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**Reading with peripheral vision: a comparison of reading dynamic scrolling and
static text with a simulated central scotoma.**

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Abstract

Horizontally scrolling text is, in theory, ideally suited to enhance viewing strategies recommended to improve reading performance under conditions of central vision loss such as macular disease, although it is largely unproven in this regard. This study investigated if the use of scrolling text produced an observable improvement in reading performed under conditions of eccentric viewing in an artificial scotoma paradigm. Participants (n=17) read scrolling and static text with a central artificial scotoma controlled by an eye-tracker. There was an improvement in measures of reading accuracy, and adherence to eccentric viewing strategies with scrolling, compared to static, text. These findings illustrate the potential benefits of scrolling text as a potential reading aid for those with central vision loss.

Keywords: Reading; Eye movements; Simulated scotoma paradigm; Scrolling text; Eccentric viewing; Central vision loss

1. Introduction

Conditions such as age-related macular degeneration can lead to a central scotoma – an at least partial functional loss of the highest acuity region of the retina for processing of visual input. The ability to perceive objects falling within this area (as is crucial for tasks such as reading) is therefore lost or seriously compromised, resulting in reading difficulties being one of the most commonly reported problems for those with macular degeneration (Hazel *et al.*, 2000). The central scotoma can force individuals to adopt a strategy of employing the relatively more preserved peripheral areas of their retina, where acuity is reduced. One viewing strategy in particular thought to be able to increase gaze stability and thus reduce reading difficulty (e.g. Nilsson & Nilsson, 1986; Palmer, 2009; Palmer *et al.*, 2009) is the eccentric viewing technique. Eccentric viewing (EV) is a technique used to look at targets using the peripheral retina (Timberlake *et al.*, 1987). This strategy also capitalises on what appears to be a relatively natural adaptation in viewing strategy of people who experience central vision loss, to adopt a ‘preferred retinal locus’ (or loci; PRL); an area to which they may automatically redirect saccades so that information that would normally be fixated by the fovea is fixated by some more peripheral part of the retina (Whittaker, Budd, & Cummings, 1988).

Improving eye movement control has been shown to be beneficial for reading with macular degeneration (Seiple *et al.*, 2005). However, an obstacle to reading with a central scotoma is that the strong natural tendency to foveate words by means of saccadic eye movements is counterproductive, and may be detrimental to the effectiveness of the eccentric viewing strategy (Crossland, Culham, & Rubin, 2004),

making this a difficult strategy to maintain in practice. A related approach called the ‘steady-eye’ technique involves holding an eccentric viewing location whilst moving the text itself (Watson & Berg, 1983). However, although the popularity of aids such as stand magnifiers and CCTV devices (particularly with individuals who experience complete central vision loss; Ahn & Legge, 1995) may anecdotally support the use of this strategy (as these devices provide not only the obvious benefit of magnification of text but also require text either to be moved manually beneath the fixed lens [for stand magnifiers] or be projected onto a screen by moving a camera over it in such a way that it presents as scrolling on the screen [for CCTV devices], allowing a steady eye strategy to be employed), such devices have recognised issues with navigation between lines of text and with the limitation to viewing a very small window of characters at any one time (Beckmann & Legge, 1996; Bowers, Cheong, & Lovie-Kitchin, 2007).

An alternative method which would provide the benefits of stand magnifiers and CCTV devices whilst eliminating these problems would be to use dynamic, horizontally scrolling text: combined with eccentric viewing and the steady eye strategy this could potentially reduce the number of counterproductive fixations made onto the text itself. Any scrolling text device would ideally present the text as a single line (e.g. Walker, 2013), simplifying complex strategies adopted by those with central vision loss to navigate reading normal blocks of text, including the combination of multiple PRLs to view different parts of a paragraph and a complex multi-step pattern to move onto the beginning of new lines (Déruaz *et al.*, 2002). Its presentation would also necessarily be digital, and therefore (as with CCTV devices; Ahn & Legge, 1995) may take advantage of the apparent benefits of reading from electronic devices over normal

printed text (via enhanced contrast; Kretzschmar *et al.*, 2013 - addressing findings that suggest low contrast sensitivity is a contributor to reading difficulty in low vision conditions; Rubin & Legge, 1989). Scrolling text may therefore have potential as a useful aid to improve reading with central scotomas, circumventing the need for the eye to actively seek out the text and thus possibly reducing the likelihood of making counterproductive eye movement.

Previous research has investigated scrolling text for this purpose, although little work has been carried out to date. For example, Legge and colleagues (1989) found that reading rates for scrolling text were around 15% higher than for static text in a low vision population (although this sample did not all have conditions involving central vision loss). Another study comparing reading rate with scrolling text and rapid serial visual presentation (RSVP; in which words are presented sequentially in one spatial location, thus also allowing reading to be carried out at fixation) with a specific central vision loss group found a trend towards faster reading with scrolling text, and proposed that the lack of significance was likely due to low power rather than lack of effect (Fine & Peli, 1995). Most relevantly for the present study, Bowers, Woods, and Peli (2004) compared horizontally scrolling text with static, RSVP, and vertically scrolling text, finding no significant differences in reading speed between these formats. Bowers and colleagues (2004) reported that, of the four formats they tested, horizontally scrolling text was most often identified as the preferred format of their low vision sample (see also: Walker, 2013). This finding would likely indicate that, despite the lack of reading speed advantage, scrolling text may be advantageous over other measures (possibly due to an exploitation of the EV technique as discussed previously). Furthermore, reading speed is directly related to the rate of dynamic text presentation

which presents a potential confound when making direct comparisons with reading static text. This study will therefore focus on a detailed examination of oculomotor measures of adherence to the eccentric viewing strategy and reading error rates.

The present study aims to investigate reading performance with eccentric viewing and horizontally scrolling text, using a gaze-contingent artificial scotoma paradigm (see e.g. Rayner & Beretra, 1979) in order to evaluate if reading performance and adherence to the EV strategy were improved with dynamic text presentation. Unlike in previous research looking similarly at different text presentation formats, which have tended to use reading speed as a main outcome measure, here the focus is instead on the adherence to the eccentric viewing strategy during reading under conditions of simulated central vision loss. Participants will be instructed to hold fixation at the eccentric location when reading scrolling text; this strategy in theory eliminating the need to make horizontal eye movements (as are crucial in reading of normal static text), and therefore possibly improving participants' ability to suppress fixations onto the text itself. This will be evaluated by analysis of eye movements falling in specified regions of interest around, above, and surrounding the text. A comfortable speed for reading scrolling text eccentrically was established prior to the study and a fixed scrolling speed used to reduce possible perceptual and oculomotor factors (such as blurring of moving text, and nystagmus eye movements) that can arise with faster scrolling rates. A region-of-interest analysis of eccentric fixation was performed along with measures of reading errors.

2. Methods

2.1 Participants

Participants were 17 students from Royal Holloway, University of London (mean age = 20.8 years, SD = 1.7; 15 female). All participants had self-reported normal or corrected-to-normal vision and spoke English as their first language (in order to try to ensure that errors made when reading were not due to misunderstanding of the text). Informed consent was collected from all participants prior to the study, as approved by departmental ethical review.

2.2 Apparatus and stimuli

Stimuli were displayed on a 1024x768 pixel CRT monitor (60Hz refresh rate) at a distance of 68cm (sustained with use of a table-mounted headrest).

The stimuli used in this study were 160 sentences; 96 from the MNRead compilation (Legge *et al.*, 1989) and a further 64 generated based on this compilation. These sentences each had an average of 59 characters (including spaces; MNRead compilation 58.8 SD 1.9; extra 59.3 SD 0.8), with an average of 12 words (MNRead compilation 11.9, 1.4; extra 10.9 SD 1.0). Letter size was taken from a lower case 'x' as 0.67°; larger than the minimum acuity limit of around 0.1° at the forced minimum text eccentricity of 2.5° (Anstis, 1974). The sentences were presented as black text (Times New Roman font) on a white background.

2.2.1 Eye-tracking

Pupil and corneal reflection were recorded monocularly (right eye, left patched) during reading by an SR Research EyeLink 1000 eye tracker at 500Hz. This was used to produce a predefined gaze-contingent scotoma, appearing at fixation as a circle of matching colour and luminance to the background. This artificial scotoma was of 5.04° diameter (i.e. greater than the 5° area of the retina consisting of the macular; Drieghe, 2011) and was the same colour as the background.

2.3 Design

All participants completed both conditions of text presentation type investigated by this study (static and horizontally scrolling). Analyses were conducted for reading accuracy, calculated as percentage of sentences in which errors were made; and adherence to eccentric viewing strategy, calculated as the proportion of total fixation duration spent fixating in regions of interests around the text and eccentric viewing area (see Fig. 1). Counterbalancing of the order of conditions was applied, and analysis comparing the results of the counterbalancing groups showed no evidence of order effects.

2.4 Procedure

Prior to the experiment, the participants were informed about the two viewing strategies (EV and SES) and asked to adhere to the appropriate strategy (i.e. EV only for static and both for scrolling text) as much as possible. They were also reminded of the appropriate reading strategy or strategies to use prior to each block of sentences (i.e.

when reading static sentences participants were asked to fixate above the line of text but otherwise to make horizontal saccades and fixations along this line as in normal reading, but when reading scrolling sentences they were asked to fixate the cross above the text and to refrain from making any eye movements as far as possible). The artificial scotoma paradigm (and its gaze-contingent nature) was also explained to the participants before the experiment started and before each scotoma condition.

A 13-point calibration was completed prior to each block of sentences, and repeated if the eye-tracker stopped tracking the pupil or if a participant took a break during a block. A drift correction was applied at the start of each trial. The participants each read 80 sentences in total, which they were asked to read aloud in order to allow reading errors (i.e. missing, additional, or incorrect words) to be recorded. Although reading aloud is slightly slower and associated with slightly more frequent fixations than silent reading (Rayner, 2009), it was assumed that this would exert a similar effect on both conditions, and was collected as an effective measure of online reading accuracy. A sentence was deemed to contain errors if the participant omitted words or read a word incorrectly (even if they subsequently corrected the error). Sentences were presented in blocks of 40 randomised sentences (with one block per condition), and participants took a short break in between blocks and as required. Sentences in the scrolling condition were scrolled smoothly at a rate of 2 pixels per refresh, equating to around 8 characters per second. For the sentences used, this is around 100 words per minute, chosen as a comfortable reading speed for reading scrolling text eccentrically (established with 7 pilot participants prior to the study) and comparable to the average maximum oral reading speed found for Bower and colleagues' (2004) sample for horizontally scrolling text. Six underscore characters were presented prior to the

scrolling sentences to ensure that the first word was not missed. A fixation cross (for scrolling; dimensions $6^\circ \times 3.5^\circ$, allowing this to retain a visible margin around the scotoma if centred on the intersection as instructed) or line (for static) was presented on all trials to guide eccentric fixation (see figure 1 for schematic of presentation for scrolling and static trials). This was positioned above the text (i.e. encouraging adoption of a preferred retinal locus in the inferior part of the visual field) as this has been shown to be advantageous over the more commonly adopted leftward PRL (Nilsson, Frennesson, & Nilsson, 2003; Petre *et al.*, 2000). In both static and scrolling text conditions the text was positioned around 2.52° below the fixation stimulus (line and cross respectively) to allow full view of the text (i.e. not obscured by the scotoma) in the periphery if proper adherence was achieved.

2.5 Analysis

Regions of interest (see Fig. 1) were defined above and around the text for analysis of adherence to the reading strategies. These differed in size for scrolling and static conditions due to the necessity of holding fixation in the former case whilst making horizontal eye movements above the line in the latter case. Two other ROIs were specified: one around the line of text and one at an intermediate location between the two.

A total of 301 trials (out of 1360, 22.1%) were excluded from analyses due to data recording issues (premature termination of trial, loss of pupil by the eye-tracker, or participant error). All multiple comparisons made throughout were corrected using the Bonferroni correction. Similarly all measures were tested for normality using the

Shapiro-Wilk test, and the appropriate non-parametric alternative tests are used as necessary. Statistical analysis was carried out using RStudio 0.97.551.

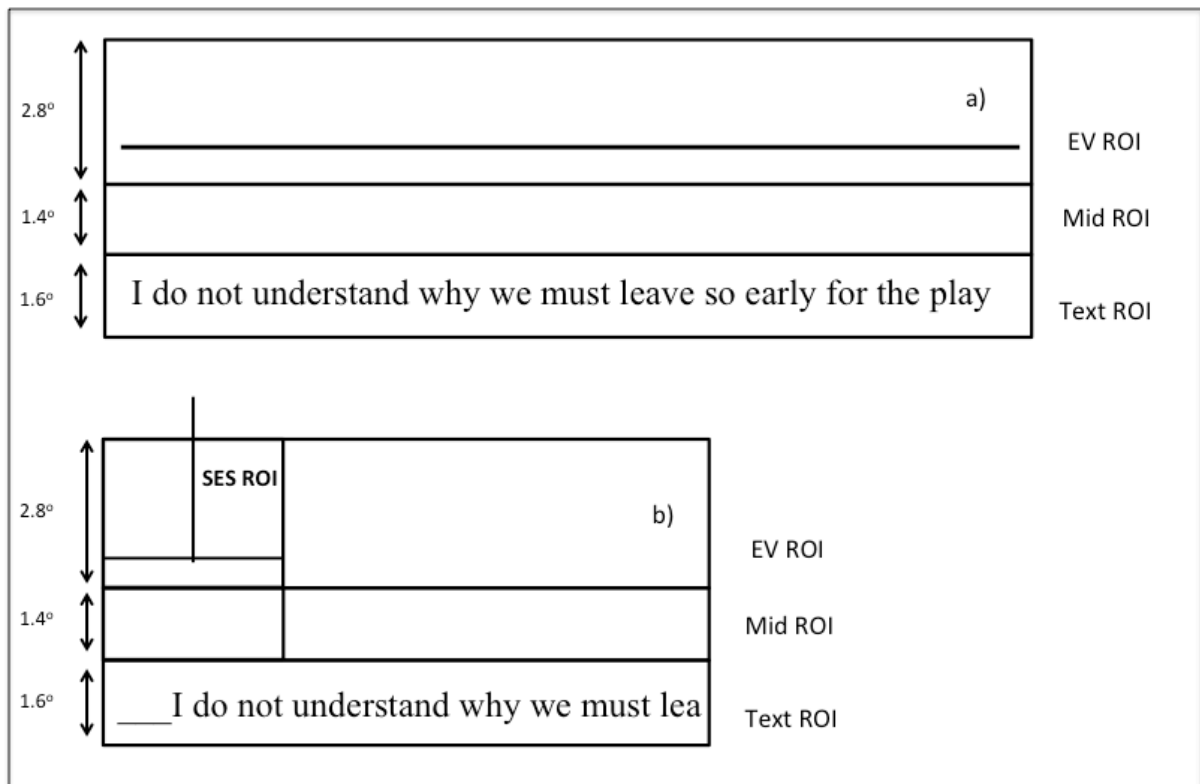


Figure 1 – Schematics for (a) static text and (b) scrolling text. Regions of interest (ROIs) are shown in black, with the eccentric viewing ROI around the eccentric fixation targets (a horizontal line above the text in the static presentation condition and an inverted T in the scrolling text condition), the text ROI around the text presentation window, and the middle ROI between the two. For scrolling text only, in addition to the EV ROI covering the length of the text window allowing a direct comparison with the static condition, a smaller ROI was also included around the fixation target (SES ROI) in order to allow a measure of steady eye adherence. Fixations falling outside any of these ROIS (Anywhere else on the screen) were also included in the analysis. The ROIs were not visible during the study.

3. Results

3.1 Eye movement records

Visual inspection of the eye movement records showed that, although not always employed, there was evidence of good adherence to both the eccentric viewing and steady eye strategies in some cases (demonstrating that this was achievable). Figure 2 shows some sample traces of typical patterns for unimpaired reading of static (2-a) and scrolling (2-d) text, and examples of trials showing good (static 2-b and scrolling 2-e) and bad (static 2-c and scrolling 2-f) adherence to EV and steady eye strategy.

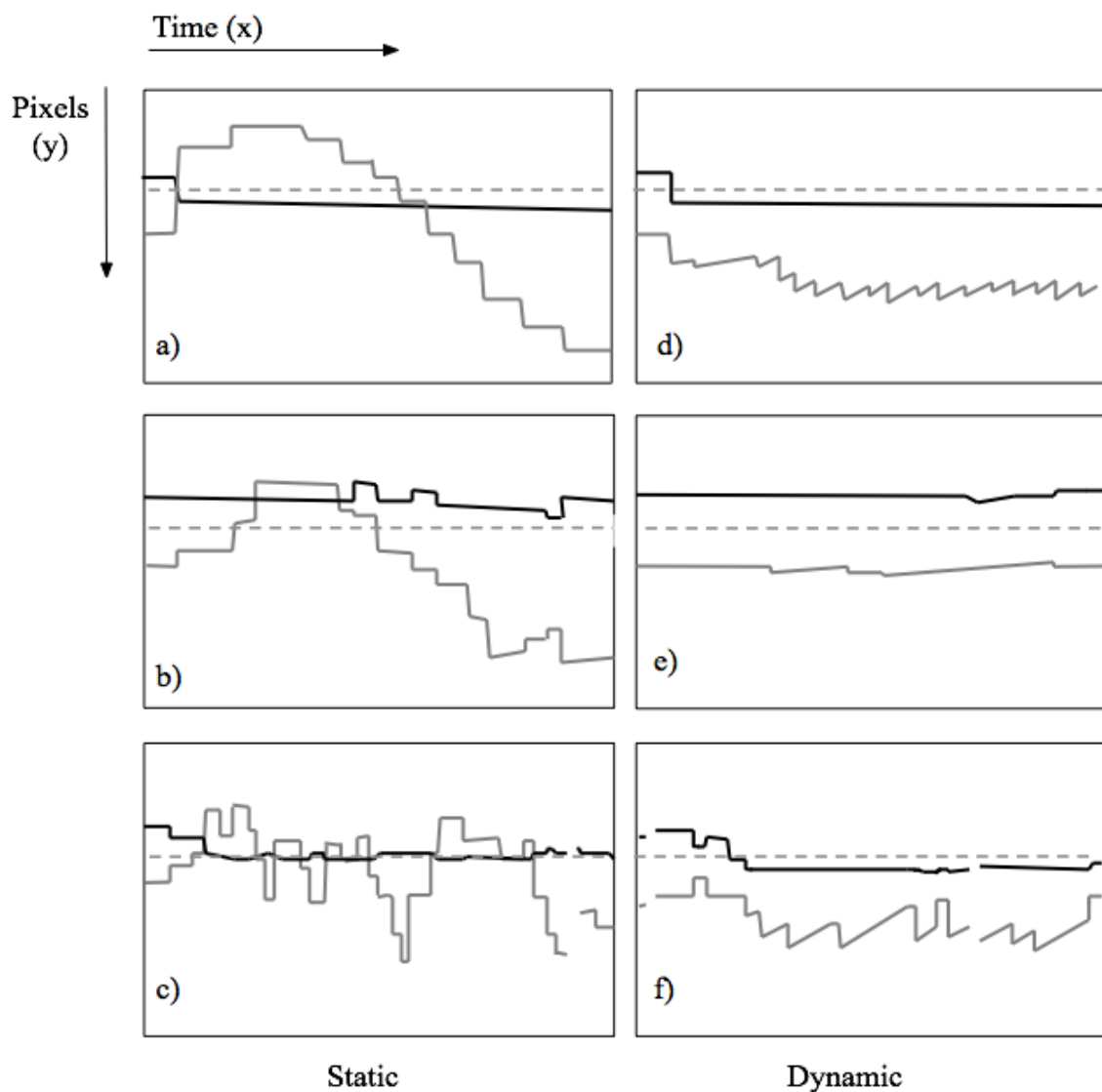


Figure 2 a)-f) – Schematic examples of eye movement records showing good and poor adherence to eccentric viewing with static and scrolling text. The x-axis represents time and y-axis position (pixels) with the top left corner of the screen being (0,0). The black line shows vertical eye position (i.e. line moving upward indicates upward saccade, downward indicates downward saccade) and the light grey line shows horizontal eye position (upward indicates left saccade, down indicates right saccade). The dashed line indicates the position of the top of the text region of interest (i.e. when the vertical eye trace descends below this fixations were being made onto the text). For: a) normal reading of static text (vertical trace shows gaze on text and a normal pattern of rightward horizontal saccades); b) reading static text with a scotoma and poor adherence to the eccentric viewing strategy (with many fixations made from EV position to the text itself); c) reading static text with a scotoma (with reasonably good adherence to the eccentric viewing strategy showing horizontal saccades were made above the line of text); d) normal reading of scrolling text (vertical trace again shows fixation on text, horizontal trace shows nystagmus pattern); e) reading scrolling text with a scotoma and good adherence to both eccentric viewing and steady eye strategies (reading is accomplished without saccades); and f) reading scrolling text with a scotoma and poor adherence to the eccentric viewing and steady eye strategies (showing fixation on text with horizontal nystagmus movements).

3.2 Adherence to eccentric fixation technique (Region of Interest analysis)

The percentage of trials on which participants were completely successful in employing the eccentric viewing strategy (i.e. in which no attempts were made to fixate anywhere other than within the eccentric fixation ROI) was 4.9% of trials (range 0-28.2%) in the scrolling condition and 0.2% (range 0-2.6%) in the static condition. Including trials where participants gaze dropped into the region between the fixation stimulus (Mid ROI) and the text (i.e. were still fixating above the text but dropped below the fixation stimulus at some point during the trial; e.g. fixations made in the EV and mid ROIs) increased these figures to 20.2% of trials (range 0-82.1%) in the

scrolling condition and 7.5% of trials (range 0-48.7%) in the static condition. This difference was statistically significant, $V = 64$, $p = 0.007$.

Inspection of an image overlay of all fixations made by all participants in each condition also appears to show a better adherence to the eccentric fixation strategy in the scrolling than the static text condition, as well as reasonable adherence specifically to the steady eye adaptation of this strategy (with a fairly tight cluster of fixations in the SES box rather than along the text as in the static condition; see fig. 3). A paired t-test was used to analyse the number of fixations made from the eccentric fixation area onto any other part of the screen as a proportion of trial length also indicated greater overall fixation stability, with a lower average proportion of fixations made with scrolling text ($t[16] = -2.71$, $p = 0.015$).

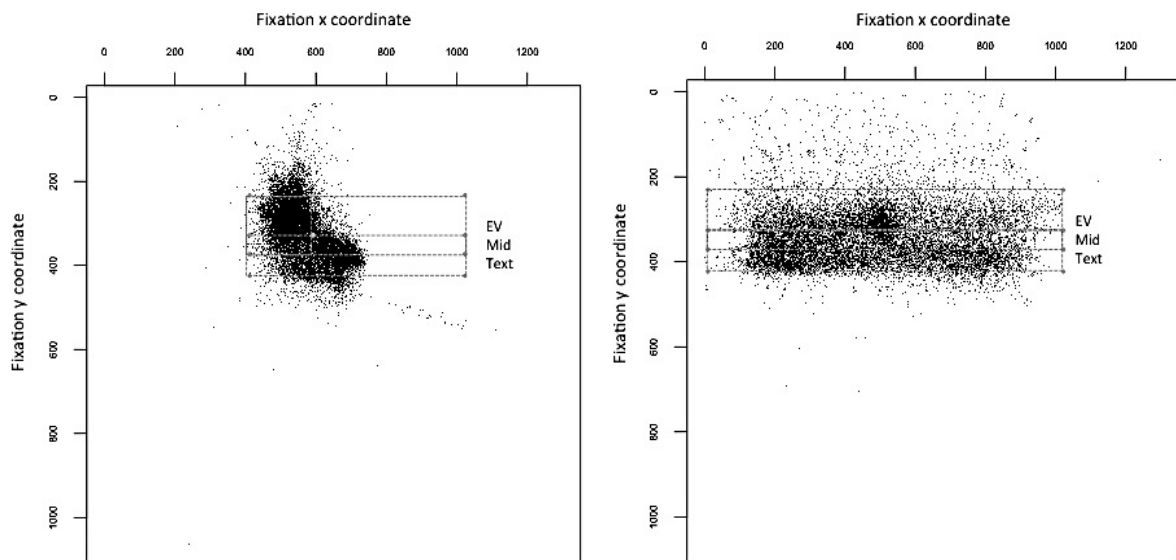


Figure 3 – Overlay images of all fixations made on the display screen of all participants in scrolling trials (left) and static trials (right). The boxes superimposed onto the scatterplots show the regions of interest analysed.

A more sensitive index of eccentric fixation success was provided by a region of interest analysis conducted for the regions defined in Fig. 1. The cumulative duration of fixations in each of these two pre-defined regions were calculated as a percentage of total fixation duration of the trial.

A 2x4 repeated measures ANOVA was carried out for text format and the four areas (EV/SES ROI, mid ROI, text ROI, and outside all ROIs; with the EV ROI for static compared to the SES portion of the EV ROI for scrolling text). This demonstrated a main effect of interest area ($F[3, 48] = 12.07, p < 0.001$) and an interaction between text format and interest area ($F[3,48] = 8.71, p < 0.001$; Fig. 4).

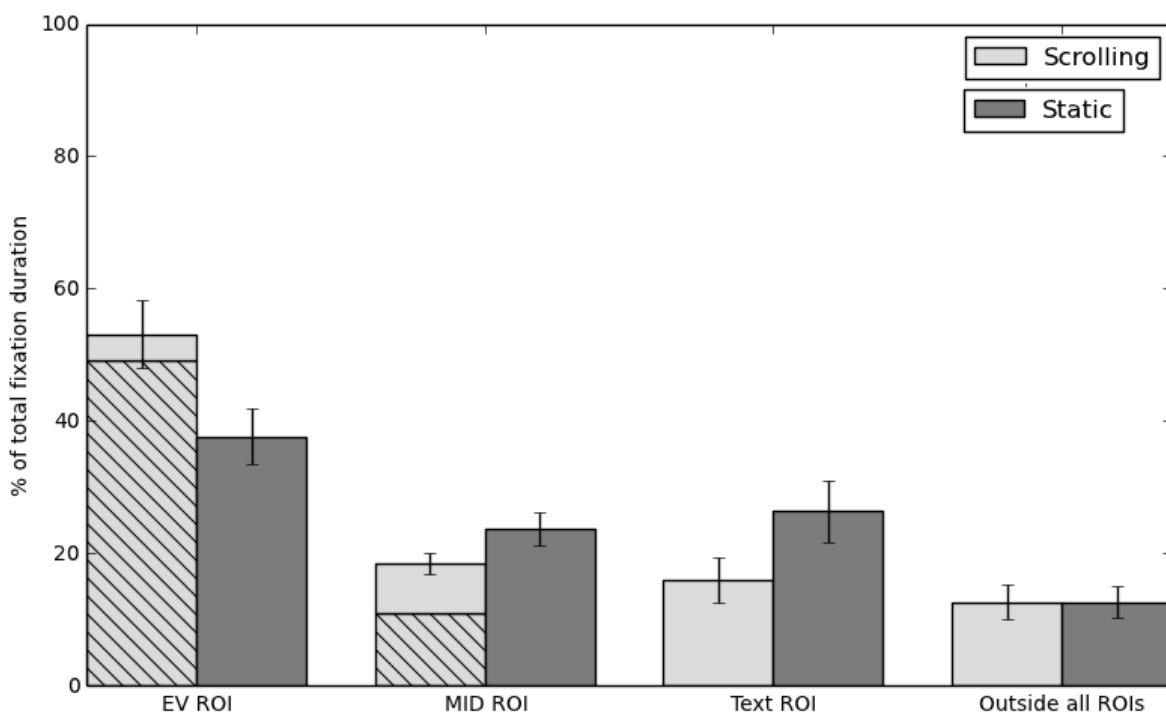


Figure 4 – Percentage of total fixation duration of trial spent fixating within the EV ROI, within the text ROI, between the two (Mid ROI), or elsewhere on the screen. Error bars show standard error (here and throughout). For scrolling text the EV and Mid ROIs are bisected, with the hatched region of each showing the proportion spent

fixating in the designated SES portion of these areas (see Fig. 1) and the smaller grey area showing the amount of time in the larger EV ROI.

Paired t-tests were carried out to compare the two conditions in each ROI. These showed that a significantly greater proportion of total fixation duration was spent in the SES ROI for scrolling than in the EV ROI for static text ($t[16] = 3.23, p=0.005$), and significantly less time was spent in the text ROI with scrolling than static text ($t[16] = 4.24, p<0.001$). There were no significant differences between conditions on the mid ROI (between EV and text ROIs; $p = 0.03$) or outside all ROIs ($p = 0.99$).

The region of interest analysis also allowed inspection of adherence to the SES strategy in the scrolling condition. No significant difference was found in a comparison of time spent fixating in the SES ROI and time spent fixating in all other regions on the screen ($p = 0.8597$). However this still demonstrates a high proportion of fixation duration spent fixating within the designated SES region, and t-tests comparing the time spent fixating in the SES ROI with each other area showed significantly higher proportions of the total fixation duration spent in this region than any other (EV outside SES region $t(16) = 9.29, p<0.001$; text ROI $t(16) = 4.00, p = 0.001$; mid ROI $t(16) = 5.12, p<0.001$; outside all interest areas $t(16) = 4.89, p<0.001$; Fig. 3). When comparing between ROIs for static text, no significant differences were found except between the time spent fixating eccentrically and outside all ROIs ($t[16] = 4.03, p<0.001$).

3.3 Errors

Types of reading errors made were omissions (e.g. “Our **old** clock chimes hourly...”), insertions (e.g. “An electrical appliance may be **more** useful...”), word order errors (e.g. “...**in late [late in]** autumn.”) and substitutions (e.g. “The leaves on my **apple [maple]** tree...”). Figure 5 shows the average percentage of sentences containing reading errors for each condition. A Wilcoxon signed ranks test was conducted for this data ($V=1$, $p=0.0008$), indicating that more errors were made when reading static text than scrolling text.

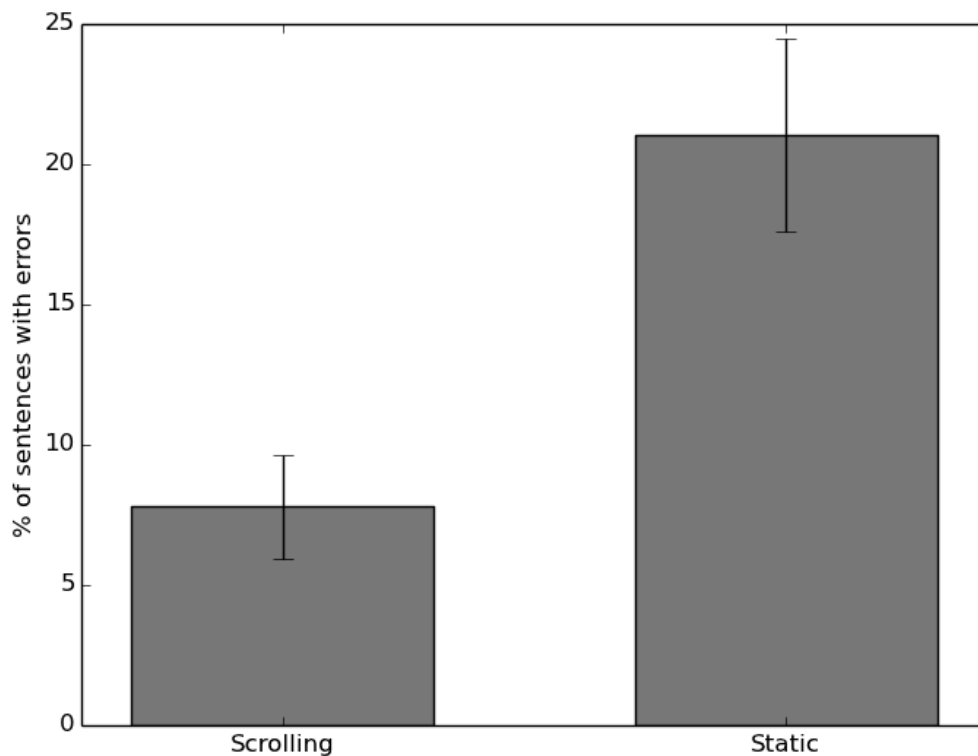


Figure 5 – Mean percentage number of sentences where errors (incorrect/missing words) were made, for static and scrolling text.

4. Discussion

This study investigated reading and the maintenance of the ‘eccentric viewing’ and ‘steady-eye’ strategies with a simulated loss of central vision (artificial central scotoma). Reading performance with an artificial scotoma was improved with scrolling text, leading to better reading accuracy and adherence to an eccentric fixation strategy (with a greater proportion of trial time spent fixating eccentrically and a lower proportion of fixations made from the EV ROI to other areas of the screen than with static text, and more time spent fixating eccentrically than in any other area of the screen in scrolling but not static text). These findings expand on previous work such as by Bowers and colleagues (2004), who found that horizontally scrolling text provided no advantage on a reading speed measure, but that subjective rating of different text formats favoured this over static text; the advantage found here with other measures may help explain this latter finding.

Reading typically relies on the ability to fixate words directly with the fovea (Drieghe, 2011), but this ability is lost with central vision loss; therefore rendering continued attempts to foveate the text counterproductive (as the high-acuity foveal region is severely impaired) and leading to a somewhat erratic pattern of eye movements (increasing the difficulty of tasks such as reading; Crossland *et al.*, 2004; e.g. Fig. 2c). The eccentric fixation technique has therefore been proposed to help improve reading ability in such conditions by directing the damaged foveal region away from the text and thus allowing the text to fall on the nearest functional part of the more peripheral retina (Timberlake *et al.*, 1987). Adherence to the eccentric fixation strategy was evaluated here (see Fig. 1 for regions analysed), by examining the amount of time

spent fixating around the eccentric fixation area (which participants were asked to try to fixate instead of the text) and around the text (which would typically be fixated during reading). Better adherence to the eccentric viewing technique was observed for scrolling text, with significantly more time spent fixating within the EV ROI than with static text, and a significantly greater proportion of total fixation duration of the trial spent within this than any other of the ROIs analysed. In addition to this, a greater proportion of scrolling than static trials was found to adhere completely to the EV strategy (i.e. with no fixations made onto the text).

One way in which this improvement in eccentric viewing adherence may be able to be explained is by the use of steady eye strategy (in addition to EV) for the dynamic format; keeping the eye fixed and moving the text manually (as opposed to the normal reading strategy of moving the eye actively around fixed text; Watson & Berg, 1983). This is clearly difficult with reading of static text, where eye movements are necessary even in conjunction with the eccentric viewing strategy. Previous research has investigated this strategy with RSVP, which has shown some benefit for reading with impaired vision (compared to static text; Rubin & Turano, 1994). Although the current data does not support a total adherence to the steady eye strategy with scrolling text, it is worth noting that, firstly, there was some evidence of reasonable adherence (with quite good adherence to the EV strategy recorded, and almost all of these eccentric fixations made around the SES stimulus rather than along the length of the full sentence, as in static text). Furthermore, although there were very few trials where an eccentric position was held throughout, this proportion was higher in the scrolling condition, and the proportions reported here use a very stringent definition of adherence (i.e. excluding all other trials, even if an eccentric position was held for the

majority of the duration). It is also worth noting that the participants had no prior experience of the eccentric viewing technique bar the approximately 40 minute testing session. In addition to this time constraint, reading may be a particularly difficult task to adapt to using a new strategy with a relatively uncommon dynamic text format. These results therefore support the use of scrolling text as a method to enhance the eccentric viewing technique, and further improvement may be achieved with practice.

The reading accuracy data also suggests that some benefit was imparted by combining EV with scrolling text above that of static text (and thus presumably of steady eye strategy combined with eccentric viewing technique above that of the latter alone), with significantly more errors made in reading of static text than of scrolling. Although little research has been carried out on reading of scrolling text, normal reading of this format creates a requirement to shift attention from left to right to process each word in the sentence (as with normal static text), whilst simultaneously tracking the text as it moves across the screen in the opposite direction (right to left). Previous research (in visual search rather than reading) has indicated that in such a situation where attention and gaze direction are incongruent, performance may be impaired (Lingnau, Schwarzbach, & Vorberg, 2010); the improved accuracy with scrolling text here therefore may be interpreted as at least some success by the participants at overcoming this normal processing of scrolling text (i.e. achieving an SES-like strategy to at least some degree). This is also supported by the finding that overall the number of fixations made as a proportion of trial length was significantly lower for scrolling than static text, suggesting some degree of increased stability of fixations with the former.

Finally it should be recognised that, although the findings of the current study fell in line with the subjective preference of actual central vision loss patients from previous studies (e.g. Bowers *et al.*, 2004; Walker, 2013), the method employed here was an artificial scotoma paradigm; although this is a well-established and frequently used alternative, the simulation uses a very defined approximation of a scotoma, whereas in cases of central vision loss scotomas may take on a variety of forms (Schuchard, Naseer, & de Castro, 1999). Furthermore, although an artificial PRL was imposed here and some authors have found that adoption of a PRL strategy may be adopted reasonably automatically under this paradigm (e.g. Pidcoe & Wetzel, 2006), others have suggested that practise is required for this to occur (e.g. Varsori *et al.*, 2004). Thus, although not to diminish the importance and usefulness of the artificial scotoma paradigm, it would clearly be important to seek confirmation of these results with a clinical sample.

5. Conclusion

The findings of this study demonstrates a clear advantage for a horizontally scrolling text format over static text in terms of reading accuracy, likely via the enhanced adherence to an eccentric viewing strategy increasing fixation stability. More in-depth exploration of this format as a potential reading aid for conditions involving central scotomas may support the further development of practical aids for people with macular disease (Walker, 2013).

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