PRL Location and Reading Rate with Four Dynamic Text Presentation Formats

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ABSTRACT

**Background:** Electronic display devices hold the potential to improve access to written material by people with visual impairment. For those with central field loss, the optimal form of electronic text presentation may vary according to the location of the preferred retinal locus (PRL), but this has never been investigated. In this study we examined the relationship between PRL location and reading rate for four electronic display formats (RSVP, 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, normal-acuity subjects. Subjects read aloud to determine maximum reading rate, and read silently to determine comfortable reading rate. **Results:** For both groups of subjects, maximum reading rates were (on average) faster than comfortable reading rates. The two rates were very similar for Page format, but the proportional difference between the two rates was greater for the other three display formats. For the low-vision group there was no difference in the maximum reading rates between the four display formats and when reading at a comfortable 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. For those with central field loss, there was no significant effect of PRL location (vertical vs. lateral) on reading rate and no significant interaction between PRL location and display format. **Conclusions:** The differences between maximum and comfortable reading rates and the lack of a relationship between reading rates and preferred display format suggest that maximum reading rate is not the best measure when the long-term use (e.g. for rehabilitation) of a device or display format is to be evaluated. Subject preference may be the best measure.
INTRODUCTION
Many people with visual impairment, especially those with central field loss (CFL), read at reduced rates, even with magnification that compensates for their reduced visual acuity. 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. One adaptive strategy commonly employed by the CFL reader is to view eccentrically using an extra-foveal 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 \(^1\rightarrow^5\). Here we define PRL location as the position of fixation relative to the central scotoma in visual space. Clinical studies consistently report that PRLs are found in all locations\(^1\) (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) \(^8\rightarrow^10\).

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 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 which 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 PRLs (above or below the scotoma) and whether vertically scrolling text would be beneficial for patients with lateral PRLs (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 the interest that there has been in using this as a display format

1 Lateral PRL (left more common than right) is more common than vertical PRL (below much more
for those with CFL due to the potential to increase reading rates through the reduction in between-word and between-line eye movements \(^{11-16}\).

**Horizontal and vertical scroll - relation to PRL location**

Based on an analysis of eye movements, Peli \(^{17}\) suggested that the optimal text presentation format for people with CFL would allow saccadic eye movements during reading that were orthogonal to a line radial from the fovea (Figure 1A), saccadic eye movements along the radial line being more difficult. As eccentricity increases, the ability to perform most visual tasks (e.g. letter recognition) decreases. Since these decreases are approximately equal in all directions, changes in visual performance orthogonal to the fovea (since eccentricity is approximately fixed) are small (Figure 1B). Toet and Levi \(^{18}\) reported radially elongated zones of spatial interaction; characters being crowded over a larger distance in the radial direction than the orthogonal direction (Figure 1C). The asymmetry of the crowding was greater than might be expected from a consideration of retinal anatomy and may be cortical in origin \(^{18}\). Again, this suggests 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. For stationary text such as a printed page, with a vertical PRL reading (conventional) horizontally aligned strings of characters or words is expected to be easier than reading vertically aligned text (as illustrated in Figure 1A). Similarly, with a lateral PRL vertically aligned text might be easier than horizontally aligned text. Initially the unfamiliarity of vertically aligned text may limit common than above) among people with CFL \(^{5-7}\).
performance, though probably this could be overcome with practice. 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\textsuperscript{19, 20} (Figure 2) that produces faster reading rates for low-vision readers than using a conventional page format\textsuperscript{20}. The ability to read horizontally scrolled text may be influenced by the subject’s PRL. Since 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 as 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\textsuperscript{18} for patients with a lateral PRL. Burns, Fine and Peli\textsuperscript{21} tested an alternative dynamic display format, where text scrolls vertically one word at a time (similar to movie credits) (Figure 2). Vertically scrolled text was read more quickly than RSVP by their low-vision readers, but more slowly by readers with normal acuity. 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 as the required eye movements would be radial (and for an above PRL\textsuperscript{2}, 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 PRLs.

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

**Maximum reading rate and comfortable reading rate**

Maximum oral reading rate, the most common experimental measure, is unlikely to be the preferred or comfortable (silent) reading rate that a person would habitually adopt when reading in a “real world” setting. Though reading rates (reading for understanding\(^2\)) have been shown to correlate with maximum reading rates\(^{20, 22, 23}\), no one has yet shown how comfortable reading rates relate to maximum reading rates for dynamic text display formats. Comfortable (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 comfortable reading rate for one display format from the maximum reading rate measured with another display format. Hence we measured both maximum and comfortable reading rates for all four dynamic display formats.

\(^2\) An above PRL is uncommon\(^5\).
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) 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. The average age of the remaining 35 patients was 70 years (median 74 years, range 34 to 87 years). An age-matched “normal acuity” (visual acuity of 20/40 or better) group comprised 17 subjects of which 14 completed the study. The average age of these 14 subjects was 69 years (median 69 years, range 40 to 84 years). Only four normal-acuity subjects had no known ocular disease, though most of those with ocular disease had one “healthy” eye. This reflects recruitment mainly from an ophthalmological practice and the categorization based solely on single letter visual acuity (Mentor B-VAT II) determined using their habitual spectacle correction. All subjects were native English speakers and had attended high school. There were almost equal numbers of male and female subjects in each group. All subjects provided informed consent in accordance with the institutional review board approval.
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 as shown in Figure 3). Indication of dense scotoma in the central 5 degrees was considered a CFL. Only four low-vision subjects had no CFL. For most patients, the PRL was determined by SLO \(^{24}\). 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 PRLs 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-tests, p > 0.7) (Table 2.). Documented PRL information was not available for three subjects, but acuity, diagnosis, and fundus photographs supported their classification as CFL.

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**Apparatus and Materials**

A modified Horizon LV Magnifier (Mentor O&O, Norwell, MA) 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 Figure 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 12, 13. 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/second, interlaced monitor, the minimum
duration of each word was 17 msec (1 field). Maximum presentation rate was restricted
to 1200 wpm 25. This did not restrict any subject, as the fastest recorded reading rate was
720 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 (wpm) 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
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. 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 be fitted 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 (wpm). For example, a page of text would be visible for 3 seconds 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. 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 characters “X”. 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 4X, and typically 6X the acuity threshold of the better eye. Whittaker and Lovie-Kitchen \(^{26}\) reported that an acuity reserve of 3X was sufficient for maximum reading rates of simple sentences, although Fine and Peli \(^{13}\) found that this might not be sufficient for the Horizontal-scroll and RSVP presentations. The viewing distance for subjects with normal acuity was 7 feet – an acuity reserve of about 10X 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) or silently (comfortable). The order of the reading condition was alternated for successive subjects. All display formats with the first reading condition (e.g. maximum) were completed before starting the four display formats with the second reading condition (e.g. comfortable). 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 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 a predetermined step size. 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 was 5 wpm, while for normal-acuity subjects these were 160 wpm and 10 wpm respectively. Comfortable 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. 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). Since the reading rate measures were approximately normally distributed, repeated measures analyses of variance (ANOVA) were 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 less than 0.05 was considered statistically significant for all analyses.

**RESULTS**

As expected, on average, the normal-acuity group read faster than the low-vision group (overall mean reading speeds across all display formats 271±95 wpm and 88±61 wpm.
respectively, $F_{1,47}= 95$, $p< 0.001$) and maximum reading rates were faster than comfortable reading rates (overall mean reading speeds across all display formats $155\pm 118$ wpm and $126\pm 101$ wpm respectively, $F_{1,47}= 29$, $p< 0.001$). 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 Figure 4A, for the normal-acuity group, maximum reading rate with RSVP ($377\pm 117$ wpm) was faster ($p< 0.004$) than the other three display formats (average $269\pm 70$ wpm). However, when subjects read at their comfortable reading rate, Page and RSVP were faster than Horizontal-scroll and Vertical-scroll ($p< 0.05$). For all display formats, maximum reading rate was correlated with comfortable reading rate ($r > 0.63$, $p <0.01$). The ratio of comfortable to maximum reading rates for Page format (103%) was significantly higher ($p= 0.003$) than for the other three display formats (RSVP 74%, Vertical-scroll 84%, Horizontal-scroll 81%).

As can be seen in Figure 4B, maximum reading rates of the low-vision group were the same for the four display formats (average $98\pm 67$ wpm). Contrary to Rubin and Turano $^{11}$, RSVP did not provide faster reading than a Page format; and contrary to Burns et al. $^{21}$ Vertical-scroll was not faster than RSVP. Our result is similar to Fine and Peli $^{12, 13}$ 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 $^{13}$). On average, comfortable reading rates were slower than maximum reading rates ($F_{1,34}= 19$, $p< 0.001$). For comfortable reading rates, Page format ($88\pm 60$ 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 reading rate was highly correlated with comfortable reading rate (r > 0.79, p <0.001). The ratio of comfortable to maximum reading rates for Page format (92%) was higher, though not significantly higher, than the other three display formats (RSVP 87%, Vertical-scroll 85%, 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 Horizontal-scroll than with 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 F1 = 5.5, p = 0.04; Figure 5) and the Page format (contrast F1 = 5.7, p = 0.03; Figure 5). Due to the conflict between orthogonal eye movements and radially aligned text, the converse prediction that the lateral-PRL group would read faster with Vertical-scroll format than 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, F1 < 2.8, p > 0.1; Figure 5). The lack of strong effects of PRL location on reading rates with the different display formats was confirmed by a repeated measures ANOVA that considered PRL location (vertical, lateral or central), reading condition and display format. Overall there was no significant effect of PRL group (F2,24 = 0.9, p = 0.4) and no significant interactions between PRL group and the other factors (p > 0.2).
Visual comparison of Figures 5A and 5B gives the impression that the difference in maximum and comfortable 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 comfortable to maximum reading rates across the four display formats was 94% for the vertical-PRL group, as compared to 79% for the lateral-PRL group. However this between-groups difference was not significant (ANOVA $F_{1,20} = 2.2$, $p = 0.16$) and there was no significant interaction between display format and PRL group for the ratio of comfortable to maximum reading rates. Our between groups comparison is limited by sample size. Only 8 subjects were included in the lateral group for this analysis because one subject (#29) could not read with the RSVP format (reading rate 0wpm), therefore the comfortable to maximum reading rate ratio could not be calculated for the RSVP condition for this subject. With 8 subjects, we could only expect to detect an absolute difference between the comfortable to maximum reading rate ratios for the two groups of greater than 31% ($\alpha = 0.05$, $\beta = 0.20$). The difference in comfortable to maximum reading rate ratios approached this value for Horizontal-scroll (95% and 68%, vertical-PRL and lateral-PRL groups respectively) and for Vertical scroll format (98% and 68% respectively).

Given that, in general, the comfortable 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, 15 preferred the Horizontal-scroll format, 6 preferred the Vertical-scroll format, and 6 preferred page format, while only 4 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 intra-subject reliability was therefore carried out. Two subjects (one with normal acuity, one with low vision) returned for a total of five sessions each within a period of two weeks. Each session was identical to that described above. No subject read the same sentence twice. At each session the order of reading condition 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 reading rate of the normal-acuity subject did not vary across the five sessions, but the comfortable reading rate increased, on average from 197±22 wpm to 237±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 PRLs did not read more quickly with horizontal-scroll than vertical-scroll format and patients with lateral PRLs did not read more quickly with vertical-scroll than horizontal-scroll. Fletcher et al. 27 also reported for a group of 99 subjects with macular scotoma that PRL location was not a statistically significant factor determining maximum reading rate on single sentences presented in a “page” format (MNREAD acuity chart). By comparison, studies that have used simulated scotomas in fully-sighted subjects show clear effects of PRL location on reading rate, with a right-PRL enabling faster reading than a left-PRL 8, 9 and a below-PRL enabling faster reading than a left-PRL 10. Similar trends (not statistically significant) in reading rates across PRL sub-groups are also evident in clinical studies 7, 27.

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 size3 e.g. Sunness et al. 7) 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 \(^{27}\). 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 \(^{4}\) confirmed that 89\% of their subjects with CFL used the same PRL when fixating a 1 degree cross and reading continuous text in an SLO (monocular viewing). The monocular and binocular PRL are not necessarily the same \(^{28}\). Therefore the recorded PRL may not be the PRL used for reading, possibly making categorization incorrect. Fletcher et al. \(^{27}\) used subjects where the monocular PRLs 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.

We compared maximum oral reading rates to the silent reading rates which subjects found to be “comfortable” for reading with each of the four electronic display formats. It is likely that the “comfortable” 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 comfortable rate and the maximum rate (achieved under forced experimental conditions) gives an indication of the potential for improvement through training. In general comfortable reading rate was a

\(^{3}\) We did not have sufficient subject numbers to perform PRL subgroup analyses to compare reading rates
relatively high proportion of maximum reading rate. Both normal acuity and low vision subjects had comfortable reading rates that were very close to maximum 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 comfortable reading rates that were fairly close to maximum. 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 CFL subjects reading electronic displays.

Although there were no statistically significant differences between the two PRL groups for maximum or comfortable reading rates, the lateral-PRL group did have noticeably lower comfortable to maximum reading rate ratios for the Vertical-scroll and Horizontal-scroll formats than the vertical-PRL group (Figure 5). The two groups were similar in terms of age and VA (Table 2.) and it is tempting to speculate that they had similar PRL abilities because they achieved similar maximum reading rates. However the data suggest that there is possibly greater potential for improvement through training for the lateral than the vertical PRL subjects to bring the comfortable reading rate closer to the maximum reading rate for the scrolling display formats. Equally it could also be argued that the data suggest that it is naturally more comfortable (or easier) to read the scrolling for right-, left-, below- and above-PRLs)

4 PRL abilities (e.g. SLO assessment of abilities for fixation, saccadic or pursuit eye movements), were not assessed in this study.
display formats used in this study with a vertical-PRL than a lateral-PRL, possibly because the spatial arrangement of the text is theoretically optimal (i.e. orthogonally aligned text) for those with a vertical-PRL in both Vertical-scroll and Horizontal-scroll formats, whereas for those with a lateral-PRL the text arrangement is less than optimal (i.e. radially aligned) in both scroll formats (Table 1.). The implication is that, for those with a lateral PRL reading Vertical-scroll format, the less-than-optimal radial alignment of the scrolling text may have a greater influence on comfortable reading rates than the theoretically optimal orthogonal eye movements elicited by the vertically scrolling text motion.

We have only limited information (1 normal acuity and 1 low vision subject) about how the maximum and comfortable rates might improve with practice over a number of sessions, however we suspect that the comfortable 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 over 5 sessions. In this study we measured comfortable reading rates for short sentences with display rate controlled by the experimenter. It is possible that comfortable reading rates might be different for extended passages as additional time may be required to integrate information within the text across multiple sentences. 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 comfortable RSVP rate was significantly slower than the
comfortable Page rate. Given that reading text in RSVP format theoretically requires fewer eye movements than the other display formats, it therefore appears 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 \(^{15, 16}\) 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 towards the goal of providing experimental electronic display situations that are representative of real world reading, both comfortable (rather than maximum) reading rates and subject control of display speed need to be considered. Arditi \(^{15}\) 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 into the impact of user-controlled presentation rates on reading performance for a range of electronic display formats.

Although the low-vision group read Page-format more quickly at the comfortable rate than the other display formats, the majority of subjects (15 out of 31 who expressed a preference) preferred the Horizontal-scroll format (for our single sentence displays). Only 4 subjects preferred the RSVP format. There was no obvious link between the display format preference and reading rate or PRL. Similarly, Harland et al. \(^{14}\) found, for reading of short passages, that horizontal-scroll was preferred over RSVP, and their user-controlled page format (using a CCTV) was approximately equally as popular as the horizontally scrolled text. 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 normal-acuity 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 people with normal acuity. 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 and comfortable reading rates and the lack of a relationship between reading rates and preferred display format suggest that maximum reading rate is not the best measure when the long-term use (e.g. for rehabilitation) of a device or display format is to be evaluated. Subject preference may be the best measure.

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TABLES

Table 1: Summary of eye movement direction and text alignment, relative to a line radiating from the fovea (Figure 1), for those with vertical and lateral PRLs reading Horizontal-scroll and Vertical-scroll formats. Theoretical considerations suggest that the optimal display format, to maximize reading rate, should utilize orthogonally aligned text and enable orthogonal eye movements.

<table>
<thead>
<tr>
<th>PRL location</th>
<th>Display format</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Vertical Scroll</td>
<td>Horizontal Scroll</td>
</tr>
<tr>
<td>Vertical</td>
<td>Eye movements: radial</td>
<td>Eye movements: orthogonal</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Text alignment: orthogonal</td>
<td>Text alignment: orthogonal</td>
<td></td>
</tr>
<tr>
<td>Lateral</td>
<td>Eye movements: orthogonal</td>
<td></td>
<td>Eye movements: radial</td>
</tr>
<tr>
<td></td>
<td>Text alignment: radial</td>
<td></td>
<td>Text alignment: radial</td>
</tr>
</tbody>
</table>
Table 2: Classification by PRL location for low-vision subjects with central field loss (n=31); PRL location is given as fixation position relative to the central scotoma in the visual field.

<table>
<thead>
<tr>
<th>PRL group</th>
<th>Number(^{(1)})</th>
<th>Age (years)</th>
<th>VA (logMAR)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Mean ± SD</td>
<td>Mean ± SD</td>
</tr>
<tr>
<td>Central</td>
<td>4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vertical</td>
<td>14 (1 above, 13 below)</td>
<td>70.6 ± 10.5</td>
<td>0.86 ± 0.18</td>
</tr>
<tr>
<td>Lateral</td>
<td>9 (5 right, 4 left)</td>
<td>71.4 ± 16.0</td>
<td>0.90 ± 0.29</td>
</tr>
<tr>
<td>Other</td>
<td>1 (above and right)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\(^{(1)}\)PRL data not available for 3 subjects
FIGURE CAPTIONS

Figure 1. Theoretical considerations concerning the effect of central vision loss on reading and eye movements. (A) Saccadic eye movements are controlled more easily when directed orthogonal to a line radiating from the fovea\textsuperscript{17}. The hatched area represents the central scotoma. (B) For equal letter detection, the size of characters needs to change more when presented along a radial than along an orthogonal line. (C) Schematic diagram showing ellipses of approximately equal spatial interaction\textsuperscript{18}. The lateral interactions (crowding) between characters in the word ‘ace’ should be equal.

Figure 2. A schematic illustration of the four text presentation formats used in this study. Both 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 leftwards, and Vertical-scroll text started at the lower edge and moved upwards.

Figure 3. A Welsh-Allyn direct ophthalmoscope was modified by replacing the visuoscopy fixation target with a large fixation target (often subjects with CFL cannot see the commercially available target). Subjects gaze was directed towards the center of the cross and the position of this PRL recorded relative to the presumed position of the former macula.

Figure 4 Mean reading rates of (A) the normal-acuity group (n=14); and (B) the low-vision group (n=35). (Note the difference in scale on the y-axis between normal-acuity and low-vision groups.) Vscroll: Vertical-scroll text started at the lower edge and moved upwards. Hscroll: Horizontal-scroll text started at the right edge and moved leftwards. Error bars represent the standard error of the mean.

Figure 5. There was no significant difference between the vertical-PRL (n = 14) and lateral-PRL (n=9) groups of central field loss subjects in (A). the maximum reading rate; or
(B). the comfortable reading rate. Error bars represent the standard error of the mean.

FIGURES
Figure 1.
Figure 2.

RSVP

Horizontal

Vertical scrolled text

Page format had three lines of text
Figure 3.
Reading dynamic text presentations

Figure 4.

A

B
Figure 5.