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A comparison of reading, in people with simulated and actual central vision loss, with static text, horizontally scrolling text, and rapid serial visual presentation

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Reading with central vision loss (CVL), as caused by macular disease, may be enhanced by presenting text using dynamic formats such as horizontally scrolling text or rapid serial visual presentation (RSVP). The rationale for these dynamic text formats is that they can be read while holding gaze away from the text, potentially supporting reading while using the eccentric viewing strategy. This study was designed to evaluate the practice of reading with CVL, with passages of text presented as static sentences, with horizontal scrolling sentences, or as single-word RSVP. In separate studies, normally sighted participants with a simulated (artificial) central scotoma, controlled by an eye-tracker, or participants with CVL resulting from macular degeneration read passages of text using the eccentric viewing technique. Comprehension was better overall with scrolling text when reading with a simulated CVL, whereas RSVP produced lower overall comprehension and high error rates. Analysis of eye movement behavior showed that participants consistently adopted a strategy of making multiple horizontal saccades on the text itself. Adherence to using eccentric viewing was better with RSVP, but this did not translate into better reading performance. Participants with macular degeneration and an actual CVL also showed the highest comprehension and lowest error rates with scrolling text and the lowest comprehension and highest errors with RSVP. We conclude that scrolling text can support effective reading in people with CVL and has potential as a reading aid.

Introduction

Difficulty with reading is regarded as the number one challenge faced by individuals with macular degeneration, resulting in profound consequences for quality of life and the ability to live independently (Elliott, Trukolo-Ilic, Strong, Pace, Plotkin, & Bevers, 1997; Petre, Hazel, Fine, & Rubin, 2000). The reading process depends on high-acuity (foveal) vision and on the systematic pattern of eye movements (fixations and saccades) made to shift the fovea onto each word in a sentence (Rayner, 1998). However, for people with central vision loss (CVL), this highly overlearned oculomotor behavior can be counterproductive, as fixating on a word brings it onto the impaired central scotoma. The difficulties in reading experienced by those with CVL have been related to impaired eye movement control (Rubin & Turano, 1994), fixation instability (Crossland, Culham, & Rubin, 2004a), and reduced perceptual span (Calabrèse, Bernard, Faure, Hoffart, & Castet, 2014). For example, saccades made by people with CVL on simple reorienting tasks have longer latency and tend to undershoot the target location (White & Bedell, 1990; Whittaker, Cummings, & Swieson, 1991). Slow reading speed, observed in age-related macular degeneration (AMD), has been attributed to a reduction in the size of forward saccades (Bullimore & Bailey, 1995). Subsequent studies using a

simulated central scotoma have shown that an increase in the total number of saccades (both forward and backward), fixation duration, and the number of fixations are the main predictors of reading speed (Scherlen, Bernard, Calabrèse, & Castet, 2008). Scherlen et al. (2008) reported that reading speed was reduced as the total number of saccades made per sentence and fixation duration increased, reflecting a strategy of repeated scanning (to left and right) to process the text. Detailed examinations of the characteristics of eye movement behavior in patients with AMD have shown that the key factors involved in slow reading speed are increased number of fixations (Calabrèse et al., 2014) and atypical patterns of clustering of fixations made to process the words in a sentence (Calabrèse, Bernard, Faure, Hoffart, & Castet, 2016).

People with CVL use adaptive oculomotor strategies by fixating eccentrically to make use of their relatively preserved peripheral vision for tasks that rely on visual analysis, including reading (Cheung & Legge, 2005; McNamara & Magliano, 2009; Palmer, Logan, Nabili, & Dutton, 2009; Timberlake, Peli, Essock, & Augliere, 1987; Whittaker, Budd, & Cummings, 1988). The perceptual and oculomotor factors that contribute to poor reading performance in people with CVL have been widely studied using dynamic text formats that enable reading speed to be measured using psychophysical methods (Legge, Ross, Luebker, & Lamay, 1989; Rubin & Turano, 1992). Two commonly used dynamic text formats are the rapid serial visual presentation (RSVP) technique, where each word is presented individually at one location (Forster, 1970; Potter, Kroll, & Harris, 1980; Rubin & Turano, 1994), and horizontal scrolling (or drifting) text similar to news tickers and digital advertising boards (Bowers, Woods, & Peli, 2004; Fine & Peli, 1996; Legge et al., 1989; Moshtael, Tooth, Nuthmann, Underwood, & Dhillon, 2020; Walker, Bryan, Harvey, Riazi, & Anderson, 2016). These formats have been used to provide a method of measuring maximum reading speed in psychophysical investigations of factors that influence reading with CVL (Chung, 2020; Legge et al., 1989; Rubin, 2013) The present study takes a different approach and aims to examine which text formats (static or dynamic) are the most effective for supporting reading comprehension when reading with CVL.

Eccentric viewing (EV) refers to a strategy adopted by people with CVL to make use of their remaining peripheral vision using an eccentric preferred retinal locus (PRL) (Fletcher & Schuchard, 1997; Fletcher, Watson, & Schuchard, 1999; Schuchard, 1995; Whittaker et al., 1991) or *pseudo-fovea* (Timberlake et al., 1987). Multiple PRLs may be used by individual patients both within and between tasks (Crossland et al., 2004a; Deruaz, Whatham, Mermoud, & Safran, 2002; Duret, Safran, & Issenhuth, 1999; Walsh & Liu, 2014; Whittaker et al., 1988), but there is not a clear

relationship between PRL location and reading speed (Calabrèse, Bernard, Hoffart, Faure, Barouch, Conrath, & Castet, 2011; Fletcher et al., 1999). Poor fixation stability is thought to be a further important factor underlying slow reading (Crossland et al., 2004a). The adoption of a PRL cannot compensate for the overall loss of visual acuity, but it can aid reading performance by improving fixation stability (Nilsson & Nilsson, 1986; Palmer et al., 2009). Training in the EV technique remains one of the main interventions used in rehabilitation programs for patients with macular degeneration (Chung, 2020) although it has also been shown that the use of one, or more, PRL may develop spontaneously (Crossland, Sims, Galbraith, & Rubin, 2004b; Crossland, Culham, Kabanarou, & Rubin, 2005). Training has been shown to result in improvements in near visual acuity, reading speed, and activities of daily living (Gaffney, Margrain, Bunce, & Binns, 2014). For reading, a task where inefficient eye movement control is a factor in poor performance (Rubin & Turano, 1994), a second technique called steady-eye strategy (Watson & Berg, 1983), in which gaze is directed eccentrically and the text itself is moved (from right to left) across the field of view, has also been incorporated into rehabilitation training (Dickinson, Subramanian, & Harper, 2016). A different but complimentary approach has been to present text on electronic displays, including the use of dynamic text formats to support more effective reading with CVL (Crossland, Silva, & Macedo, 2014; Walker, 2013; Wu, Calabrèse, & Kornprobst, 2021).

One rationale for using dynamic text formats, including RSVP and horizontal scrolling text (also called drifting, gliding text, or Times Square), for reading eccentrically is that the text can be processed using atypical eye movement behavior that may support reading when using the EV and steady-eye strategy techniques (Legge et al., 1989; Rubin & Turano, 1992). In the case of RSVP, each word from a sentence is presented individually and sequentially in the center of the screen, enabling it to be read while holding steady fixation without the need to make eye horizontal movements (Forster, 1970; Potter et al., 1980). Horizontally scrolling text is read by sighted observers using a combination of leftward pursuit fixations and rightward saccades that resembles nystagmus (Buettner, Krischer, & Meissen, 1985; Harvey, Godwin, Fitzsimmons, Liversedge, & Walker, 2017; Ong, Brown, Robinson, Plant, Husain, & Leff, 2012; Valsecchi, Gegenfurtner, & Schütz, 2013). Scrolling text can also be read with a steady gaze, so it moves smoothly across the retina, similar to how people with CVL read with high-powered optical magnification or closed-circuit TV magnifiers (Gustafsson & Inde, 2004; Nilsson, Frennesson, & Nilsson, 2003).

Both RSVP and scrolling text have been used in investigations into the factors that influence reading in

patients with low vision (defined as the inability to read newspaper print with corrective lenses and which can include various retinal disorders) (Legge, Pelli, Rubin, & Schleske, 1985a; Legge, Pelli, Rubin, & Schleske, 1985b), using maximum reading rate as the measure of reading performance (Chung, 2002; Chung, 2011; Chung, Mansfield, & Legge, 1998; Legge et al., 1985a; Legge et al., 1985b; Legge et al., 1989). One advantage of using reading speed as a psychophysical measure is that there is a sharp transition at higher rates of text presentation at which errors are observed, which is not the case with reading comprehension (Legge et al., 1985a; Legge et al., 1985b; Legge et al., 1989). Although reading speed can be a useful psychophysical and clinical measure of reading performance (Rubin, 2013), it may be less optimal for directly comparing reading performance with static and dynamic text formats (Harvey & Walker, 2014). One reason why reading speed is not an optimal measure when comparing reading with RSVP and horizontal-scrolling text is that reading speed is constrained by the rate of text presentation, which in turn is constrained by perceptual and oculomotor factors specific to each format. RSVP, for example, can be read (normally) without the need to make eye movements at very high speeds (over 600 words per minute [wpm]) (Rubin & Turano, 1992), whereas scrolling text is normally read at much slower speeds (100–200 wpm) due to perceptual and oculomotor limitations imposed by the leftward movement (Buettner et al., 1985; Harvey et al., 2017; Harvey, Anderson, & Walker, 2019; Chen, Valsecchi, & Gegenfurtner, 2017). In the case of reading multiple lines of static text, navigating through the text and locating the start of the next line is an additional difficulty for those with CVL (Deruaz et al., 2002), which is not a factor with scrolling text or RSVP. Reading comprehension and error rates are therefore a more appropriate measure when comparing reading with static and dynamic formats (Harvey et al., 2017). Although comprehension may not be a useful clinical measure of reading performance (Rubin, 2013), it is the main goal of reading and does not introduce the confounds of rate of dynamic text presentation when comparing different dynamic text formats, which is the aim of the present study. Walker et al. (2016) assessed reading in people with macular degeneration with static and scrolling sentences presented on an iPad tablet (Apple Inc., Cupertino, CA). Accuracy was improved with scrolling text, with similar rates of reading speed and comprehension. Participants also expressed a preference for reading with the scrolling format, consistent with other reports (Harland, Legge, & Luebker, 1998).

RSVP can support high reading speeds with normal vision (Potter, 1984) and in people with low vision (Rubin, 2013) but is also known to compromise comprehension and memory of the material (Benedetto,

Carbone, Pedrotti, Le Fevre, Bey, & Baccino, 2015; Di Nocera, Ricciardi, & Juola, 2018; Ricciardi & Di Nocera, 2017). Small decrements in comprehension have also been observed at speeds above 200 wpm with scrolling text (Legge et al., 1989). A limitation of the RSVP procedure is that each word is presented for a duration set by the device, unlike in normal reading where the time spent fixated on an individual word will be modulated by a range of factors such as word frequency and length, as well as ongoing cognitive processing of the text (Rayner, 1998; Sauvan et al., 2020; Stolowy et al., 2019). Presenting single words also removes the parafoveal preview of upcoming text, which is regarded as a major contributing factor for fluent reading (Schotter, Angele, & Rayner, 2012). It also means that readers are unable to make regressions to reinspect text, which can also negatively affect comprehension (Fischler & Bloom, 1980; Schotter, Tran, & Rayner, 2014). Despite the potential limitations of both RSVP and scrolling text for readers without visual impairments, it is possible that these are offset by them being able to support of effective reading in people with CVL.

A complementary approach to testing potentially elderly patients with actual CVL has been to use gaze-contingent simulated (or artificial) scotoma controlled by an eye tracker with normally sighted participants (Fine & Rubin, 1999a; Fine & Rubin, 1999b; Rayner & Bertera, 1979). Numerous studies have used the simulated scotoma paradigm to investigate reading with CVL for a variety of purposes (e.g., Bernard, Aguilar, & Castet, 2016; Harvey et al., 2019; Lingnau, Schwarzbach, & Vorberg, 2008; Maniglia, Jogin, Seitz, & Maniglia, 2020; Scherlen et al., 2008; Wallis, Yang, & Anderson, 2018). The use of a gaze-contingent central scotoma enables greater control over factors such as size and shape of the scotoma and the recording of the observers' eye movements, in addition to eliminating the need to test potentially elderly participants who may have multiple eye disorders as well as CVL. Harvey and Walker (2014) examined reading accuracy and adherence to EV in a laboratory-based study using a simulated central scotoma (5°) controlled by an eye tracker. Participants read single sentences (MNRead) (Legge et al., 1989) presented as either static or scrolling single lines of text, with their gaze held 2.5° above the text. More time was spent reading when the gaze was held eccentrically above the text with the horizontal-scrolling format, and there was a small reduction in reading errors. A subsequent study examined the effects of reducing the effects of perceptual crowding on eccentric reading and showed improvements in accuracy (errors) and memory with triple-word spacing with scrolling text (Harvey et al., 2019). Despite the advantages of the simulated scotoma technique, one limitation is that it is not clear if the findings can be generalized to people with actual

CVL, given such differences as the size and shape of the scotoma and time to adapt to performing visual tasks with CVL.

The aims of the present study were to compare oculomotor behavior (Study 1) and reading comprehension (Studies 1 and 2) with static (single- and multiple-line displays) and dynamic (RSVP and horizontal-scrolling) text formats in people with a simulated and actual CVL. Reading comprehension and accuracy were examined (from a standardized comprehension test battery) while participants read paragraphs displayed in all four display formats, under instructions to use the EV strategy with gaze held above the text. Adopting a fixation location above the text means that the text is presented in the lower visual field, which has been found to be better for reading with a PRL (Nilsson et al., 2003; Petre et al., 2000; Prahalad & Coates, 2020). This lab-based study also additionally examined oculomotor behavior using a simulated central scotoma (controlled by an eye tracker). The overall goal was to identify the method of text presentation that supports the most effective reading performance in people with CVL.

Study 1. Simulated central scotoma

Methods

Participants

Fifteen students (11 female), 18 to 32 years old (mean age, 20.40; $SD = 3.94$) were recruited from Royal Holloway, University of London. The participants had normal or corrected-to-normal vision (best-corrected binocular visual acuity of 0.0 logMAR or better), spoke English as their first language, and had no language or reading deficits (self-report). All of the participants gave written informed consent prior to participating in the study, which followed the tenets of the Declaration of Helsinki and was approved by the College Ethics Committee at Royal Holloway, University of London (Ethics ID 2017/633).

Apparatus

Stimuli were presented on a light-emitting diode, 1920 × 1080-pixel monitor (BenQ, Taipei, Taiwan) running at a refresh rate of 100 Hz. Viewing distance was maintained at a distance of 70 cm through the use of a table-mounted head and chin rest. An EyeLink 1000 remote desktop-mounted eye-tracker (SR Research, Kanata, ON, Canada) recorded pupil and corneal reflection from the right eye at a sample rate of 1000 Hz. Experiment Builder software (SR Research) was used to control the stimulus (text) presentation and to control a gaze-contingent central scotoma (8° diameter) that matched the color and luminance of the background (black). The Experiment Builder program included custom Python code (Harvey et al., 2019) to mitigate some of the known limitations of gaze-contingent paradigms attributed to pupil size changes due to blinks (Aguilar & Castet, 2011). Saccades were detected by the SR Research online parser using velocity and acceleration criteria of 30°/s and 8000°/s, respectively. The position of the scotoma was based on the previous sample of eye position (sampled every 10 ms), unless a blink was detected, in which case the last sample location was used to redraw a scotoma every 10 ms until the blink ended. Blinks were identified when the size of the pupil dropped below 90% of the size of a three-sample moving average window until it no longer violated this criterion, at which point the scotoma was redrawn at the latest sample location.

Stimuli

Stimuli consisted of passages of text taken from the York Assessment of Reading for Comprehension (YARC) (Stothard, Hulme, Clarke, Barmby, & Snowling, 2010). Four passages were selected as being similar in length and complexity: "Food in Medieval Times" (457 words), "The Schoolboy" (472 words), "Honey for You, Honey for Me" (463 words), and "Louise Nevelson" (464 words). The YARC is a standardized assessment (designed for 12- to 16-year-olds) that assesses three aspects of reading: decoding (word reading), fluency (reading rate), and text comprehension (literal and inferential meaning). The test is designed to assess literal comprehension, including details that were specifically stated in the passage (e.g., "Why do bumble bees never swarm?") and inference-based comprehension involving a deeper level of understanding (e.g., "How are people affecting bumble bees?"). The comprehension questions were given immediately after the participant read each passage, although some questions were omitted if they required the participants to have access to the passage. Participants were also required to summarize key points of the passage, with correct points being scored from a predefined list. All passages were displayed in white Courier New 36-point font—which may be advantageous for reading with CVL (Bernard, Aguilar, & Castet, 2016; Tarita-Nistor, Lam, Brent, Steinbach, & González, 2013)—on a black background, complete with punctuation marks and with the first letter of each sentence capitalized. The text size (visual angle, 0.71°) was four times greater than the letter acuity threshold at 4° eccentricity (Chung et al., 1998). The passages were presented in four formats as follows: single, horizontally scrolling lines (which scrolled from the right edge of the screen to the left); series of single words presented in the center of the screen using RSVP; single static lines presented in the center of the screen; and multiple-line
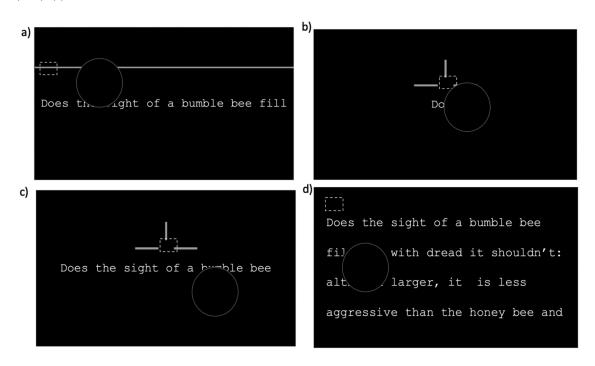
Figure 1. Schematic diagram (not to scale) of text displays (a) horizontally scrolling text (sentence moves smoothly from right to left), where the cross acted as an eccentric fixation target; (b) RSVP with an eccentric fixation target; (c) single-line static text with a solid horizontal guideline; and (d) multiple-line paragraph display that did not include an eccentric fixation guide. The 8° simulated (artificial) scotoma is shown as a black circle (note that the dashed line is for visualization purposes and was not visible during the experiment). The gaze-contingent trigger region is shown as a dashed square and disappeared once triggered.

paragraphs (see Figure 1). Double character inter-word spacing was used to reduce the effects of perceptual crowding (Blackmore-Wright, Georgeson, & Anderson, 2013). For the static sentences, a gray guideline was presented (4° above the text) to help participants maintain their gaze above the text; for the scrolling and RSVP dynamic formats, a fixation cross was presented 4° above the text position in the middle of the screen. The multiple-line paragraph format was presented as four lines of text (without guidelines, as these would have obstructed the text).

Procedure

A within-subjects design was used whereby participants read passages of text (randomized across participants to avoid order effects) presented in each of the four text formats. Participants were informed about the central scotoma and the EV reading technique and were asked to read while holding their gaze above the text (marked by a gray horizontal guideline for the single-line static text and a central fixation cross for scrolling text and RSVP) while reading. Short passages of text taken from BBC news articles were used to enable participants to familiarize themselves with reading each of the different display formats with a central scotoma using EV, taking around 5 minutes per

text format. During the practice trials with the scrolling text display, participants selected a preferred scrolling speed (using the computer keyboard to increase or decrease the scrolling rate). This rate was then used for both the scrolling text and RSVP formats in the main reading test.

A nine-point calibration (without a scotoma) was performed at the start of each block of reading which involved participants fixating on targets that appeared on a 3 × 3 horizontal and vertical grid. The same calibration points were presented a second time as a spatial validation and the calibration was repeated if the average gaze position deviated by >0.5°. A gaze-contingent square of one-character width was then presented on the left of the screen for the static text formats (single-line and multiple-line) and in the center above the word for the scrolling and RSVP text displays. Participants were instructed to fixate within this region (without the central scotoma, above the location where the first word would appear in all conditions). Steady fixation on this square was required to initiate the start of the trial (requiring a minimum of 40 ms of constant fixation to trigger the text). This procedure ensured that participants were holding their gaze at the required EV location when the sentence(s), or first word, in the case of RSVP, appeared on the screen. In the case of static text, participants progressed through the text by pressing the spacebar on the

keyboard to display the next section; for scrolling text and RSVP text, they progressed until the end of the passage was reached. The gaze-contingent triggering of the trial also started an internal timer that stopped when the participant pressed the spacebar to indicate they had reached the end of the passage, allowing an accurate measure of reading duration. The use of EV was reinforced before the experiment started, and further prompts were given during reading. All passages were read aloud (and were recorded) to enable reading accuracy to be scored (errors consisted of word substitutions, word omissions, insertions, or words read in the incorrect order). Participants completed the standardized comprehension questions immediately after reading each passage. None of the participants read the same passage of text twice, and the order of testing was randomized across all conditions and counterbalanced across participants.

Data analysis

Saccade records were processed using the SR Research Data Viewer, which extracted the raw data samples (eye position and time) which were then processed using R (R Foundation for Statistical Computing, Vienna, Austria), with the eyeTrackR and ez packages. Saccades were detected based on a velocity criteria of 30°/s. In the case of scrolling text, periods of smooth pursuit were classified as fixations (see Harvey et al., 2017). For each measure, fixations were excluded from analysis if they were less than 60 ms as a lower limit cutoff, allowing any meaningful lexical processing to take place (Liversedge et al., 2004), resulting in between 0.9% and 34% data loss, and fixations shorter than 60 ms were removed from the analysis. For the

saccade analyses, horizontal saccades of less than the horizontal amplitude of one character were excluded from the main analyses, resulting in the removal of 8% of the saccades at that point. Vertical saccades, classified as those with more than 1° vertical movement from launch to landing point (accounting for 19% of saccades) were analyzed and presented separately. All measures were analyzed using within-subject ANOVAs, and all following pairwise comparisons were Bonferroni corrected for multiple comparisons.

The ability to maintain an EV gaze position was examined by a region of interest (ROI) analysis to examine the proportion of time spent holding gaze away from the text and on the text itself. The positions of fixations were classified in relation to the position and dimensions of the ROIs as shown in Figure 2 (fixations made in the EV region, positioned above the line of text and text region). For the scrolling text display, RSVP text, and single-line static text display, the ROIs were positioned 4° above the text to enable a full view of the text in the peripheral visual field when the participants fixated on the guide line. The ROI analysis was not performed for the multiple-line format due to spatial constraints that would result in overlapping ROIs.

Results

Eye movement behavior

Figure 3 presents eye movement *x*-*y* plots for one representative observer who read a single line of scrolling text, RSVP text, single line of static text, and multiple-line static text. The light-gray solid line indicates the vertical eye position (upward line

Figure 2. Schematic diagrams showing the ROIs used to examine fixation behavior. (a) ROIs used for both the scrolling and single-line static text displays. The width of the EV ROI (red) was the radius length of the static and scrolling sentences (1920 pixels), and the height of the EV ROI was 384 pixels. The text ROI (black) was 1920 pixels (width) by 211 pixels (height). (b) ROI used for RSVP. The EV ROI (red) was 420 pixels (width) by 384 pixels (height), and the text ROI was 420 pixels (width) by 211 pixels (height). For all of the text display types, the EV region was positioned 4° above the text ROI.

Figure 3. Examples of eye movement traces (*x-y* plots) from the same participant for (a) horizontally scrolling text, (b) single-line static text, (c) RSVP, and (d) multiple-line static text. The *x*-axis corresponds to time and the *y*-axis (pixels) to location. The top-left corner of the display is (0,0). The dark-gray solid line represents the horizontal eye position where a line moving upward represents a leftward movement (pursuit or saccade) and a downward line represents a rightward sa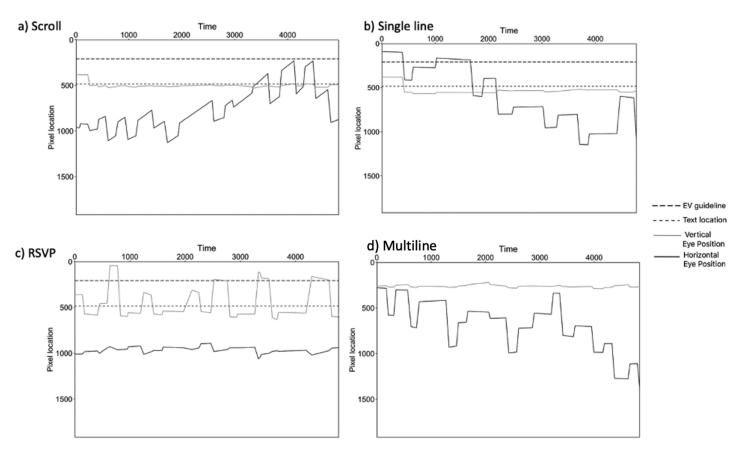ccade. The light-gray solid line represents vertical eye position, where an upward line reflects an upward movement and downward line a downward movement. The top gray dashed line represents the EV guideline, and the bottom gray dashed line represents the location of the text. Participants were instructed to hold their gaze above this position.

represents a saccade made upward and a downward line represents a downward saccade). The dark-gray solid line indicates the horizontal eye position; an upward line represents a leftward saccade, and a downward line position represents a rightward saccade. When the light-gray vertical eye position is on or below the dashed line, this indicates that the participant's gaze was on the text. For scrolling text (Figure 2a), initial fixation was located on the central fixation cross, and following the onset of the text a downward vertical shift occurred (light-gray line) that moved gaze onto the line of text, followed by a horizontal leftward tracking movement (dark-gray line). This was then followed by an initial pattern of leftward saccades and pursuit tracking with rightward saccades which then became the more typical leftward pursuit and rightward saccade nystagmus-like pattern. For single-line static text (Figure 2b), poor adherence to the EV strategy is indicated by an initial downward vertical saccade made onto the text followed by multiple leftward and rightward saccades made in a

"see-saw" pattern scanning the line of text. The RSVP eye movement record (Figure 2c) shows multiple vertical saccades made upward and downward onto each word and then back to the EV position, with small-amplitude horizontal saccades. For the multiple-line static text (Figure 2d), leftward and rightward saccades were again observed along the sentences, with a large leftward saccade being made to locate the start of the next line. For all four text formats, the participant tended to shift gaze onto the text; for scrolling text and RSVP text, the participant's eye movement behavior was broadly similar to that observed for reading without a CVL (Harvey & Walker, 2014; Juola, Haugh, Trast, Ferraro, & Liebhaber, 1987); for the static text formats, many more leftward saccades were made to reinspect the text, suggesting that a horizontal scanning strategy had been used.

Figure 4a shows the relative frequency of saccade size for each condition. As expected for RSVP, the majority of saccades were of small amplitude (around
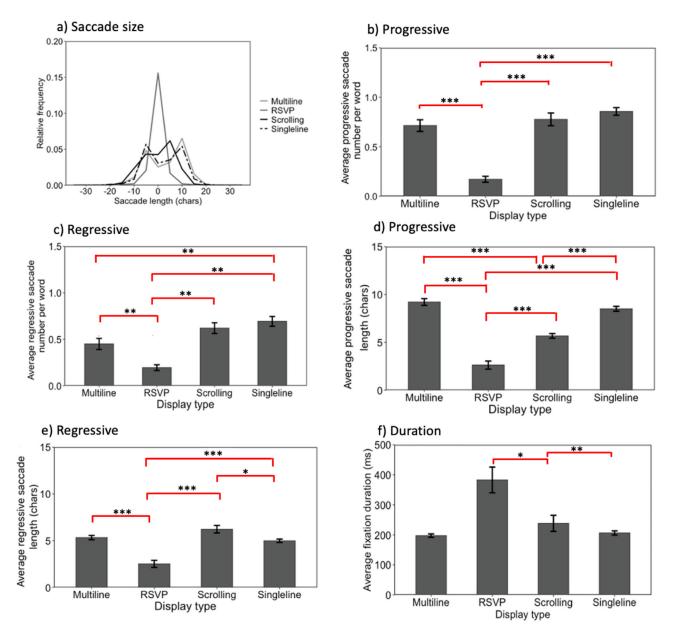
Figure 4. (a) Relative frequency of saccade amplitude (in characters) for all saccades (progressive and regressive) made in the multiple-line, RSVP, scrolling, and single-line static text displays. (b) Mean number of progressive saccades per word for each text display. (c) Mean number of regressive saccades per word for all text displays for each text display. (d) Mean saccade length (amplitude) in characters for progressive saccades for each text display. (e) Mean saccade length (amplitude) in characters for regressive saccades for each text display. (f) Average fixation duration in milliseconds. Error bars show standard error here and in all following figures.

three characters); for the other formats, numerous larger horizontal saccades of five to eight characters were made in both directions. Figure 4 also shows that the mean numbers of progressive (Figure 4b) and regressive saccades (Figure 4c) made per word were modulated by the text display, $F(3, 45) = 42.30$, $p < 0.001$, and $\eta^2_G = 0.66$, and pairwise comparisons showed that significantly fewer progressive saccades occurred with RSVP than for any other text display type ($p < 0.001$ for all). All other comparisons were statistically non-significant ($p > 0.20$). The number of regressive saccades made were also significantly different across the text display formats, $F(3, 45) = 23.98$, $p < .001$, and $\eta^2_G = 0.48$. Significantly fewer regressive saccades were made with RSVP than any other text display type ($p < 0.01$ for all), and significantly fewer regressive saccades with multiple-line text display type than single-line text display ($p < 0.01$). All other comparisons between text display types were statistically non-significant ($p > 0.10$).

The mean amplitude of progressive (Figure 4d) and regressive (Figure 4e) saccades differed across all four text formats, and this difference was confirmed by ANOVA: progressive $F(3, 45) = 96.58$, $p < 0.001$, and $\eta^2_G = 0.81$ (Figure 4d); regressive $F(3, 45) = 33.67$, $p < 0.001$, and $\eta^2_G = 0.56$. The scrolling text display resulted in longer progressive saccades compared with RSVP ($p < 0.001$), and amplitude was significantly longer with both the single-line and multiple-line formats than with scrolling text and RSVP ($p < 0.001$ for all comparisons). Progressive saccade amplitude was comparable in the two static text conditions ($p = 0.79$). The amplitude of regressive saccades was significantly shorter for the RSVP format compared with all of the other text displays ($p \leq 0.001$). Regressive saccades were significantly longer with scrolling text than the single-line static text display ($p = 0.04$). All of the other comparisons were statistically non-significant ($p > 0.20$).

Figure 4f displays the mean fixation duration for each text formats. ANOVA indicated significant differences in fixation duration for each text format, $F(3, 42) = 9.21$, $p < 0.01$, and $\eta^2_G = 0.32$. Further pairwise t-tests indicated that fixation duration was significantly longer with the RSVP text display (mean $= 365.21$, $SE = 45.18$) than for scrolling text display, mean $= 231.07$, $SE = 28.07$), $t(14) = 2.52$, and $p < 0.05$, and single-line static text display, mean $= 104.94$, $SE = 8.61$, $t(14) = 196.94$, and $p < 0.01$. There were no significant differences between the scrolling and single-line static text displays ($p = 0.27$).

Figure 5a shows that more vertical saccades were made with the RSVP (174.25) and multiple-line (128.06) text formats. ANOVA confirmed a difference in vertical saccade frequency, $F(3, 45) = 3.25$, $p = 0.03$, and $\eta^2_G = 0.13$), with a significant difference between RSVP and scrolling text only ($p = 0.04$; all others, $p > 0.10$). Figure 5b shows mean vertical saccade amplitudes (in characters), which differed across text formats, with larger saccades being made with the multiple lines and small vertical saccades with RSVP (multiple-line, 25.63 characters; RSVP, 7.63 characters; scrolling, 12.11 characters; single-line static, 15.23 characters). ANOVA confirmed a significant overall difference in amplitude, $F(3, 45) = 94.91$, $p < 0.001$, and $\eta^2_G = 0.82$, and pairwise comparisons showed significant differences between all but the scrolling and single-line static format ($p = 0.051$; all other comparisons significant at $p < 0.001$).

Adherence to eccentric viewing

The fixation positions for all participants combined are shown in Figure 6, and the fixations for each individual participant are displayed in Figure 7 in relation to the location of the text. Figure 6 shows the individual fixations from all participants combined
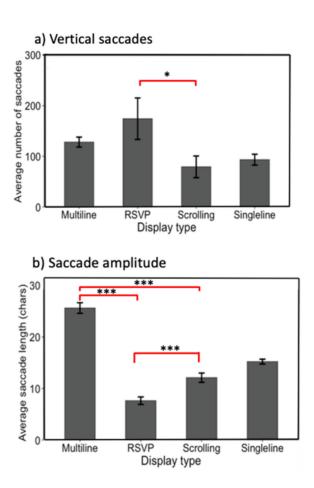

Figure 5. (a) Average number per passage of vertical saccades for each text display (multiple-line, RSVP, scrolling, and single-line), and (b) average saccade amplitude (in characters) of vertical saccades.

when reading with each text display. The horizontal lines indicate the position of the text, with the upper line indicating the EV region. The fixation plots are consistent with the eye movement records shown in Figure 3, such that the majority of fixations made with static and scrolling text were located on or below the text, covering the whole horizontal extent of the text, with fewer fixations at the upper EV location. The ability to hold gaze at the EV location was, however, better in the single-word RSVP condition than for the static or scrolling sentences. This confirms the impression that participants found it very difficult to avoid making fixations onto the text despite the presence of the central scotoma.

The fixation plots for individual participants (Figure 7) show that some individual participants (participants 2, 3, 11, and 13) did attempt to read while holding their gaze above the text. These individuals made numerous fixations above the text in the scrolling text condition, but fewer fixations above the sentence are apparent in the static text condition. Participant
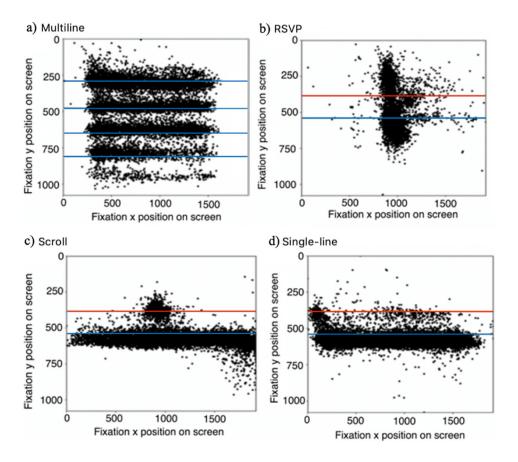
Figure 6. Individual fixation positions for all participants when reading: (a) multiple-line, (b) RSVP text, (c) scrolling text, and (d) single-line static text. For the RSVP, scrolling text, and single-line static text displays, the top horizontal line (red) indicates the EV guideline, and the lower line (blue) indicates the location of the text on the screen.

13 showed clear signs of adopting a steady-eye viewing strategy, with gaze being held in the center of the screen and few fixations being made onto the text with the scrolling format. This participant managed to maintain the EV strategy 88.4% of the time with scrolling text, 8.69% with the RSVP text display, and 1.93% with the single-line static text display. The maintenance of EV with the scrolling text was rather exceptional, and the participant did not appear to be able to do this when reading static text.

Participants were better at implementing the EV strategy with the RSVP text display (see Figure 8), but overall only ∼27% of time was spent reading with gaze held above the text. For the scrolling text display, only 10% of time was spent reading eccentrically and around 5% with the single-line static text format. Thus, in these cases, some 90% to 95% of the time was spent with gaze and therefore the simulated scotoma, positioned on the text itself. One possibility is that the participants were poorly motivated to comply with the task instructions; however, this was not the impression of the experimenter, and the presence of fixations made

away from the text indicates some attempts to read at the eccentric location. A few individuals made more fixations away from the text, also indicating willingness to read using EV with scrolling text but not with static text. Instead, participants adopted a strategy of making multiple scanning eye movements on the lines of text, presumably sampling the text to either side of the scotoma.

Reading performance (speed, comprehension, and accuracy)

A goal of the methods used here was to control the rate of dynamic text presentation so reading speed was balanced as far as possible across the dynamic text formats (scrolling and RSVP) to avoid potential difficulties in interpreting the comprehension results due to speed–accuracy confounds. This method was reasonably successful, with a 25-wpm difference between RSVP and scrolling text (scrolling, 121 wpm; RSVP, 146 wpm). There was an overall significant effect of text display on reading speed, $F(3, 42) = 5.59$, $p < 0.05$, and $\eta^2_G = 0.23$. Participants read with

Figure 7. Fixation positions for each individual participant: (a) RSVP, (b) scrolling single-line, and (c) single-line static text display. The top line for each participant represents the EV guideline, and the bottom line represents the location of the text.

the multiple-line text display at the fastest reading speed (mean = 163.17 wpm, SE = 12.90), which was significantly faster than for the single-line static text format (mean = 117.12 wpm, SE = 3.84, $p < 0.05$). Reading speed was also faster for the RSVP condition (mean = 145.84 wpm, SE = 10.08) than with scrolling text (mean = 121.31 wpm, SE = 7.35, $p < 0.001$) and

single-line static text (mean = 117.12 wpm, SE = 3.84, $p < 0.001$). All other pairwise comparisons were statistically non-significant ($p > 0.05$).

Figure 9a shows better literal comprehension with the dynamic formats (RSVP mean = 51.67%, SE = 6.57; scrolling text mean = 36.27%, SE = 9.55) than with static text (single-line mean = 18.47%, SE = 7.32;

Figure 8. Proportion of time participants spent fixating eccentrically for the three text formats. ANOVA confirmed a significant effect of text display on the ability to hold gaze at the eccentric location in the ROI, $F(2, 30) = 4.02$, $p < 0.05$, and $\eta^2_G = 0.22$. The RSVP text display (mean = 26.69%, $SE = 9.10$) had significantly better maintenance of EV than the single-line static text display (mean = 2.89%, $SE = 0.58$, $p < 0.05$), but there was no difference between the scrolling text (mean = 11.17, $SE = 5.89$) display and RSVP ($p = 0.19$) or static text ($p = 0.18$).
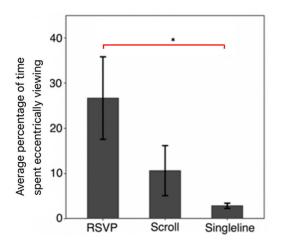
multiple-line paragraph format mean = 18.13%, $SE = 7.37$). One-way, within-subjects ANOVA confirmed a significant effect of display type on comprehension, $F(3, 42) = 4.81$, $p < 0.01$, and $\eta^2_G = 0.19$. Further pairwise comparisons showed that the RSVP text display showed significantly better literal comprehension than the single-line text display, $t(14) = 2.72$ and $p < 0.05$, and the multiple-line paragraph format, $t(14) = 3.09$ and $p < 0.01$, and scrolling text resulted in better literal comprehension than the single-line static text display, $t(14) = 2.11$, and the multiple-line paragraph format, $t(14) = 2.21$ and both $p \leq 0.05$. There was no significant difference between the scrolling and RSVP formats ($p = 0.26$).

Inferential comprehension (Figure 9b) was better with the scrolling text display (mean = 67.27%, $SE = 5.66$) and poorest with RSVP (mean = 37.22%, $SE = 7.84$). The multiple-line format had the second highest inference comprehension (mean = 63.65%, $SE = 7.37$), followed by the single-line static text (mean = 50.55%, $SE = 7.16$). One-way ANOVA confirmed a significant effect of display on comprehension, $F(3, 42) = 4.30$, $p = 0.01$, and $\eta^2_G = 0.17$, and pairwise comparisons confirmed a significant improvement between the scrolling text display and the single-line static text, $t(14) = 2.35$ and $p < 0.05$, and RSVP formats, $t(14) = 3.07$ and $p < 0.01$. The RSVP text display produced significantly worse comprehension than the multiple-line paragraph format, $t(14) = 2.37$ and $p < 0.05$.

Overall comprehension (Figure 9c) was better for the scrolling text format (mean = 57.22%, $SE = 6.02$) than for RSVP (mean = 32.53%, $SE = 6.46$) and with single-line static text (mean = 36.15%, $SE = 6.07$). One-way ANOVA showed a significant effect of display type on comprehension, $F(3, 42) = 4.56$, $p < 0.01$, and $\eta^2_G = 0.17$. The pairwise comparisons showed significantly better comprehension with scrolling text than with either RSVP $t(14) = 53.44$ and $p < 0.01$, or single-line static text, $t(14) = 2.93$ and $p = 0.01$. The multiple-line paragraph format (mean = 51.08, $SE = 5.41$) resulted in significantly better overall comprehension than the single-line static text format, $t(14) = 2.35$ and $p < 0.05$.

The percentage of key points recalled by participants (Figure 9d) was highest with scrolling text (mean = 44.75%, $SE = 4.26$) than with all other formats (RSVP mean = 24.59%, $SE = 4.55$; single-line mean = 30.25%, $SE = 4.30$; multiple-line paragraph format mean = 29.57%, $SE = 4.98$). ANOVA confirmed a significant effect of display type, $F(3, 42) = 5.51$, $p < 0.01$, and $\eta^2_G = 0.16$. Pairwise comparisons indicated that significantly higher scores were achieved with scrolling than with RSVP, $t(14) = 4.83$ and $p < 0.001$, single-line static text display, $t(14) = 3.30$ and $p < 0.01$, or multiple-line paragraph format $t(14) = 2.75$ and $p < 0.05$.

Reading errors were much higher with the RSVP format (mean = 49.31%, $SE = 8.02$) than for all other display types (scrolling mean = 1.12%, $SE = 0.36$; single-line static text mean = 1.38%, $SE = 0.29$; multiple-line paragraph format mean = 1.51%, $SE = 0.26$). One-way ANOVA confirmed an effect of display type on error rates, $F(3, 108) = 1.76$, $p < 0.001$, and $\eta^2_G = 0.66$, and paired comparisons confirmed that the RSVP format yielded higher reading errors than the other formats: RSVP versus scrolling text, $t(14) = 6.15$ and $p < 0.001$; RSVP versus single-line static, $t(14) = 5.96$ and $p < 0.001$; RSVP versus multiple-line, $t(14) = 5.98$ and $p < 0.001$.

To summarize reading performance observed with a simulated CVL, literal comprehension was better with RSVP and scrolling text and poorest with the static text formats; however, inferential comprehension (requiring a deeper level of understanding) was better with scrolling text and multiple-line static text and poorest with RSVP. The key point summary scores were also higher for scrolling text, with the lowest scores observed for RSVP. Reading error rates were low (<2%) with all formats, except RSVP, for which very high error rates (almost 50%) were observed. Overall, this indicates that scrolling text appears to support more effective reading than static text, and RSVP appears to be the approach least able to support effective reading. The eye movement analysis indicated that, in the case of RSVP, more time was spent employing EV, but this has not resulted in a deeper level of
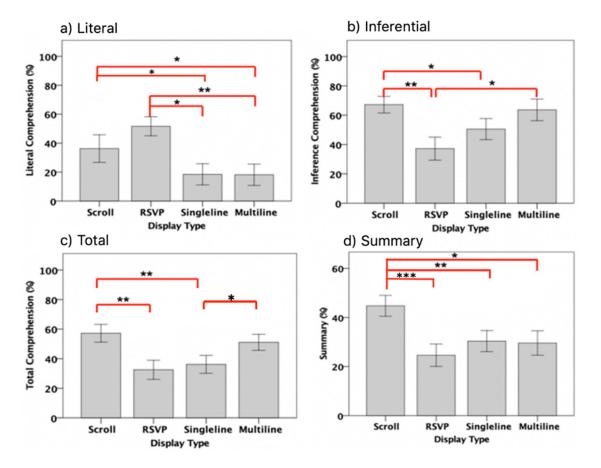
Figure 9. Mean percentage comprehension for reading with a simulated CVL for each text format: (a) literal comprehension, (b) inference-based comprehension, (c) overall comprehension, and (d) summary key points score. $*p < 0.05$; $**p < 0.01$; $***p < 0.001$.

understanding of the material, possibly due to the known limitations of this as a method of reading (see discussion). For scrolling and static text, participants spent the majority of time reading with their gaze on the text itself. For static text, reading involved a strategy of making multiple left–right saccades to scan backward and forward along the line. For scrolling text, eye movement behavior involved leftward pursuit tracking followed by rightward saccades, comparable to the strategy used with static text. For reasons that are not clear, scrolling text was better able to support comprehension with this strategy than was static text or RSVP (with the exception of literal comprehension). Participant 3 (Figure 7b), for example, spent less time eccentrically fixating (28.14%) with the scrolling text display, but this participant's comprehension score was better than that of other participants (scoring 42.86%). Overall, there was not a significant correlation between amount of time spent eccentrically viewing and (total) comprehension for the scrolling and single-line static text display, but there was a strong negative correlation between time spent eccentrically viewing and overall comprehension ($r_s = -0.704$, $p = 0.003$, $N = 15$).

Study 2. Macular degeneration participants

Methods

Participants

A total of 37 participants (32 female, five male) with a diagnosis of macular degeneration (mean age = 77.54 years and $SD = 10.89$; mean years since diagnosis = 8.68 and $SD = 5.14$) (Table 1) were recruited from the membership of the Macular Society UK. All participants spoke British English as their primary language and were within the normal (unimpaired) range on the Six-Item Cognitive Impairment Test (6CIT, Kingshill Version 2000). The inclusion criteria were a diagnosis of macular degeneration (wet, dry, or both or other forms of macular degeneration, such as Stargardt disease), with confirmed CVL in at least one eye, and English as the primary language. The exclusion criteria consisted of ocular comorbidities and any language, reading, or cognitive impairment. All of

ID	Age (years)	Gender	Diagnosis	Reading acuity (logMAR)	Distance visual acuity (logMAR)	Diagnosed (years)
1	73	F	Both eyes dry AMD; CVL in RE	0.64	0.72	9
2	78	F	Both eyes wet AMD; CVL in both eyes	0.59	0.74	7
3	83	M	Both eyes dry AMD; CVL in both eyes	0.21	0.78	28
4	82	F	Both eyes dry AMD; CVL in both eyes	1.22	1.46	9
5	87	M	Both eyes wet AMD; CVL in LE	0.17	0.96	8
6	76	F	Wet in LE with CVL; dry AMD in RE	0.52	0.62	5
7	85	M	Dry AMD in LE; wet AMD in RE with CVL	0.9	1.32	12
8	81	F	Both eyes dry AMD; CVL in both eyes	−0.18	0.48	6
9	77	F	Both eyes dry AMD; CVL in both eyes	1.06	0.52	12
10	82	F	Both eyes wet AMD; CVL in LE	0.90	0.82	6
11	85	F	Both eyes wet AMD; CVL in both eyes	0.62	1.22	11
12	64	F	Both eyes wet AMD; CVL in RE	0.7	1.12	5
13	73	F	Both eyes dry AMD; CVL in LE	0.46	0.42	5
14	78	F	Both eyes dry AMD; CVL in RE	0.94	1.04	7
15	36	M	Stargardt disease	1.06	1.42	7
16	46	M	Stargardt disease	0.75	1.28	6
17	87	F	Both eyes wet AMD; CVL in both eyes	−0.18	0.52	9
18	78	F	Both eyes dry AMD; CVL in RE	0.1	0.34	7
19	65	F	Wet AMD in LE with CVL; dry AMD in RE	0.3	0.70	4
20	74	F	Both eyes dry AMD; CVL in LE	0.73	0.26	5
21	82	F	Both eyes wet AMD; CVL in RE	0.1	0.82	7
22	73	F	Both eyes wet AMD; CVL in LE	0.17	0.42	8
23	95	F	Both eyes dry AMD; CVL in LE	1.26	1.48	19
24	79	F	Both eyes dry AMD; CVL in RE	0.19	1.12	9
25	87	F	Both eyes wet AMD; CVL in RE	−0.09	0.32	14
26	74	F	Both eyes dry AMD; CVL in LE	1.09	1.12	6
27	79	F	Both eyes wet AMD; CVL in RE	1.15	1.12	10
28	78	F	Both eyes dry AMD; CVL in RE	1.06	1.42	6
29	80	F	Dry AMD in RE; wet AMD in LE; CVL in both eyes	0.51	0.70	2
30	77	F	Both eyes dry AMD; CVL in RE	0.48	0.52	2
31	85	F	Both eyes dry AMD; CVL in LE	0.78	1.20	10
32	88	F	Both eyes wet AMD with CVL	0.31	0.72	7
33	84	F	Both eyes dry AMD; CVL in LE	0.88	0.92	5
34	76	F	Both eyes dry AMD; CVL in RE	0.45	0.92	22
35	74	F	Both eyes dry AMD; CVL in RE	0.26	0.72	8
36	82	F	Both eyes wet AMD with CVL	0.59	0.72	10
37	86	F	Both eyes wet AMD with CVL	0.78	0.72	8

Table 1. Visual characteristics of participants with macular degeneration including age, gender, self-reported diagnosis, reading acuity (logMAR), distance visual acuity (logMAR), and years since diagnosed. F = female; M = male; RE = right eye; LE = left eye.

the participants were aware of the EV technique, and the majority had had at least one training session in EV (provided through the Macular Society UK) previous to taking part. All participants gave verbal consent and written informed consent prior to participating in the study. The study was reviewed and approved by the College Ethics Committee at Royal Holloway, University of London (Ethics ID 2017/633).

Apparatus and procedure

The study design was as described above with the following differences in apparatus and procedure.

The study was conducted in each participant's own home, and the passages of text taken from the YARC (primary) reading test were "Bees" (179 words), "Reptiles" (182 words), and "Shoes" (229 words), presented on a tablet device; eye movements were not recorded. Static and scrolling text was presented on an Apple iPad 2 (10.1-inch retina display) in white Arial font (as Courier was not an option on either of the apps used) on a black background. Reading acuity was measured using the digital MNRead presented on the iPad (Calabrèse et al., 2014) ranging from 1.42 to –0.18 logMAR (mean logMAR = 0.58, *SD* = 0.40). Binocular-distance visual acuity was assessed

using the Bailey–Lovie Visual Acuity chart (Bailey & Lovie, 1976) (mean logMAR= 0.86, SD = 0.35). The font size used in the reading assessment was set as two times each participant's critical print size from the digital MNRead. The horizontally scrolling format was presented using the MDevReader app (Walker, 2013), and the single-line and multiple-line static text was presented using PowerPoint (Microsoft Corporation, Redmond, WA). Due to the screen size, only three lines were presented in the multiple-line format. Guidelines were not used with these formats. RSVP was presented on a Galaxy Tab E 9.7-inch display (Samsung, Suwon-si, South Korea) using a custom-coded Android application (designed in-house for this study). The scrolling text display was given before the RSVP in a practice session that enabled the participant to select a comfortable reading speed using a trackpad on the MDevReader screen. This speed was then set as the speed of text presentation for both scrolling text and RSVP in the main reading assessment. For single-line and multiple-line static text, participants progressed through the passage by using the touch screen to progress through the PowerPoint presentation. Participants were instructed to employ the EV technique while reading aloud, and a stopwatch was used, which allowed reading speeds to be calculated. Participants completed the standardized comprehension questions after each passage. The order of text format and passages used was randomized among participants.

Results

Reading speed

Similar to the simulated scotoma group, the speeds of both dynamic text displays (RSVP and scrolling) were matched as close as possible to avoid a comfortable reading speed with both formats. The method of balancing the rate of text presentation for the scrolling and RSVP text displays was successful and resulted in similar reading speeds (scrolling mean = 71.90 wpm, SE = 3.84; RSVP mean = 71.70 wpm, SE = 3.79). The fastest reading rates were observed with the two static text formats that were similar (multiple-line mean = 104.72 wpm, SE = 6.80; single-line mean = 102.11 wpm, SE = 7.78). One-way, within-subjects ANOVA indicated an overall effect of reading speed on display type, $F(3, 108) = 19.96$, $p < 0.001$, and $\eta^2_G = 0.17$. Further analyses of pairwise comparisons indicated that the single-line static text was read faster than the scrolling text display, $t(36) = 4.46$ and $p < 0.001$, and the RSVP text display, $t(36) = 4.44$ and $p < 0.001$. The multiple-line text display was also read faster than the scrolling text display, $t(36) = 4.90$ and $p < 0.001$, and the RSVP text display, $t(36) = 4.91$ and $p < 0.001$.

Reading comprehension

Figure 10 displays average comprehension for participants with macular degeneration for each of the text displays. The highest scores for literal and inferential comprehension were observed with the scrolling text format, and, in contrast to the simulated scotoma, the lowest scores for both literal and inferential comprehension were observed for the RSVP format. Literal comprehension (Figure 10a) for the scrolling format (mean = 79.46%, SE = 3.58) was better than all other display types (RSVP mean = 50.41%, SE = 4.45; single-line static text mean = 52.97%, SE = 5.13; multiple-line paragraph format mean = 59.23%, SE = 5.59). One-way ANOVA indicated an overall significant effect of display type on literal comprehension scores, $F(3,108) = 7.71$, $p < 0.001$, and $\eta^2_G = 0.14$, and pairwise comparisons confirmed better literal comprehension with scrolling text than with RSVP, $t(36) = 5.20$ and $p < 0.001$, single-line static text $t(36) = 3.91$ and $p < 0.001$, or multiple-line paragraph format, $t(36) = 2.76$ and $p < 0.01$. All other comparisons were statistically non-significant ($p > 0.05$). Inferential comprehension (Figure 10b) was also better with scrolling text (mean = 70.64%, SE = 4.64) than for the other text displays (RSVP mean = 45.85%, SE = 5.39; single-line static text mean = 51.21%, SE = 4.91). There was an overall effect of display type on inference-based scores, $F(3, 108) = 5.78$, $p = 0.001$, and $\eta^2_G = 0.18$. Pairwise comparisons indicated that reading with scrolling text produced higher scores than for RSVP, $t(36) = 3.55$ and $p < 0.01$, and single-line static text displays, $t(36) = 2.96$ and $p < 0.01$. Comparisons between the scroll and multiple-line formats (mean = 61.76%, SE = 4.34) were statistically non-significant ($p = 0.07$).

Total comprehension (Figure 10c) was better with the scrolling text display (mean = 74.15%, SE = 3.33) compared with all other text display types (RSVP mean = 46.22%, SE = 3.81; single-line mean = 50.66%, SE = 4.05; multiple-line paragraph format mean = 58.31%, SE = 3.65). One-way ANOVA showed a significant difference in overall comprehension scores across all four text displays, $F(3,108) = 13.02$, $p < 0.001$, and $\eta^2_G = 0.18$. Pairwise comparisons indicated that scrolling text resulted in better comprehension than RSVP, $t(36) = 5.83$ and $p < 0.001$; single-line static text display, $t(36) = 4.61$ and $p < 0.001$; and multiple-line paragraph format, $t(36) = 3.15$ and $p < 0.01$.

Reading error rates

For the participants with MD, a higher proportion of errors was observed for the RSVP format (mean = 11.39%, SE = 2.76) than for all other text displays (scrolling text display mean = 1.35%, SE = 0.38; single-line static text mean = 2.13%, SE = 0.69; multiple-line paragraph format mean = 2.82%, SE
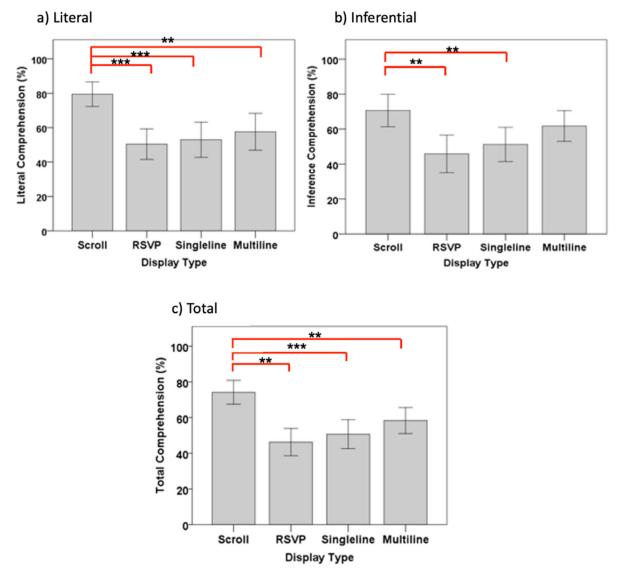
Figure 10. Average reading comprehension for macular degeneration participants across display formats: (a) literal comprehension, (b) inferential comprehension, and (c) total overall comprehension. *$p < 0.05$; **$p < 0.01$; ***$p < 0.001$.

= 0.69). There was an overall effect of display type with reading accuracy, $F(3, 108) = 12.94$, $p = 0.001$, and $\eta^2_G = 0.17$, and pairwise comparisons indicated a significantly higher proportion of reading errors made with the RSVP display than with the scrolling text display, $t(34) = 3.96$ and $p < 0.001$; single-line static text display, $t(34) = 3.52$ and $p < 0.01$; and multiple-line paragraph format, $t(34) = 3.46$ and $p < 0.01$.

Discussion

We report the findings from two complementary studies of reading with CVL; the first examined the eye movement behavior and reading performance when reading with a simulated CVL, with text presented in different formats (static text, horizontally scrolling, and single-word RSVP). A second complementary study assessed reading performance with the same text formats but in people with macular degeneration and an actual CVL. The aim was to evaluate the potential of dynamic text formats (horizontal scrolling text and RSVP) as a way of enhancing reading with CVL by supporting effective use of the EV reading technique. Reading performance was assessed using a standardized measure of comprehension and by recording reading errors.

Reading performance

Reading speed and error rates

The methods used in these studies were designed to ensure comparable reading speeds with the two dynamic text formats. The procedure was reasonably successful.

In the simulated scotoma study, a reading speed of around 120 wpm was observed with scrolling text and static text, which was 25 wpm less than observed with RSVP. The highest reading speed was observed with the multiple-line static text format (163 wpm), which was faster than the single-line static text. This may reflect the procedure used, where participants progressed through the single static sentences by pressing the keyboard spacebar, and the greater availability of text with the multiple-line format enabled a faster reading speed. The higher reading speed observed with the multiple-line format shows that the rates of text presentation for scrolling text and RSVP formats should be within the participant's reading ability. Reading errors were low (<2%) with static and scrolling text but were much higher with RSVP (50%). The high error rates with RSVP did not seem to simply reflect a speed–accuracy effect, as higher reading speeds were achieved with the multiple-line format with low error rates, and may instead reflect a strategy of guessing words based on the context of the material with RSVP.

The participants with macular degeneration read scrolling sentences at an average speed of ∼70 wpm, which is broadly consistent with the speed observed in an earlier study of macular participants with scrolling and static text (Walker et al., 2016), and a similar speed of 72 wpm was observed with RSVP. Higher reading speeds were observed with static and multiple-line text (102 and 104 wpm, respectively) and were higher than those reported by Crossland et al. (2004) in a study of static text reading with 25 participants with macular degeneration, indicating that the rates of dynamic text presentation used here were well within the participants' reading capabilities. Reading error rates were low (<3%) with all formats except for RSVP, which had the highest error rates (11%). Although RSVP can support very high reading speeds in normal vision, studies that have compared scrolling text and RSVP in low-vision participants have reported similar reading rates (Fine & Peli, 1995) except at a very large font size (over eight times the readers' acuity threshold), when some advantages were observed for RSVP (Fine & Peli, 1998). The findings here are consistent with some earlier reports, such as Fine and Peli (1998), who found that around one-quarter of their low-vision participants had higher reading speeds with the scrolling format. Legge et al. (1989) also reported an increase in reading speed in low-vision participants with scrolling text, with the greatest improvements observed for the slowest readers. Harvey et al. (2016) found a reduction in error rates with scrolling text, showing that scrolling text can support good reading performance at a reasonable rate of text presentation, and their participants also reported a subjective preference for reading with this format. There were clear differences in reading speed, suggesting that there is a possible trade-off between speed and comprehension. However, it is unlikely that speed would account for those differences in comprehension. Static text reading speed is largely under cognitive control, but for dynamic text speed depends on the rate set by the device. The possibility of differences in reading speed accounting for differences in comprehension seems unlikely given the pattern of results. For example, in Study 1, where RSVP resulted in a 25-wpm difference with scrolling text, literal comprehension was better with RSVP, but the inferential comprehension score was low. The highest reading speed, observed with the multiple-line format, was some 46 wpm faster than for the static single-line sentences, but literal comprehension was comparable for the two static text formats. In Study 2, reading speed was comparable for scrolling text and RSVP and higher for the two static text formats. All measures of comprehension were better for scrolling text and were comparable for the other formats despite static text having a 30-wpm faster speed.

Comprehension

In the simulated scotoma study, inferential comprehension and reading accuracy were significantly better for the scrolling text display compared with RSVP and single-line static text. Literal comprehension was better with RSVP, but the summary scores were higher with the scrolling text display, demonstrating better gist comprehension, which is more reflective of the aim of everyday reading. The participants with macular degeneration obtained the highest literal and inferential comprehension scores with scrolling text and the lowest with RSVP. Overall, the results for both the simulated and actual CVL participants show that reading performance (comprehension and error rates) were better with scrolling text, the exception being the better literal comprehension with RSVP. This may be because it is easier to recall or guess the correct answers than it is to draw inferences based on a more complete recollection of the material. A further possibility is that different strategies were being used by the two groups (undergraduate participants and elderly participants with macular degeneration) in their approach to guessing answers to the literal questions, and age-related differences in the adoption of different eye movement strategies (McGowan, White, Jordan, & Paterson, 2014) may also be a factor. The better inferential and gist comprehension for the participants with macular degeneration with scrolling text suggests that they were better able to retain information from the passage and expand upon their responses with scrolling text. The degree of similarity in reading performance across text formats between the two groups is encouraging and adds further support to the use of scrolling text to support effective reading with CVL.

Eye movement behavior

The oculomotor strategy observed consistently by participants when reading static and scrolling text was to sample the text by making multiple leftward and rightward eye movements to shift the scotoma across the text (or slightly below the text), presumably enabling words to be recognized to the left and right of the simulated scotoma. For static text, the oculomotor strategy with intact vision involved a sequence of rightward saccades made to progress through the sentence, with occasional leftward regressions made to reinspect regions of text if required (Rayner, 1989). The oculomotor behavior with a central scotoma differs from this, with numerous leftward and rightward saccades perhaps reflecting a sampling strategy designed to enable words to be recognized at the borders of the scotoma. The length of the forward saccades and fixation durations in our studies were greater than those reported by Scherlen et al. (2008). This could reflect small procedural differences in our study (such as scotoma and text size, reading aloud vs. silent reading). Reading scrolling text, with intact vision, involves a pattern of leftward pursuit movements (pursuit fixations to sample a word), with slightly larger amplitude rightward saccades to progress to the next word (Harvey et al., 2017). When reading scrolling text with a simulated central scotoma, the participants adopted a broadly similar strategy, with the average amplitude of leftward and rightward eye movements being broadly comparable to those reported by Harvey et al. (2017) in participants with intact vision. The pattern of eye movements when reading scrolling text observed here with a simulated central scotoma is, therefore, similar to normal reading behavior with this format. More vertical saccades were made from the EV location onto the words with RSVP, which could reflect the onset of the word-capturing gaze; however, the subsequent offset of the word means that the overall time spent fixating on the word location was reduced and the time spent holding gaze above the text at the EV location was enhanced. There was evidence of small-amplitude horizontal saccades being made in both directions within these single words, mimicking the strategy used with sentences but on a reduced spatial scale.

An interesting question to ask is why participants would engage in the oculomotor behavior of directing gaze onto the text, which appears to be counterproductive. It is suggestive of the view that the saccade–fixate sampling repertoire is a highly evolved strategy that is fundamental to our visual behavior (Findlay & Gilchrist, 2003). Indirect support for this view comes from a single case study investigating participant AI, a subject diagnosed with congenital, extraocular muscular fibrosis leading to ophthalmoplegia. AI was unable to make any eye movements and instead made head movements to compensate for the inability to make eye movements while reading (Gilchrist, Brown, & Findlay, 1997). The head movements showed a saccade-like behavior, and it was suggested that that these movements reflect the most optimal visual sampling strategy. AI demonstrated that saccades are a natural tendency; thus, the participants in this present study with a simulated scotoma were unlikely to adopt an atypical, different strategy over the short duration of this experiment. The eye movement analyses here support the view that it is particularly challenging to overcome the oculomotor reflex response, especially in the case of individuals without visual impairment (Buchardt et al., 1997). We cannot discount the possibility that our participants were poorly motivated and simply did not try to read while holding gaze away from the text, but the presence of some vertical saccades back to this location and the better performance of some of them would suggest that they were trying to follow the task instructions. It is also interesting to note that holding an eccentric gaze position was best with RSVP, a condition that involves peripheral stimulus onsets, and poorest with static text that is continuously displayed. This may be because lines of text cannot be read without making horizontal eye movements to progress along the sentence, and being in the "set" (mode) to make a horizontal eye movement may make it difficult to suppress making vertical saccades. For example, it has been shown in a patient with damage to the frontal cortex that the visual grasp reflex apparent during an anti-saccade task was reduced if the patient was asked to hold their gaze rather than make a saccade (Walker, Husain, Hodgson, Harrison, & Kennard, 1998).

The eye movement performance in the present study is broadly similar to that described by Rubin (2001), where readers with a simulated scotoma (3.5° scotoma) adapted their eye position to the right, compared to when they read static text without a scotoma. It was suggested that this demonstrated that they had shifted their gaze slightly and were using a region in the left visual field to aid their reading. Their results showed a disorganized oculomotor behavior with an increased number of fixations and multiple small saccades made within words. In the current study, there were also more saccades made to the right and a larger saccade amplitude observed to the right. Thus, participants with normal vision who were reading with a simulated scotoma appeared to deviate back to the highly overlearned oculomotor behavior of fixating on the text, making numerous saccades backward and forward on the line, with some attempts to adopt the EV strategy. This behavior could be a result of the inability to overcome the normal oculomotor pattern when reading with different text presentations, such that participants engaged in this oculomotor behavior 85% of the time. Our results reveal a left-right scanning

strategy made along or below the line of text, but we cannot be sure where participants were attending. It is likely that their attention was in the direction of the saccade (or pursuit) movement (Lingnau et al., 2008) and potentially using a PRL in their superior, rather than inferior, visual fields. People with an actual CVL may be better able to learn to compensate for their vision loss than the typically sighted participants here, but we cannot be sure what oculomotor strategy they used. However, the similarity in reading performance (comprehension and accuracy) across the two groups is noteworthy.

Adherence to eccentric viewing

The region of interest analysis showed that participants with a simulated scotoma did not appear able to implement the EV strategy during reading, despite being prompted and encouraged to do so by the experimenter. A minority of participants (participants 3, 11, and 13) did attempt to adopt the EV technique more often with the scrolling text format than with static text. Furthermore, participant 13 applied the EV strategy well (88.4% of the time) with scrolling text but did not score well on the comprehension test (scoring an overall 28.57% of questions correctly).

People with macular degeneration and a CVL adapt to using their peripheral vision for visual tasks (Crossland et al., 2005), although whether they were implementing the EV strategy in the present study is unclear, as eye movements were not recorded. It is possible that the participants with macular degeneration in this study used an oculomotor strategy similar to that observed with the participants with a simulated scotoma, or that the long-term nature of their disorder meant that they were more successfully able to read while holding gaze away from the text than the naïve participants. We cannot discount the possibility that the oculomotor strategy used by the typically sighted participants may not be comparable to that used by people with an actual central scotoma. It remains to be examined whether oculomotor behavior with simulated CVL can be generalized (accurate eye-tracking with participants with CVL is difficult due to the calibration process typically relying on direct fixation of targets), but this remains an interesting possibility for further examination. The eye movement behavior shows that participants with a simulated scotoma were engaged in a behavior that would not be regarded as being effective (i.e., making saccades on the text is not aiding the delivery of clear visual input and results in foveal disruption). The eye movement records revealed a left–right scanning strategy presumably attempting to identify and attend to words from the edges of the scotoma, rather than attempting to hold gaze above the text and read the continuous line of text. Thus, participants may have been trying to adopt

the instructed strategy of reading (as was apparent in the behavior of some participants shown in Figure 7) while holding gaze above the line but appeared unable to avoid the natural tendency to look at the text. The participants with macular degeneration may have been more successfully reading with their gaze held at the instructed location (above the text), and it is possible that using a different fixation location (e.g., below the text) may have altered the results obtained for each text format.

With a simulated CVL, the participants' maintenance of EV was better with RSVP compared with static text, but the potential benefits for comprehension appeared to be offset by factors thought to make this a less effective method of reading (Acklin & Papesh, 2017; Benedetto et al., 2015; Legge, Mansfield, & Chung, 2001). The overall poor performance observed with RSVP in both studies (with the exception of literal comprehension in the simulated CVL group) may be due to the lack of a parafoveal preview effect of upcoming words, which is required to support fluent reading. Regressions account for some 15% of the eye movements made when reading static text (Rayner, 1998); higher rates of regressions are observed with scrolling text (Harvey et al., 2017) and are thought to be important in supporting effective comprehension (Schotter et al., 2014). Rereading is not possible with RSVP, and the inability to go back over text to reinspect it may result in the reader prioritizing single-word processing with a diminished level of integration between words (Schotter et al., 2014). This may be intensified by reduced availability of cognitive resources to retain items in the working memory as a result of increased attentional load (Kennedy, 1982; Kerzel & Ziegler, 2005). By contrast, parafoveal preview and regression movements are possible with static and scrolling text, and these formats, unlike RSVP, enable fixation duration to be determined by ongoing cognitive processing, allowing for more fluent reading and further understanding of the text by being able to go back over text to reinspect it.

The present studies have demonstrated some advantages for the reading process and comprehension with scrolling text compared to static text, consistent with earlier reports that have shown other benefits, including increased speed and accuracy (Legge et al., 1989; Harvey et al., 2016). Here, the consistent finding is that both largely unpracticed participants reading with an artificial CVL and participants with an actual CVL showed better comprehension with scrolling text compared with static sentences and RSVP. Our initial prediction was that scrolling text and RSVP would improve the participants' ability to hold their gaze away from the text, enabling the text to move across peripheral retina away from the central scotoma. The eye movement analysis showed that adherence to reading with EV was poor overall,

including with scrolling text. The oculomotor strategy used by the participants with macular degeneration was not examined, but the observation from Timberlake et al. (reported in Legge et al., 1989) that some patients with macular scotomas "execute an erratic pattern of forward and backward saccades while reading static text" is similar to that observed with a simulated CVL. A similar observation has been made by E. Castet (personal communication, 2021): "In our macular patients we often see a very chaotic oculomotor pattern with many oblique saccades (both forward and backward) occurring during page reading, consistent with the oculomotor statistics (Calabrèse et al., 2014; Calabrèse et al., 2016), although this pattern varies greatly from patient to patient."

An interesting question is why comprehension and accuracy should be better with scrolling text than with static sentences read at a broadly comparable reading speed. What advantage does horizontal scrolling text confer for reading with CVL? Legge et al. (1989) offered tentative explanations for the improvement in reading with scrolling text, suggesting that the drifting text required a more orderly sequence of saccades during reading, the single-line format reduced difficulties in localizing the start of each sentence, or there was a reduction in glare with the procedures used for drifting text in their study. The issue of return sweeps is less of a consideration with single sentences as used here, and glare can be discounted, as the screen brightness was controlled across formats. The scrolling text format may provide some benefits when combined with the oculomotor strategy of making multiple oblique saccades, possibly by enhancing the deployment of attention at the edges of the central scotoma. The numerous vertical saccades made to shift gaze above the text may give a perceptual advantage by enhancing peripheral visual acuity with the slowly drifting sentence, as has been found with other slowly drifting stimuli (Brown, 1972).

Summary and conclusions

This study examined oculomotor behavior and reading performance in participants with simulated and actual CVL with static text and two dynamic formats (RSVP and horizontally scrolling text). It was found that adherence to EV in the simulated scotoma group was poor, and, although it was better with RSVP, this format resulted in poor comprehension and accuracy. With static text and scrolling lines, participants adopted a strategy of scanning around the text itself and appear to have been reading by recognizing words on either side of the central scotoma. Reading performance was best with the scrolling text format, although this cannot be attributed to better adherence to EV with a

simulated CVL. Participants with macular degeneration and genuine CVL also showed much better reading performance with scrolling text than with static text and performed poorly overall with RSVP. We suggest that studies of reading should include more than one measure of performance, and we conclude that scrolling text may support effective reading in people with CVL and as such has potential as a reading aid (Moshtael et al., 2020) on digital devices (Walker et al., 2012; Walker et al., 2016).

Keywords: macular degeneration, reading, central vision loss, scrolling text, RSVP

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