotoma. Am J Optom Physiol Opt 1985;62:833–43.

[e] For subjects whose vision did not impede reading rate, maximum oral rate may be limited by the time taken to vocalize the words. Maximum silent reading rate, which is not limited by vocalization, was not investigated in this study.

6. Timberlake GT, Peli E, Essock EA, Augliere RA. Reading with a macular scotoma. II: retinal locus for scanning text. Invest Ophthalmol Vis Sci 1987;28:1268–74.
7. White JM, Bedell HE. The oculomotor reference in humans with bilateral macular disease. Invest Ophthalmol Vis Sci 1990;31: 1149–61.
8. Trauzettel-Klosinski S, Tornow R-P. Fixation behaviour and reading ability in macular scotoma assessed by Tuebingen manual perimetry and scanning laser ophthalmoscopy. Neuro-ophthalmology 1996;16: 241–53.
9. Guez JE, Le Gargasson JF, Rigaudiere F, O'Regan JK. Is there a systematic location for the pseudo-fovea in patients with central scotoma? Vision Res 1993;33:1271–9.
10. Sunness JS, Applegate CA, Haselwood D, Rubin GS. Fixation patterns and reading rates in eyes with central scotomas from advanced atrophic age-related macular degeneration and Stargardt disease. Ophthalmology 1996;103:1458–66.
11. Rayner K, Well AD, Pollatsek A. Asymmetry of the effective visual field in reading. Percept Psychophys 1980;27:537–44.
12. Fine EM, Rubin GS. Reading with simulated scotomas: attending to the right is better than attending to the left. Vision Res 1999;39: 1039–48.
13. Petre KL, Hazel CA, Fine EM, Rubin GS. Reading with eccentric fixation is faster in inferior visual field than in left visual field. Optom Vis Sci 2000;77:34–9.
14. Rubin GS, Turano K. Low vision reading with sequential word presentation. Vision Res 1994;34:1723–33.
15. Fine EM, Peli E. Scrolled and rapid serial visual presentation texts are read at similar rates by the visually impaired. J Opt Soc Am (A) 1995;12:2286–92.
16. Fine EM, Peli E. Benefits of rapid serial visual presentation (RSVP) over scrolled text vary with letter size. Optom Vis Sci 1998;75:191–6.
17. Harland S, Legge GE, Luebker A. Psychophysics of reading. XVII: low-vision performance with four types of electronically magnified text. Optom Vis Sci 1998;75:183–90.
18. Arditi A. Elicited sequential presentation for low vision reading. Vision Res 1999;39:4412–8.
19. Aquilante K, Yager D, Morris RA, Khmelnitsky F. Low-vision patients with age-related maculopathy read RSVP faster when word duration varies according to word length. Optom Vis Sci 2001;78: 290–6.
20. Peli E. Control of eye movement with peripheral vision: implications for training of eccentric viewing. Am J Optom Physiol Opt 1986;63: 113–8.
21. Toet A, Levi DM. The two-dimensional shape of spatial interaction zones in the parafovea. Vision Res 1992;32:1349–57.
22. Buettner M, Krischer CC, Miessen R. Characteristics of gliding text as a reading stimulus. Bull Psychon Soc 1986;23:479–82.
23. Legge GE, Ross JA, Luebker A, LaMay JM. Psychophysics of reading. VIII: the Minnesota Low-Vision Reading Test. Optom Vis Sci 1989; 66:843–53.
24. Burns CW, Fine EM, Peli E. Alignment of dynamic text can affect reading rates in patients with central scotoma. In: Vision '96: International Conference on Low Vision Proceedings. Madrid, Spain: Organización Nacional de Ciegos Españoles, 1998:225–35.
25. Carver RP. Reading Rate: a Review of Research and Theory. San Diego: Academic Press, 1990.
26. Lovie-Kitchin JE, Bowers AR, Woods RL. Oral and silent reading performance with macular degeneration. Ophthalmic Physiol Opt 2000;20:360–70.
27. Timberlake GT, Mainster MA, Peli E, Augliere RA, Essock EA, Arend LE. Reading with a macular scotoma. I: retinal location of scotoma and fixation area. Invest Ophthalmol Vis Sci 1986;27: 1137–47.
28. Rubin GS, Turano K. Reading without saccadic eye movements. Vision Res 1992;32:895–902.
29. Fletcher DC, Schuchard RA, Watson G. Relative locations of macular scotomas near the PRL: effect on low vision reading. J Rehabil Res Dev 1999;36:356–64.
30. Labianca AT, Peli E. Monocular preferred retinal loci are inconsistent with binocular viewing. In: Vision '96: International Conference on Low Vision Proceedings. Madrid, Spain: Organización Nacional de Ciegos Españoles, 1998:381–7.
31. Culham LE, Fitzke FW, Timberlake GT, Marshall J. Use of scrolled text in a scanning laser ophthalmoscope to assess reading performance at different retinal locations. Ophthalmic Physiol Opt 1992;12: 281–6.
32. Lei H, Schuchard RA. Using two preferred retinal loci for different lighting conditions in patients with central scotomas. Invest Ophthalmol Vis Sci 1997;38:1812–8.
33. Duret F, Issenhuth M, Safran AB. Combined use of several preferred retinal loci in patients with macular disorders when reading single words. Vision Res 1999;39:873–9.
34. Deruaz A, Whatham AR, Mermoud C, Safran AB. Reading with multiple preferred retinal loci: implications for training a more efficient reading strategy. Vision Res 2002;42:2947–57.
35. Potter MC, Kroll JF, Harris C. Comprehension and memory in rapid sequential reading. In: Nickerson R, ed. Attention and Performance VIII. Hillsdale, NJ: Erlbaum, 1980:395–417.
36. Masson ME. Conceptual processing of text during skimming and rapid sequential reading. Mem Cognit 1983;11:262–74.
37. Potter MC. Rapid serial visual presentation (RSVP): a method for studying language processing. In: Kieras DE, Just MA, eds. New Methods in Reading Comprehension Research. Hillsdale, NJ: Erlbaum & Associates, 1984:91–118.

Alex R. Bowers
Schepens Eye Research Institute.
20 Staniford Street
Boston, MA 02114
e-mail: abowers@vision.eri.harvard.edu