Oculomotor And Linguistic Processing Effects In Reading Dynamic Horizontally Scrolling Text

Hannah Harvey[1], Hayward J. Godwin[2], Gemma Fitzsimmons[2], Simon P. Liversedge[2], Robin Walker[1]

[1] Royal Holloway, University of London;

[2] University of Southampton

Correspondence: Department of Psychology, Royal Holloway University of London, Egham Hill, Egham, TW20 0EX, Hannah.Harvey.2010@live.rhul.ac.uk

Acknowledgements: Hannah Harvey is funded by a Royal Holloway Reid studentship. Gemma Fitzsimmons is funded by the Research Councils UK Digital Economy Programme, Web Science Doctoral Training Centre, University of Southampton. EP/G036926/1. Simon Liversedge acknowledges support from Leverhulme Trust Grants RPG-2013–205 and grant F/00 180/AN.

Abstract

Two experiments are reported investigating oculomotor behaviour and linguistic processing when reading dynamic horizontally scrolling text (compared to reading normal static text). Three factors known to modulate processing time in normal reading were investigated: word length and word frequency were examined in Experiment 1, and target word predictability in Experiment 2. An analysis of global oculomotor behaviour across the two experiments showed that participants made fewer and longer fixations when reading scrolling text, with shorter progressive and regressive saccades between these fixations. Comparisons of the linguistic manipulations showed evidence of a dissociation between word-level and sentence-level processing. Word-level processing (Experiment 1) was preserved for the dynamic scrolling text condition with no difference in length and frequency effects between scrolling and static text formats. However, sentence-level integration (Experiment 2) was reduced for scrolling compared to static text in that we obtained no early facilitation effect for predictable words under scrolling text conditions.

*Keywords***:** reading; eye-movements; scrolling text

Oculomotor And Linguistic Processing Effects In Reading Dynamic Horizontally Scrolling Text

Reading is a complex task requiring decoding and integration of many sources of information, including orthography, syntax, and semantics (Just & Carpenter, 1980). However, at a simplified level, there are three key processes that need to take place in order for us to read: perceptual parsing of the body of text into meaningful subunits (words in the case of English), identification of what each of these subunits means individually, and the construction of a coherent discourse representation through the combination of the meanings of the individual words according to the structural relationships that exist between those words. The manner in which these processes occur during reading can be studied by a detailed examination of eye movement recordings, to see how the characteristics of fixations and saccades are affected by the manipulation of linguistic variables (Rayner, 1998).

For the most part, the existing literature has focused on reading static sentences (i.e., where the text remains still). Here, we report two experiments examining how reading behaviour changes when participants read dynamic, horizontally scrolling text, producing a more challenging reading task. In doing so, our goal is to better understand the limiting factors for successful reading of any text display format. The scrolling presentation creates an unusual series of challenges to the reading process, notably: increased complexity in allocation attention (with a conflict likely arising between pursuing the text to the left and progressive saccades to the right); an increase in perceptual load resulting from the increased complexity of processing the dynamic stimulus; reduced availability of text for reinspection; and increased difficulty in spatially mapping the text to make such regressive saccades. The changes to reading with this format are therefore of significant theoretical interest as a paradigm for studying unusual reading situations; potentially comparable, for example, to influential methods such as the disappearing text paradigm (Liversedge et al., 2004; Rayner, Liversedge, White, & Vergilino-Perez, 2003; Rayner, Liversedge, & White, 2006), the transposed letter paradigm (Acha & Perea, 2008a, 2008b; Johnson, 2009; Johnson, Perea, & Rayner, 2007), and the unspaced text paradigm (Rayner, Fischer, & Pollatsek, 1998). The scrolling format is encountered quite frequently in real world situations (e.g., train information displays, television news tickers, websites, etc.), and for this reason, it is intrinsically interesting to understand how this visual presentation of text affects processes underlying reading. Furthermore, given the increase in use of electronic readers that can make use of dynamic presentation formats (e.g. Sharmin, 2015; So & Chan, 2013; Walker, 2013) it is important to know if the reading process is compromised. In our investigation, we measured readers' eye movements to assess how scrolling text presentation modulates the influence of the so-called "Big Three" of linguistic processing effects (see Clifton et al., 2016: word length, word frequency, and word predictability. Measuring the impact of the scrolling format on these key processes provides further insight into how robust each of these are resistant to interference, and which factors may disrupt successful linguistic processing of text.

Word length and word frequency effects

The word length effect is regarded as a relatively low-level perceptual effect based on the physical property of the number of letters in a word (Hautala, Hyönä, & Aro, 2011; Rayner & Fischer, 1996). In normal reading, shorter words (e.g. *rude*) are processed more quickly than longer words (e.g. *popular*) as revealed by shorter fixation durations, reduced refixation probability and a higher probability of skipping for shorter than longer words (Pollatsek, Juhasz, Reichle, Machacek, & Rayner, 2008;

Rayner & McConkie, 1975; Rayner, Sereno, & Raney, 1996; Rayner, Slattery, & Drieghe, 2011). This effect has been found to be similar in magnitude for both known and novel words (for the initial fixation on words from both categories; Lowell & Morris, 2013), and is present even in z-reading studies (where words are replaced by z-strings and participants are instructed to 'read' these as they would normal text; Rayner & Fischer, 1996). Given how robust word length effects are in reading, it stands to reason that such effects should appear in the eye movement record whenever the perceptual unit of an individual word can be visually parsed from the surrounding text stimulus (i.e. from within a sentence). The word frequency effect provides a temporal index of the ease or difficulty associated with lexically identifying a word. More frequent words (e.g. *popular*) are processed more quickly than less frequent words (e.g. *fabulous*) (Pollatsek et al., 2008) with the former eliciting shorter fixation durations (Inhoff, 1984; Inhoff & Rayner, 1986; Just & Carpenter, 1980; Kliegl, Grabner, Rolfs, & Engbert, 2004; Pollatsek et al., 2008; Rayner, 1977; Rayner, Ashby, Pollatsek, & Reichle, 2004; Rayner & Duffy, 1986; Rayner & Raney, 1996). These two factors (word length and frequency) are highly (negatively) correlated: however, in an experiment in which word length and frequency were orthogonally manipulated, Pollatsek et al. (2008) demonstrated interactive effects of the two variables such that the frequency effect is greater for long than for short words, an effect probably driven by the fact that increased refixations are more likely on long than short words.

Word predictability effects

Successful identification of individual words alone is clearly not sufficient to ensure effective reading. As each new word is encountered in a sentence, its meaning must be integrated into the representation of the meaning of the sentence developed up to that point. The word predictability effect, therefore, is a reflection of the ease with which a word can be integrated into the existing sentence representation. When information from the preceding sentential context constrains the likely candidate words that might follow, then those words that are more likely to appear in the sentence are predictable. For example, the word *finger* in *Russell had hurt his hand in the door of the car. He had trapped his finger while playing*. As such highly predictable words are processed more quickly than those that are not easy to predict (e.g. *finger* in *Russell had to go to the hospital. He had trapped his finger while playing*; Fitzsimmons & Drieghe, 2013), as indicated by shorter fixations and increased skipping (see Balota, Pollatsek, & Rayner, 1985; Ehrlich & Rayner, 1981; Fitzsimmons & Drieghe, 2013; Inhoff, 1984; Kliegl et al., 2004; Rayner et al., 2004, 2011). In due course, we will consider word length, frequency and predictability effects in the context of our primary experimental manipulation, namely that of text presentation (scrolling text compared to normal, static text). However, before doing this, we will first consider experimental work that has investigated how horizontally scrolling text influences eye movements during reading.

Horizontally scrolling text

Extensive work has been carried out examining the oculomotor and cognitive processing that takes place during reading of static text (see Rayner & Liversedge, 2011; Rayner, 1998; 2009; Vitu, 2011 for reviews). However, to date, there has been very little research to investigate reading performance when text is presented in a dynamic horizontally scrolling manner: that is to say, when the text is moved smoothly in a single horizontal line across a display screen from right-to-left during reading. As noted earlier, this format is often encountered in digital media, and presenting text in this way poses a set of challenges in relation to how the eyes must be moved and controlled during reading in order for accurate processing and good understanding of the text to occur. For instance, compared to static text, scrolling text may compromise saccadic targeting accuracy, and maintenance of a stable fixation on a word. This in turn could impact efficiency of word identification and efficacy of attentional deployment to upcoming words in a sentence. It may also potentially compromise a reader's ability to make regressions to revisit parts of the text for ambiguity or uncertainty resolution (an important part of the comprehension process; Schotter, Tran, & Rayner, 2014), since creating an accurate spatial representation of each part of the text to plan such regressive saccades will require constant updating to account for the movement of the text, and, moreover, availability of the text is not sustained. All of these factors may be expected to be influential with respect to visual and cognitive processing as a direct consequence of the text being a dynamic, as opposed to a static stimulus, and we discuss each of these in detail below.

Only a small number of studies have investigated oculomotor changes for scrolling text thus far (notably Buettner, Krischer, & Meissen, 1985; Valsecchi, Gegenfurtner, & Schütz, 2013) with the primary finding from these studies being that periods of smooth pursuit (a slow tracking movement employed to stabilise the retinal motion induced by a moving target; Krauzlis, 2004; Robinson, 1965) replaces the fixation periods seen in static text reading. Following a moving object in this way reduces blurring of the target across the retinal image, meaning that, at least at a stimulus velocity allowing for a comparable reading rate as for static text (around 250wpm; Rayner, 1998), dynamic visual acuity is comparable to that for static targets (Ludvigh & Miller, 1958). These pursuit periods are clearly distinct from standard fixations that are made in reading, as the eye is not stationary but rather moving throughout; however, for simplicity, we will hereafter refer to them as fixations, reflecting their similar functional role.

Buettner et al., (1985) compared reading of short stories presented either dynamically (scrolling speed set individually by each participant) or as single lines of static text, and reported lower saccade amplitude, longer fixation durations, and slower reading speeds with scrolling than static text. They suggested that these changes reflected difficulty in directly switching between leftward pursuit movements and rightward saccades. However, the spatiotemporal characteristics of the fast phase of voluntary (or 'look') nystagmus have been found to be very similar to volitional, visually-guided saccades (Kaminiarz et al., 2009). Voluntary nystagmus is a relatively automatic stabilising gaze pattern resembling alternating slow pursuit periods and fast saccades seen when participants follow particular elements in a horizontally-moving array (Kaminiarz et al., 2010; Ter Braak, 1936). Such eye movements appear comparable to the oculomotor pattern adopted when reading scrolling text, and this would suggest that the transition between leftward pursuit and rightward saccade is no more costly than between static fixation and rightward saccade, and therefore Buettner et al.'s suggestion that the changes can be attributed to difficulty in making these transitions may be overly simplistic. The longer fixation durations and reduced saccade amplitudes observed by Buettner et al. may instead reflect changes resulting directly from carrying out the already complex cognitive task of reading in conjunction with tracking text using a combination of pursuit and saccades.

A more detailed investigation of oculomotor behaviour with scrolling text (Valsecchi et al., 2013) also found longer fixation durations with scrolling than static text, along with a small increase in the dispersion of saccade landing positions. This was interpreted as reflecting the increased difficulty in saccadic targeting for the dynamic stimulus. The accuracy of saccadic targeting to moving targets has indeed been found to be reduced by as much as 27% (Gellman & Fletcher, 1992; as compared to targeting of static targets). However, other studies have found that the displacement of the target during the period between the decision to launch the saccade and the saccade's ending can be well-compensated for by the oculomotor system (Beers, 2001; Havermann, Volcic, & Lappe, 2012; Ohtsuka, 1994; Schlag, 1990). This is particularly the case if, as for scrolling text, the speed of the stimulus is known and constant, and the saccade target is available for some time before the saccade must be made (Blohm, Missal, & Lefèvre, 2005). Further evidence that the oculomotor system can compensate for predictable movement is provided by studies that have imposed a targeting error (i.e. by shifting the target between launch and landing of the target saccade) when a saccade is required to a target that appears orthogonally to the direction of the ongoing smooth pursuit. This situation may be analogous to the oculomotor behaviour required for making fixations to each word in a line of scrolling text and there is evidence that the oculomotor system can adapt to this type of position error even before landing on the new target (Schütz & Souto, 2011). An accurate saccade can also be made whilst covertly monitoring a separate dynamic target, and attentional deployment can be successfully remapped just before the saccade allowing for uninterrupted processing of the pursuit target which may help compensate for any hypothesised reduction in accuracy (Szinte, Carrasco, Cavanagh, & Rolfs, 2015). These findings suggest that any potential loss of targeting accuracy on landing position (as found by Valsecchi et al., 2013) should likely be minimal with scrolling text (and therefore its impact on text processing correspondingly minor).

Another way in which the movement of the text might impact on reading performance is via altered demands on visuospatial attention. The direction of scrolling text provides a potential conflict for the attentional system, as text must be pursued as it moves leftward, while a conflicting pattern of rightward shifts of gaze are required to fixate each successive word in the sentence. According to the premotor model of visual attention (Rizzolatti, Riggio, Dascola, & Umilta, 1987; Rizzolatti, Riggio, & Sheliga, 1994; Sheliga, Riggio, Craighero, & Rizzolatti, 1995; Sheliga, Riggio, & Rizzolatti, 1994), visual attention and eye movements are intrinsically linked. This coupling of attention and saccadic eye movements is supported by evidence showing that attention cannot be directed away from a location targeted by a saccade to enable the simultaneous processing of a target at a spatially separate location (Deubel & Schneider, 1996). For reading static text, an attentional 'window' asymmetric around the point of fixation has been established, the perceptual span, from which useful information can be processed (Rayner & McConkie, 1975). This window allows visual and linguistic processing of parafoveal text, particularly word *n* +1, to begin whilst word *n* is still being fixated. On some fixations, the parafoveal word might be identified prior to direct fixation, and on these occasions it may well be skipped (e.g., see Drieghe, Rayner, & Pollatsek, 2005).

Given the constraint of the attentional window by spatial deployment of finite attentional resources (Jordan et al., 2013; Miellet, O'Donnell, & Sereno, 2009; Paterson et al., 2014), it may well be expected that the extent of these attentional windows would be constricted by the conflict in attentional deployment when reading scrolling text, reducing parafoveal availability of text and thus average progressive saccade length. This may occur via increased foveal processing difficulty: in other situations, an increase in foveal load has been proposed to reduce the rightward extent of the attentional window (Henderson & Ferreira, 1990; White, Rayner, & Liversedge, 2005). A priori, this may be expected during reading of scrolling text when taken in the context of findings with more standard target pursuit tasks in which the deployment of attention is typically biased towards the area ahead of target movement. This would be to the left for scrolling text, opposite to the side from which parafoveal preview would ordinarily be obtained (Khan, Lefevre, Heinen, & Blohm, 2010). Effects similar to these, namely a reduction in the size of the attentional window, have been demonstrated for non-reading tasks (Seya & Mori, 2012; Van Donkelaar & Drew, 2002). Valsecchi et al. (2013) suggested that parafoveal processing was comparable for scrolling as for static text, however, the pattern of findings in their report may not be conclusive since they found fixation periods of equivalent durations to be associated with longer preceding saccades for static than scrolling text.

Processing of the text may also be affected by how well the eye is able to establish a stable ‘fixation’ on the text. Whereas for static text, maintaining stability of the retinal image of a fixated word is simple, for scrolling text this requires careful matching of the eye velocity to the movement of the stimulus. This is known to be achievable after a certain period of acclimatisation to the stimulus movement when the stimuli are presented at a constant velocity, as is the case with scrolling text in the present experiments (e.g. Lovejoy, Fowler, & Krauzlis, 2009). Consequently, if the eyes move in smooth pursuit synchronously with the text, this will allow the precise portion of the word under fixation to remain under stable foveal inspection. However, if the eye moves slower than the text, the character initially foveated will move out of foveal vision in a leftward direction, and subsequent characters in word *n*, and possibly even word *n* + 1, could potentially come under central fixation.

Alternatively, if the eyes move faster than the text, the converse situation will occur and letters earlier in the word, as well as possibly letters from word *n* -1 will move into central foveal vision. Evidence from studies where an attentionally demanding secondary task is performed concurrent to a smooth pursuit task suggests that oculomotor behaviour, specifically, pursuit gain, may suffer as a result of the extra processing demand (Hutton & Tegally, 2005). On the basis of these studies, pursuit gain is therefore unlikely to be perfect during scrolling text reading, where the demands of linguistic processing occur concurrently with pursuit of the scrolling text.

A final consideration for scrolling text is that the words eventually move out of the field of view and this loss of availability for reinspection may also affect how people move their eyes when they read. In order to maintain good levels of comprehension (as reported for scrolling text by Valsecchi et al., 2013), readers may be forced to prioritise identification and linguistic processing of words correctly during first pass inspection because the text will quite quickly move off the screen as they progress to its left edge. As the words disappear off the screen to the left, they will be unavailable for reinspection. Assuming that readers are aware that this is the case, and that they are able to modify their reading strategy to take this into account, it may be the case that they make longer average fixation durations for scrolling compared to static text. This prediction is consistent with other work showing that tasks which require more concentrated reading, such as proof reading, produce increased fixation durations (e.g. Schotter, Bicknell, Howard, Levy, & Rayner, 2014), or where less careful reading is required, as in skim reading, in which case the opposite pattern is found (Duggan & Payne, 2011; Fitzsimmons, Weal, & Drieghe, 2014).

In addition to such effects, we might also expect a reduction in long-range regressive saccades, due to two factors: first, the limited time window of visual availability of the text, and second, the increased difficulty in maintaining a spatial representation of the location of particular words within the text that has already been inspected. The spatial mapping of text has been shown to be important for planning regressive saccades when static text is read, and is suggested to be reliant on a visual working memory buffer (Kennedy, 1982; Tanaka, Sugimoto, Tanida, & Saito, 2014). The capacity of the memory buffer for storing position information in an array has been found to be reduced during oculomotor pursuit compared to at fixation (Kerzel & Ziegler, 2005), once again suggesting that the reader's ability to initiate and accurately target regressive saccades may be curtailed with scrolling text. It might be reasonably expected, therefore, that we would observe regressive eye movement behaviour for scrolling text reading similar to that observed in other reading paradigms where the opportunity for regressions is limited (e.g., Fischler & Bloom, 1980; Schotter, Tran, & Rayner, 2014).

The Present Study

To investigate how the scrolling text format affects reading success across the three key levels that we have highlighted (perceptual parsing, word identification, and sentence-level integration), we conducted two experiments. In the first experiment, we used single sentence stimuli from a previous study (Pollatsek et al., 2008), each of which included a target word that was orthogonally manipulated for word length and frequency. We used these stimuli because they are known to induce robust effects of these variables. We presented our stimuli in two formats: a static text format and a scrolling text format. The inclusion of the static text format allowed us to establish that we observed similar effects to those reported by Pollatsek et al. The scrolling text condition provided us with the opportunity to establish how this format modulated any such effects. In the second experiment, we used a set of stimuli from Fitzsimmons and Drieghe (2013) in a similar experimental design to contrast word predictability effects associated with a scrolling text format with those of a static text format. In both of these experiments, we assessed word length and frequency effects (Experiment 1), and predictability effects (Experiment 2) through local analyses of eye movements in relation to the target words. In addition, we considered the eye movement data across the entire sentence, pooling the data sets from Experiments 1 and 2 to allow us to undertake global analyses and characterise eye movement behaviour more generally when reading scrolling text.

A first aim was to further characterise global aspects of oculomotor behaviour during reading of scrolling text. In line with previous research (Buettner et al., 1985; Valsecchi et al., 2013), we expected to observe a pattern of periods of smooth pursuit to track the moving words that replace static periods of fixation in normal reading. We also expected that these periods would be of longer duration than typical fixations. Previous work has produced conflicting results with regards to saccade length during scrolling text reading. However, on the basis that slippage between the point of fixation and the scrolling word under fixation might occur, and that there might be a reduction in the rightward extent of the perceptual span due to attentional conflict, and due to increased foveal processing difficulty for scrolling text (Henderson & Ferreira, 1990; Jacobs, 1986; Rayner, 1998; White et al., 2005), we predicted that saccade amplitudes would be reduced for scrolling compared to static text. We also predicted that regressive saccades would be shorter in amplitude for scrolling text given the reduced opportunity for larger saccades and the increased difficulty in maintaining an accurate memory representation of the spatial layout of the scrolling text (Kennedy, 1982; Kerzel & Ziegler, 2005; Murray & Kennedy, 1988). We also examined launch and landing site distributions for scrolling text. In consideration of findings from non-reading studies indicating that spatiotemporal saccade dynamics are similar when made between periods of fixation or pursuit (Kaminiarz et al., 2009), and that making saccades to moving targets can be achieved with comparable accuracy as for static targets (Beers, 2001; Blohm et al., 2005; Havermann et al., 2012; Ohtsuka, 1994; Schlag, 1990; Schütz & Souto, 2011), we expected the impact on launch and landing site distributions to be minimal (cf. Valsecchi et al., 2013) when participants were reading scrolling as opposed to static text.

The results of the global analyses are reported prior to the local analyses for each of Experiments 1 and 2 conducted to determine the effects of the scrolling text format on linguistic processing.

Experiment 1: Word Frequency and Word Length Effects in Scrolling Text

Next, let us consider predictions for the target words in our sentences. In reading of static text, shorter words have been found to elicit reduced fixation durations and increased skipping probability (i.e. increased likelihood of not being fixated at all) than longer words (Rayner & McConkie, 1975). Likewise, the frequency of the word impacts on fixation durations, with low frequency short words being less likely to be skipped and eliciting longer reading times than high frequency words of comparable length (Rayner & Raney, 1996). Also, Pollatsek et al. (2008), found interactive effects of frequency and length such that the frequency effect was greater for long than short words. They also found reduced probability of skipping a long than a short word. We expected to replicate these effects in static text reading conditions. Furthermore, neither the changes to the oculomotor approach to reading predicted for scrolling text, nor the identified additional challenges to the reading process associated with this format (notably restricted sustained availability of the text and changes to attentional deployment) should unduly affect lexical processing. This is because, assuming that pursuit movements effectively act as fixations, stabilising the retinal image of words as they scroll across the screen, the reader's access to an orthographic representation of a fixated word should be maintained. The interactive word length and word frequency effects are therefore expected to occur similarly to as with static text during pursuit movements when reading scrolling text.

Method

Participants. Participants for Experiment 1 were 83 students from Royal Holloway, University of London (mean age 20.4 years, SD = 2.0, 69 female). All participants had self-reported normal or corrected-to-normal vision and spoke English as their first language. All gave informed consent prior to taking part in the study approved by the departmental ethical review committee.

Stimuli and Apparatus. Stimuli for Experiment 1 were the 48 sentences used by Pollatsek et al., (2008). Overall, the sentences used had on average 10.7 words (SD 1.6) and 63.9 characters (SD 8.3). Each sentence frame provided a context within which target words could be embedded to allow for an orthogonal manipulation of word length and frequency. High frequency words had a mean frequency of 197 occurrences per million, compared to 5 per million for low frequency words (Kucera & Francis, 1982; This difference was significant $t(46) = 5.17$, $p < 0.001$). Long words were 7-9 characters long (mean 7.8) and short words were 3-4 characters long (mean 3.8) characters. This difference was again significant $t(46) = -21.06$, $p < 0.001$). Each participant read one version of the sentence *The judge summoned the* [*thin/rude/popular/fabulous*] *solicitor to the bench.* In total there were 48 sentences with a quarter of the items appearing in each of the four conditions, and each item appeared in a different condition across lists. No participant was presented with the same sentence frame twice. The 48 sentences were also presented either as scrolling text or static text (24 sentences in each condition).

All sentences were displayed in black Courier font (12pt; horizontal character width 11 pixels, 0.4°) with a white background on a 1024 x 786 pixel (96 DPI) CRT monitor at a refresh rate of 100 Hz. The viewing distance was 70 cm, and we used a table-mounted head and chin rest. Pupil and corneal reflection were recorded from the left eye during sentence reading by an SR Research EyeLink II eye-tracker using a 250 Hz sampling rate (i.e., 1 sample every 4 ms).

Design. Experiment 1 employed a 2 (Display Format: static vs. scrolling) x 2 (Word Frequency: low vs. high) x 2 (Word Length: short vs. long) within-subjects and within-items design. Word length and word frequency were orthogonally manipulated, producing 8 conditions with each of the four combinations of frequency and word length manipulations presented in static and scrolling text, all of which were completed by all participants. The order of the conditions was counterbalanced across participants.

Procedure. Each participant completed 10 static and 10 scrolling text practice trials prior to the experiment. Following these they read two blocks of 29 sentences each (one block each of static and scrolling presentation), with 6 trials for each type of target word manipulation (i.e. 24 experimental trials) plus 5 ‘filler’ trials with no manipulation. Participants were asked to read for comprehension, and simple comprehension questions (forced choice yes/no answer e.g. for the sentence *Opening night was held at a [red/tan/special/gorgeous] theatre in the centre of London*, participants were asked *Was the opening night held in central London?*) were asked on 50% of experimental trials to ensure engagement with the task. A key press was required to end the trial as soon as reading of the sentence was complete.

A 9-point calibration was performed before each block and as required. A drift correction was performed prior to presentation of each sentence, and participants were required to make a stable fixation within a gaze-contingent square of 2.5 characters width (0.8^{o}) prior to the presentation of each sentence. Sentence onsets took less than 0.5 s to trigger on average. Text in the scrolling text condition moved from a starting position in the centre of the screen horizontally across the screen from right to left at a rate of 3 pixels per refresh (established as a comfortable reading speed with 18 pilot participants), equating to around 240 words per minute (approximately 10 ^{o}/s) for the sentences used. This is close to the normal reading rate for static text (around 250 wpm; Rayner, 1998).

Analytic Approach. All analyses were carried out using R 3.0.3 (R Core Team, 2014), with eyeTrackR and ez packages. Scrolling and static text were analysed and processed in an identical fashion, with periods of smooth pursuit in scrolling text treated as fixations. These periods were delineated from saccades using a saccadic velocity criterion of 30^{o}/s. For each measure, fixations were excluded from analysis if they were more than 2.5 standard deviations away from the mean per participant per condition, resulting in between 0.5-4% data loss. As is standard in eye movement experiments investigating reading, fixations shorter than 80 ms and longer than 1200 ms were removed from the analysis. We allocated a region of interest around each word in the sentence, with the space before the first letter of a word included in that word's region of interest.

For scrolling text only, there were some occasions when slippage occurred between the movement of the reader's point of fixation and the movement of the word. Consequently, there were a certain proportion of pursuit fixations (37%) during which a participant's point of fixation moved across the boundary between two words (i.e., from one region of interest into another). To compensate for occasions where this occurred, we adopted the following approach: If the fixation remained on one of the two words for less than 80 ms, then the full duration of the pursuit fixation was allocated to the region in which the longer period of fixation time occurred. Alternatively, if each of the two words was fixated for a period of 80 ms or more, then two independent fixations were registered (one on each word); see Figure 1.

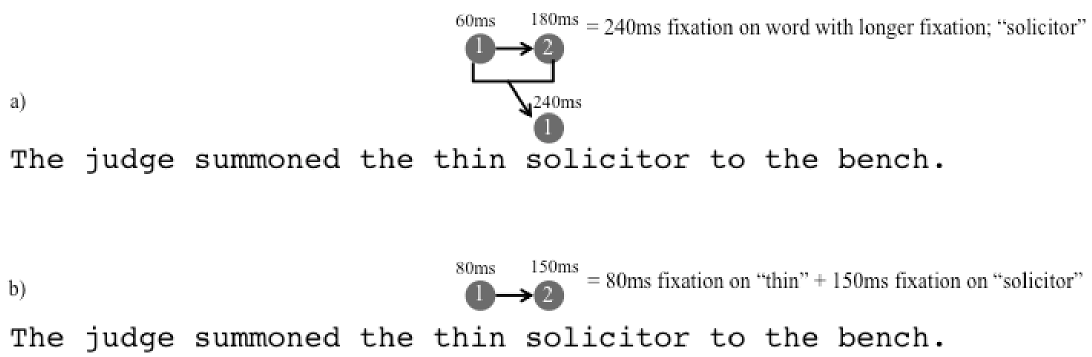


Figure 1. Allocation of split pursuit periods to a single word for scrolling text analysis: during pursuit period spanning two words, if the duration spent on one word was less than 80 ms (a), the duration of these were pooled onto the word where the majority of the pursuit period occurred; however, if more than 80 ms was spent on each word (b), this was recorded as two separate fixations.

Experiment 2: The Effects of Predictability on Static versus Scrolling Text

Experiment 1 investigated lexical processing when reading scrolling or static text. However, word length and word frequency are both intrinsic characteristics of a word: their influence comes about as a consequence of the characteristics of the word itself.

Another important component of successful reading is the ability to incrementally construct an understanding of the discourse as each new constituent of the sentence is encountered. The formation of a representation of the meaning of the sentence is a fundamentally important goal of most sustained reading tasks. Furthermore, the nature of the discourse representation has been demonstrated to affect how a word is processed. Arguably, the most obvious example of such influences is the predictability effect (Clifton et al., 2016; Erlich et al., 1981; Fitzsimmons & Drieghe, 2013; Rayner & Well, 1996), whereby the extent to which a target word is predictable based on preceding sentential context directly influences the ease with which it is processed. Critically, from our perspective, predictability effects arise not exclusively from intrinsic characteristics of the word itself, but instead from a combination of the characteristics of the word itself and those of the words that comprise preceding text. Manipulation of the extent to which a target word may be predicted (prior to being fixated) from previous sentence context provides a measure of the success of sentence-level processing. More predictable words attract shorter fixation durations and a higher probability of being skipped altogether (Erlich et al., 1981; Fitzsimmons & Drieghe, 2013; Rayner et al., 2004; Rayner, Binder, Ashby, & Pollatsek, 2001; Rayner & Well, 1996).

In Experiment 2 we examined predictability effects for scrolling and static text (as in Experiment 1). This second experiment was based on a previous study by Fitzsimmons and Drieghe (2013) that used static text presentation only. As before, we expected to replicate the findings from this study in our static text condition. However, in contrast to our expectations for Experiment 1, we anticipated that predictability effects would be reduced or lost completely when sentences were presented in scrolling text format. We made this prediction on the basis that when readers are prevented from reinspecting text during reading, then reduced levels of comprehension can occur. For example, when text is presented serially word by word (RSVP; Fischler & Bloom, 1980), comprehension can suffer, as it does, to some extent at least, when static text is read and regressive saccades are prevented (Schotter, Tran, et al., 2014). The lack of availability of the text for reinspection (i.e. arising with scrolling text due to its gradual movement through and off of the screen, and potentially from increased difficulty in mapping the position of text to be returned to) may force the reader to engage in a more superficial level of understanding, perhaps causing them to prioritise individual word processing with a reduced level of integration between words. Such effects may be exacerbated by a possible reduction in the cognitive resources available for the maintenance of items in working memory due to the increased attentional load as discussed previously (Kennedy, 1982; Kerzel & Ziegler, 2005).

Method

Participants. Eighty one students from Royal Holloway University of London (mean age 21.2 years, SD = 1.9, 69 female) took part in the experiment. All participants had self-reported normal or corrected-to-normal vision and spoke English as their first language. All gave informed consent prior to taking part in the study, as approved by departmental ethical review.

Stimuli and apparatus. For Experiment 2, sentences from Fitzsimmons and Drieghe (2013) were used. Forty-eight target words were embedded in sentence pairs, with two versions for each condition giving 96 sentence pairs overall with context predictability for the target word being either high (cloze completion ratio of 72%), or neutral (cloze completion 14%). For example, for the target word *finger*, each participant read one version of the sentence pair [*Russell had hurt his hand in the* *door of the car./Russell had to go to the hospital.] He had trapped his* ***finger*** *while playing*. The target word *finger* is clearly more predictable when prefaced by the first than the second sentence. Each participant read 12 target words per condition (high and neutral predictability for static and scrolling text), and these were combined with 26 filler sentences (half static, half scrolling); each participant therefore read 74 sentences in total, 48 of which included the experimental manipulation. Due to the length of the stimuli, the sentences were displayed across two lines in the static text condition (one sentence per line). The experimental sentences (i.e. those with embedded target word) overall contained 11.5 words (SD 2.6) and 53.7 characters (SD 15.2).

All sentences were displayed similarly to Experiment 1 at a viewing distance of 70 cm in black, 12pt Courier font (horizontal character width 11 px, 0.4^{o}) with a white background on a 1024x786 pixel CRT monitor running at 100 Hz. The head was stabilised with a table-mounted head and chin rest, and pupil and corneal reflection were recorded from the left eye by an SR Research EyeLink II eye-tracker sampling once every 4 ms.

Design. The experiment employed a 2 (Display Format: static vs. scrolling) x 2 (Word Predictability: high or neutral) within-subjects design. This gave four conditions (with high and neutral predictability sentences displayed in both static and scrolling format). Each participant saw each sentence in one condition only and an equal number of sentences per condition. The order of factors was counterbalanced across participants.

Procedure. Participants were asked to read 74 sentences (37 each of static and scrolling) for comprehension, which was ensured with a fixed choice (yes/no) comprehension question asked after half of the sentences. Procedure otherwise was the same as Experiment 1.

Global Analyses

Results

Recall that we pooled the eye movement data from Experiments 1 and 2 for the global analyses. This provided 148 participants in total. In these analyses, we computed the following measures: mean fixation duration, mean number of fixations, mean saccade amplitude (forward, regressive and overall), total sentence reading time, the probability of skipping a word on the first pass over the sentence, the probability of making a regression, the probability of refixating a word, and landing and launch sites.

Table 1.

Global reading measures for scrolling and static text, reported for Experiments 1 and 2 separately: Skipping probability, mean fixation duration, mean number of fixations, probability of immediately refixating a word following initial fixation, saccade amplitude (overall, forward and regressive), probability of making a regression, and total sentence reading time. Standard errors are shown in parentheses.

	Display format	Skipping probability (%)	Average fixation duration (ms)	Number of fixations	Refixation probability (%)	Saccade amplitude (chars)			Regression probability (%)	Total reading time (ms)
						Overall	Forward	Regressive		
Exp. 1	Scrolling	18.22 (0.56)	226.88 (3.24)	10.79 (0.34)	31.35 (1.85)	5.08 (0.17)	4.45 (0.17)	6.05 (0.22)	52.19 (0.98)	2449.45 (95.88)
	Static	17.25 (0.70)	216.79 (3.40)	12.07 (0.40)	33.27 (2.01)	7.45 (0.14)	6.78 (0.12)	10.99 (0.47)	20.64 (1.07)	2617.39 (101.95)
Exp. 2	Scrolling	36.40 (0.77)	214.13 (3.39)	14.03 (0.31)	15.43 (1.04)	5.30 (0.19)	4.68 (0.18)	6.33 (0.21)	46.29 (0.98)	2981.54 (81.05)
	Static	34.62 (0.93)	202.76 (3.12)	15.80 (0.42)	22.33 (1.11)	8.53 (0.16)	6.92 (0.15)	14.17 (0.40)	27.94 (0.84)	3206.51 (104.95)

Two-way (Display Type x Experiment) ANOVAs were computed for a series of measures to explore the changes in the global reading pattern employed for reading scrolling text compared to static text (see Table 1). These analyses indicated that readers made 1.53 fewer fixations on average when reading scrolling compared with static text (Display Type: $F(1, 146) = 47.46$, $p < 0.001$, $\eta^2 = 0.05$; Experiment: $F(1, 146) = 54.27$, $p < 0.001$, $\eta^2 = 0.23$; Interaction: $F(1, 146) = 1.22$, $p = 0.27$, $\eta^2 = 0.001$), and the average duration of scrolling text fixations was increased by 11 ms relative to fixations made on static text (Display Type: $F(1, 146) = 39.52$, $p < 0.001$, $\eta^2 = 0.03$; Experiment: $F(1, 146) = 9.54$, $p = 0.002$, $\eta^2 = 0.05$; Interaction $F(1, 146) = 0.14$, $p = 0.71$, $\eta^2 < 0.001$). Relatedly, refixation probability was also reduced when reading scrolling text (Display Type: $F(1, 146) = 15.61$, $p < 0.001$, $\eta^2 = 0.02$; Experiment: $F(1, 146) = 46.90$, $p < 0.001$, $\eta^2 = 0.20$; Interaction: $F(1, 146) = 5.13$, $p = 0.03$, $\eta^2 = 0.01$), with 4.3% lower probability of immediately refixating a word once it had been fixated with this display format compared to static text. This is likely one factor contributing to the increased average fixation duration seen for scrolling text.

Mean saccade length was reduced by 2.80 characters (Display Type: $F(1, 146) = 655.25$, $p < 0.001$, $\eta^2 = 0.50$; Experiment: $F(1, 146) = 10.23$, $p = 0.002$, $\eta^2 = 0.05$; Interaction: $F(1, 146) = 15.56$, $p < 0.001$, $\eta^2 = 0.02$). The interaction between experiment and display type was accounted for by a significantly longer average saccade length in Experiment 2 with static text only ($p < 0.001$; $p = 0.38$ for scrolling), attributable to saccades made between the two sentences, which were presented over two lines (see Experiment 2: *Methods*). The probability that readers made a regression increased significantly (Display Type: $F(1, 146) = 780.18$, $p < 0.001$, $\eta^2 = 0.70$; Experiment: $F(1, 146) = 0.44$, $p = 0.51$, $\eta^2 = 0.002$; Interaction: $F(1, 146) = 53.79$, $p < 0.001$, $\eta^2 = 0.14$) when they read scrolling compared with static text.

The interaction between experiment and display type reflects a higher regression rate in Experiment 2 than Experiment 1 with static text (20.6% Exp 1, 27.9% Exp 2; explained by the longer stimuli length in Experiment 2), but a lower rate with scrolling text (52.2% Exp 1, 46.3% Exp 2).

In order to further investigate whether the increase in regression probability may result in part from the adoption of a nystagmus-like oculomotor pattern, we investigated the breakdown of saccade direction patterns (i.e. the proportion of saccades where a progressive saccade was followed by another progressive saccade, a progressive saccade was followed by a regressive saccade, a regressive saccade was followed by another regressive saccade, or a regressive saccade was followed by a progressive saccade). This showed significant effects of saccade direction pattern $F(3, 348) = 664.69$, $p < 0.001$, $\eta^2 = 0.71$, of display type $F(1, 146) = 25.80$, $p < 0.001$, $\eta^2 = 0.02$ and of experiment $F(1, 146) = 54.03$, $p < 0.001$, $\eta^2 = 0.03$. There was no interaction of display type and experiment, indicating that the pattern of effects was similar across both experiments $F(1, 146) = 0.93$, $p = 0.34$, $\eta^2 < 0.001$. Most importantly, there was an interaction of display type and saccade direction pattern $F(3, 438) = 396.49$, $p < 0.001$, $\eta^2 = 0.49$, with t-tests showing that there were significantly more instances of two successive progressive saccades with static than scrolling text (59.4% vs. 35.7%; $t(147) = -16.51$, $p < 0.001$, $d = 1.36$), and correspondingly significantly fewer instances of every other combination of saccade direction combinations with static than scrolling text (all $p < 0.001$, $d > 1$).

We also broke down the overall saccade data to examine progressive and regressive saccades separately. Regressions were 6.36 characters shorter for scrolling than for static text (Display Type: $F(1, 146) = 310.25$, $p < 0.001$, $\eta^2 = 0.53$; Experiment: $F(1, 146) = 26.78$, $p < 0.001$, $\eta^2 = 0.08$; Interaction: $F(1, 146) = 16.12$, p

< 0.001, $\eta^2 = 0.06$); as for overall saccade length, the effect of experiment and interaction is attributable to saccades made in static text between the two sentences in Experiment 2 (static text $p < 0.001$, scrolling text $p = 0.24$). Consistent with our predictions, longer-range saccades were less common in the scrolling text format (see Figure 2), probably due to the fact that often text that would have been targeted with a regression would not be available to re-read since it would have already disappeared beyond the left edge of the screen. Note, though, that progressive saccades were also significantly shorter in scrolling text (Display Type: $F(1, 146) = 447.17$, $p < 0.001$, $\eta^2 = 0.42$; Experiment: $F(1, 146) = 0.94$, $p = 0.33$, $\eta^2 = 0.005$; Interaction $F(1, 146) = 0.19$, $p = 0.67$, $\eta^2 < 0.001$), although this difference was quite small (2.29 characters difference). This is likely reflective of a reduced word identification span for scrolling text as hypothesised.

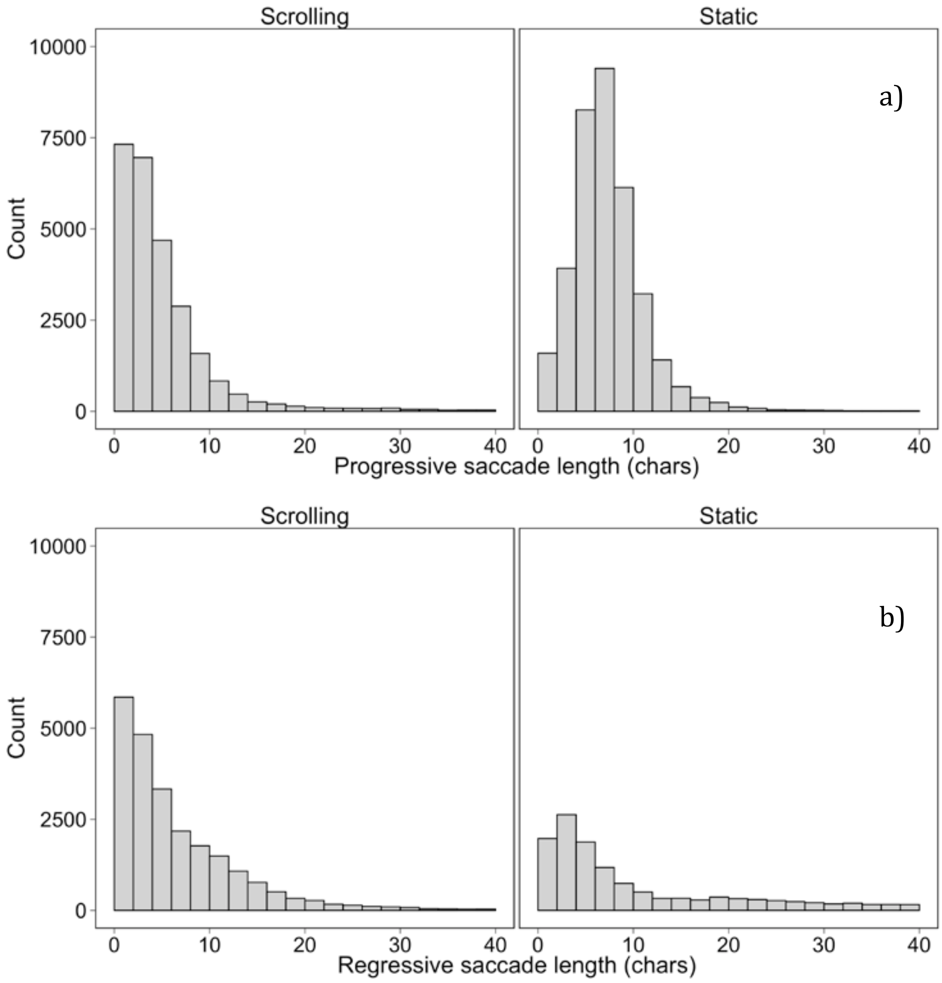
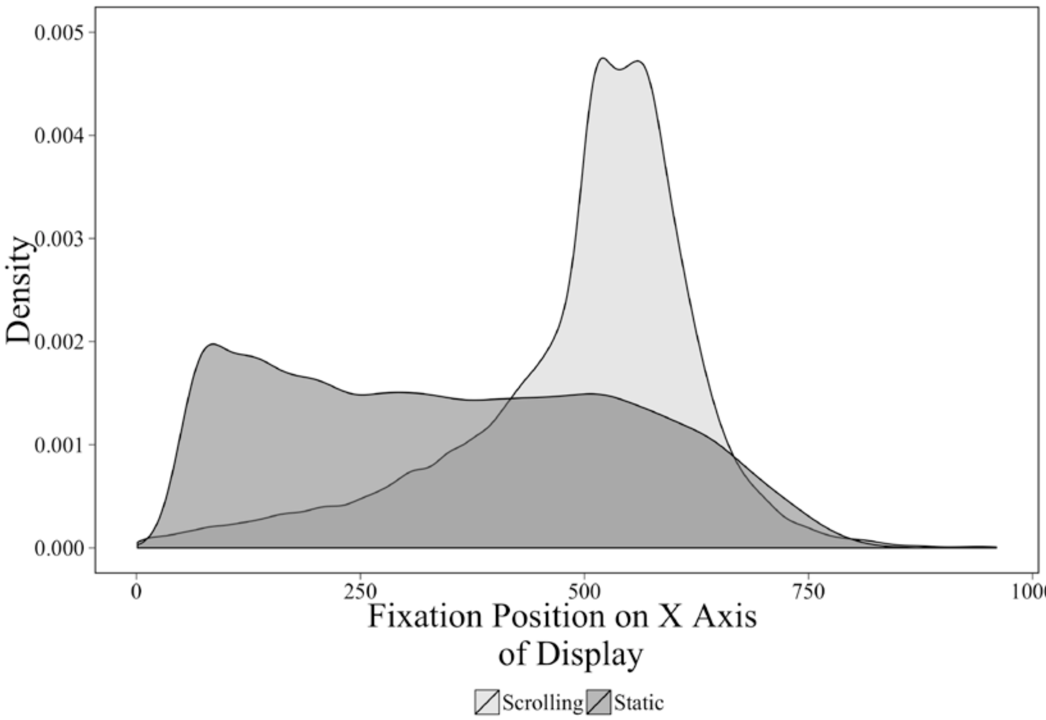


Figure 2. Frequency histograms of progressive (a) and regressive (b) saccade lengths for scrolling and static text.

Contrary to our predictions, skipping rates were significantly higher with scrolling text (by 1.36%; Display Type: $F(1, 146) = 12.48$, $p < 0.001$, $\eta^2 = 0.01$; Experiment $F(1, 146) = 325.36$, $p < 0.001$, $\eta^2 = 0.66$; Interaction: $F(1, 146) = 1.12$, $p = 0.29$, $\eta^2 < 0.001$). This finding was unexpected, and we consider possible reasons for this in the Discussion (the effect of experiment reflects higher skipping rates in Experiment 2, $p < 0.001$, possibly attributable to shorter average word length in this study). Furthermore, a lower percentage of skipped words were later returned to for direct fixation in scrolling than in static text (Display Type: $F(1, 146) = 55.65$, $p < 0.001$, $\eta^2 = 0.15$; Experiment: $F(1, 146) = 8.16$, $p = 0.005$, $\eta^2 = 0.03$; Interaction: $F(1, 146) = 12.98$, $p < 0.001$, $\eta^2 = 0.04$; 6.3% of skipped words later fixated with static text compared to 1.1% for scrolling text). Again, this is perhaps unsurprising given the reduced availability of the scrolled text for regressions, and suggests that once a word has been skipped in this display format it is unlikely to undergo further processing. The effect of experiment and interaction of the two factors was due to a significantly higher rate of regression to skipped words for static text in Experiment 1 compared to Experiment 2 ($p = 0.001$; for scrolling text $p = 0.20$).

Total sentence reading time was on average 197 ms shorter, not longer as predicted, for scrolling compared to static text sentences (Display Type: $F(1, 146) = 10.00$, $p = 0.002$, $\eta^2 = 0.01$; Experiment: $F(1, 146) = 21.19$, $p < 0.001$, $\eta^2 = 0.10$; Interaction: $F(1, 146) = 0.21$, $p = 0.65$, $\eta^2 < 0.001$). Although this effect differs from some of the previous research examining scrolling text reading, it may be explained by the faster scrolling rate used in this study (for example the average scrolling rate used by Buettner et al. (1985), who reported longer total reading durations with scrolling text, was around 148 wpm, compared to around 240 wpm here; total reading time was not reported by Valsecchi et al. (2013)). For scrolling text, the average proportion of the stimuli left on the screen when the trial was terminated was 61.3% (SE 0.45). There was no significant difference in this proportion between experiments (p = 0.42; Experiment 1: 63.2%, Experiment 2: 59.7%). Average horizontal position of the eye on the screen was also significantly different for the different display formats (Display Type: $F(1, 146) = 1292.17$, $p < 0.001$, $\eta^2 = 0.80$; Experiment: $F(1, 146) = 2.09$, $p = 0.15$, $\eta^2 = 0.01$; Interaction: $F(1, 146) = 91.85$, $p < 0.001$, $\eta^2 = 0.23$), with a sharp peak slightly to the right of the centre of the screen in scrolling text reading compared to a relatively flat distribution of eye position across the full extent of the screen in static text reading (as required to read along the extent of static sentences; see Figure 3). This indicates that the speed of the text movement was quite comfortable for participants, as they were neither chasing the text off to the leftmost aspect of the screen, nor waiting for the text to appear from the right. The interaction of display type with experiment is explained by the disparate effects of different stimuli length in the two studies, with slightly shorter sentence lengths of two sentences displayed on different lines in Experiment 2 (compared to one slightly longer sentence in Experiment 1) resulting in a more leftward average position than in Experiment 1 for static text (279.6 pixels Exp 2 compared to 347.5 pixels Exp 1), whilst for scrolling text the two sentences displayed along one line in Experiment 2 resulted in text appearing from the right edge of the screen for longer than in Experiment 1 (thus entraining the eye towards this side of the screen for longer; average position in Exp 2 558.7 pixels compared to 509.7 pixels in Exp 1).



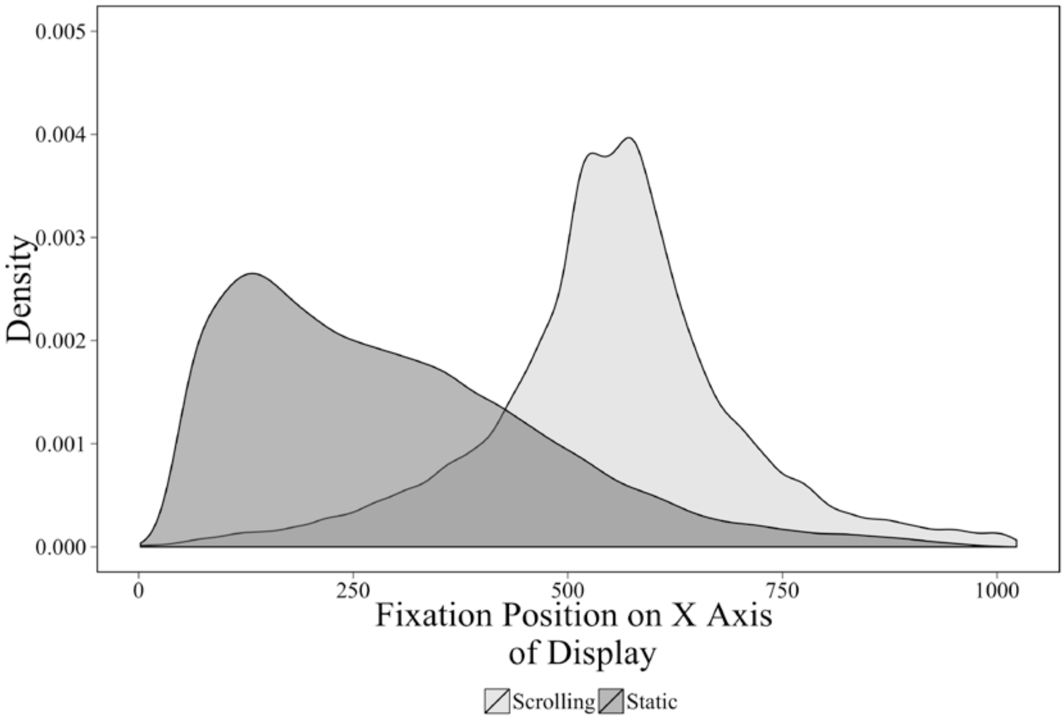


Figure 3. Density distribution of fixation positions in the x-axis of the display screen during reading for scrolling and static text in Experiment 1 (top pane) and Experiment 2 (bottom pane). The leftward skew in Experiment 2 for static text is due to short sentence lengths for one of the sentences in some of the sentence pairs (e.g. the first

sentence of the item *We had a terrible weekend. It turned out there was ice on the road.).*

In order to assess the degree of slippage between the text and the movement of the readers' point of fixation during pursuit periods, the velocity gradient of eye position for scrolling text was compared to the gradient of text velocity (-0.3 pixels/ms). The average slope for eye velocity was found to be -0.22 pixels/ms (SE 0.004), indicating that, on average, the eye moved slightly but significantly slower than the text during pursuit fixations (see Figure 4; Eye/Text: $F(1, 146) = 493.85$, $p < 0.001$, $\eta^2 = 0.63$; Experiment: $F(1, 146) = 10.76$, $p = 0.001$, $\eta^2 = 0.04$; Interaction: $F(1, 146) = 10.76$, $p = 0.001$, $\eta^2 = 0.04$). The effect of and interaction with experiment was due to a slightly smaller disparity between average eye pursuit speed and text speed in Experiment 2 (-0.21 for Experiment 1 compared to -0.23 for Experiment 2; this could be due to the longer stimuli lengths in Experiment 2 (i.e. with two sentences presented in Experiment 2 cf. just one sentence in Experiment 1), allowing more time for the participants to adapt to the text speed). This disparity resulted in a significant difference between the distance (in characters) the eyes travelled during a fixation period for scrolling and static text (Display Type: $F(1, 146) = 373.35$, $p < 0.001$, $\eta^2 = 0.37$; Experiment: $F(1, 146) = 6.47$, $p = 0.01$, $\eta^2 = 0.03$; Interaction: $F(1, 146) = 0.34$, $p = 0.56$, $\eta^2 < 0.001$), with 0.9 (SE 0.03) characters travelled during a pursuit period in scrolling text reading compared to 0.4 (SE 0.02) characters in static text reading.

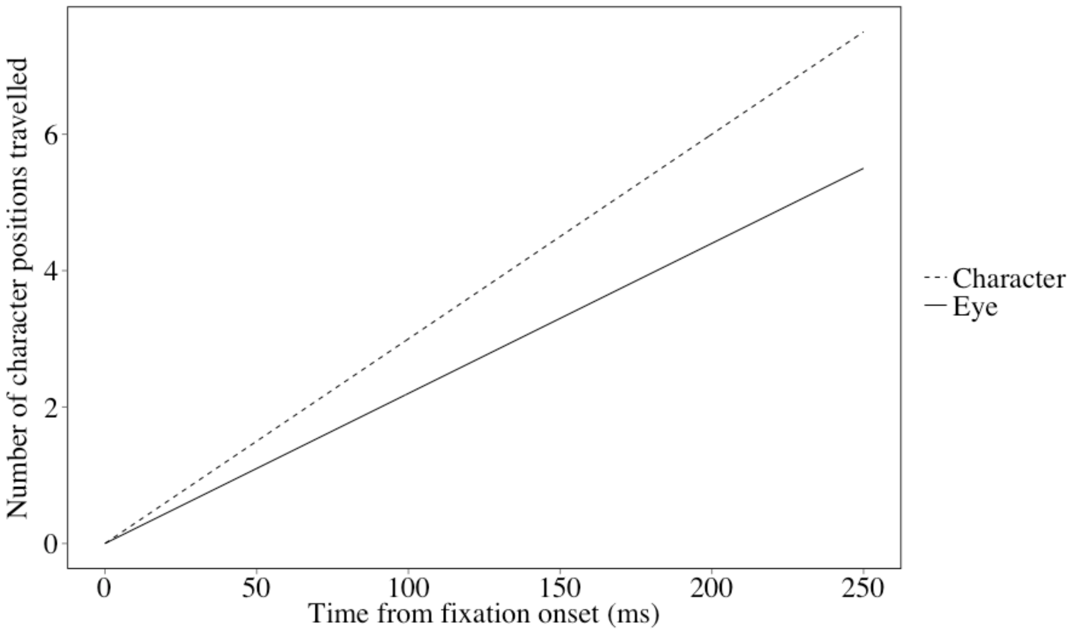


Figure 4. Comparison of the average number of character positions moved by an initially foveated scrolling character (dashed line) and the eye during pursuit fixation phases (full line) during an example pursuit fixation of 250 ms. Text velocity was constant at 0.3 pixels/ms. This comparison demonstrates that, on average, the text was moving quicker than the eye in pursuit, resulting in slippage by the eye off of the initially foveated character and along the rightward extent of the text.

Finally, in order to investigate whether saccadic targeting was affected by the scrolling text format, the landing position distributions on words for static and scrolling text were also analysed. To do this, we compared mean landing positions over all words in the experimental sentence for Experiments 1 and 2, for static and scrolling text. In consideration of the large proportion of regressive saccades made with scrolling text, we restricted this analysis to progressive saccades. There was a significant difference in mean landing position between the two text display types $F(1, 146) = 70.04$, $p < 0.001$, $\eta^2 = 0.15$, with a mean landing position difference of 0.31 characters for static and scrolling text (scrolling mean 3.16 SE 0.04, static mean 2.84 SE 0.03). There was also an effect of experiment ($F(1, 146) = 40.73$, p < 0.001,

$\eta^2 = 0.15$), and an interaction of this factor with display type ($F(1, 146) = 12.63$, $p < 0.001$, $\eta^2 = 0.03$). This is due to a larger difference between average landing positions in Experiment 1 (0.45 characters further through the word with scrolling text) than in Experiment 2 (0.18 characters further through the word with scrolling text). However, crucially, in both experiments this difference in landing position is significant. As in Valsecchi et al. (2013), we also compared average dispersion of landing sites (standard deviation) across the two display formats. This showed a significant difference in mean dispersion $F(1, 146) = 53.84$, $p < 0.001$, $\eta^2 = 0.12$, corroborating the finding of Valsecchi et al. that the distribution of landing sites is slightly flatter for scrolling text, with a 0.19 higher mean standard deviation for this format (scrolling mean 1.77 SE 0.03, static mean 1.57 SE 0.02; see Figure 5). This was modulated by experiment $F(1, 146) = 12.94$, $p < 0.001$, $\eta^2 = 0.03$, with a significant difference in the standard deviation of landing positions in scrolling but not static text between the two experiments.

We also investigated the effect of display format on launch site (see Fig. 6). Display format had a significant effect on launch site $F(1, 146) = 10.43$, $p = 0.002$, $\eta^2 = 0.03$, with saccades launched from 0.11 characters closer in scrolling text than static text (scrolling mean 3.38 SE 0.03, static mean 3.27 SE 0.03). Unlike for landing sites, there was however no significant difference in the dispersion of the launch sites ($F(1, 146) = 1.60$, $p = 0.21$, $\eta^2 = 0.01$), suggesting that this was a consistent strategic change in reading behaviour. This shift is likely due to the slippage in fixation position through the word and reduced saccade length for scrolling text.

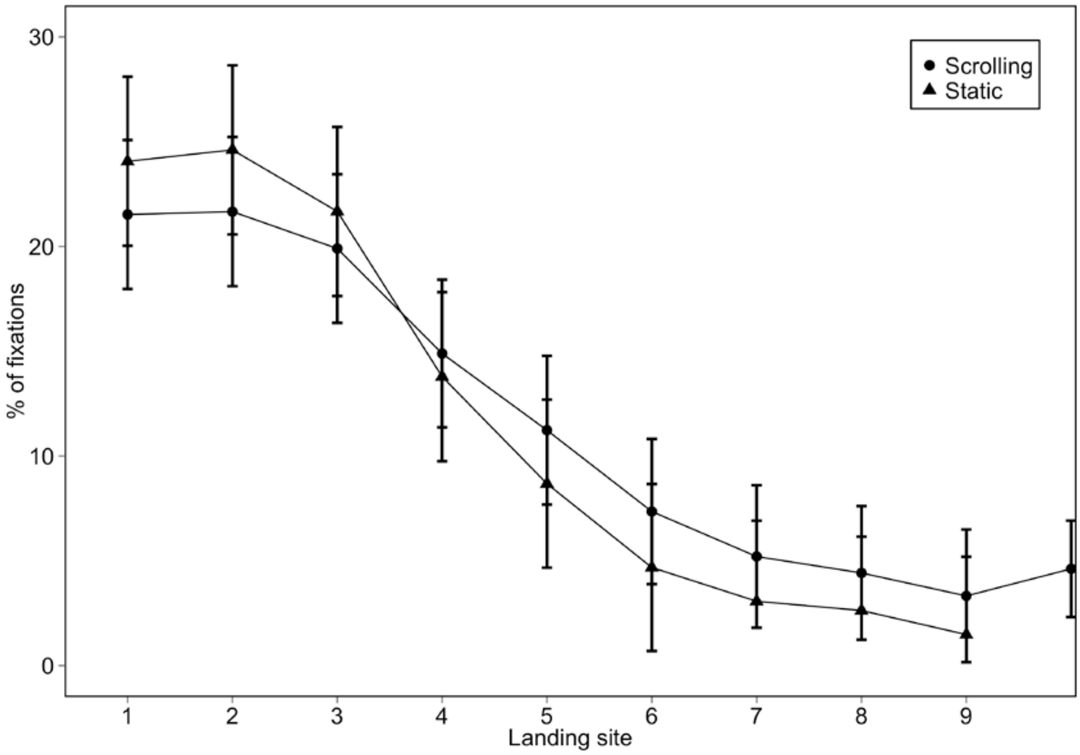


Figure 5. Landing position distributions under static and scrolling text conditions.

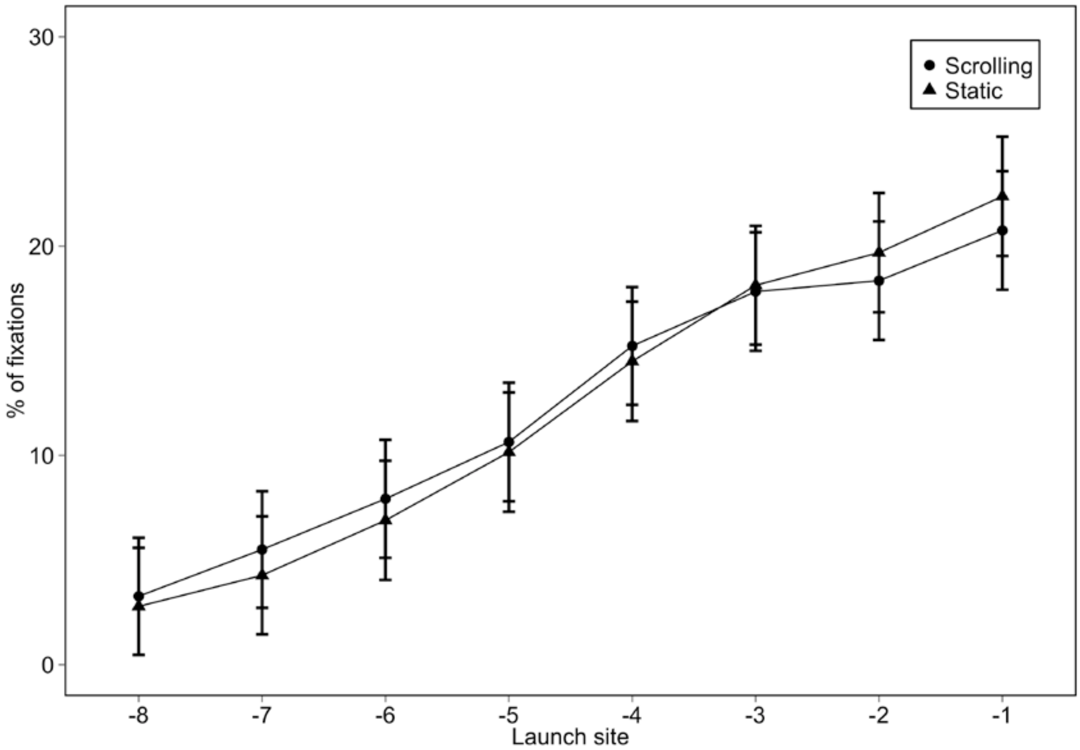


Figure 6. Launch site distributions under static and scrolling text conditions.

Discussion

Before moving into the analysis of local linguistic manipulation effects, we analysed the global oculomotor reading pattern for scrolling and static text (pooling data across both Experiment 1 and Experiment 2, presented subsequently, in order to maximise statistical power for these comparisons). These measures included: fixation duration and count, saccade amplitude, skipping, refixation, and regression probabilities, landing and launch sites, and total reading time.

In line with previous findings (Buettner et al., 1985; Valsecchi et al., 2013), global analyses of the reading pattern showed that reading of scrolling text elicited a switch from fixations to periods of smooth pursuit and that these periods were longer than fixation durations recorded during reading of static text. It is assumed that using a pursuit movement to track each word allows the reader to maintain a stable image of the word on the retina whilst identification takes place, and to retain their position within the sentence to progress from that point once processing of any given word is sufficient. The increase in average fixation duration was complemented by a reduction in fixation count, with reduced number of fixations employed in reading of scrolling text. The average saccade amplitude was also reduced for reading scrolling text. Together with the finding that over half of consecutive saccades analysed were targeted in opposite directions with scrolling text (i.e. a progressive saccade followed by a regressive saccade or vice versa; cf. static text approximately two thirds of saccade pairs consisted of two consecutive progressive saccades), these results are suggestive of the adoption of an OKN-like oculomotor pattern for reading scrolling text. The large number of small saccades with scrolling text can therefore be explained as small corrective or ‘catch-up’ saccades, typically associated with this oculomotor pattern (de Brouwer, Missal, Barnes, & Lefevre, 2002; de Brouwer, Yuksel, Blohm, Missal, & Lefevre, 2002; Harrison, 2014; Krauzlis, Basso, & Wurtz, 2000). However, results from low-level visual tasks comparing visually-guided saccades to the comparable fast phase of look-OKN (which is similar to the oculomotor pattern observed for reading scrolling text) have indicated no differences in peak velocity or duration between these two phenomena (Kaminiarz et al., 2009), suggesting that the change in saccade amplitude can be attributed specifically to the additional difficulty of processing text whilst it is moving (as opposed to being a generalised oculomotor effect in pursuing any scrolling stimulus in this way).

To investigate the reduction in saccade length further, forward and regressive saccade amplitudes were compared separately. This indicated that saccades made in both directions were shorter than the comparable movements seen in static text reading. However, the margin of this difference was greater for regressive saccades than forward saccades, which may be accounted for by the reduced availability of scrolling text, making long-range regressive saccades impossible (c.f., Schotter, Tran, & Rayner, 2014). Furthermore, we hypothesised that regressions require maintenance of some kind of positional representation of words in a memory buffer (similar to the Spatial Coding Hypothesis; e.g. Murray & Kennedy, 1988). This coding of position would clearly be more complicated when reading scrolling text, as an additional computation would have to be included in the storage buffer to continuously update the position of each unit according to the movement of the text.

In the context of this reduced regression length, the increased regression probability also observed is likely attributable to a change in regression function, with very short regressive saccades largely being made to correct for errors in landing position or to compensate for oculomotor tracking lag (with average eye velocity seen to be slower than text velocity). This lag may also help explain the reduction in forward saccade amplitude, with some movement through the word (on average around one character) occurring during the fixation period due to the velocity difference. To reach the same point in the upcoming words from the start of one fixation period to the next fixation, the saccade would necessarily be shorter for scrolling than for static text as part of the distance may already have been covered during the corresponding pursuit period. This lag however does not account for the total reduction in saccade length seen with scrolling text (of around 2.3 characters); another possible factor in explaining this reduction could be a reduced parafoveal preview due to fewer attentional resources being available for deployment to the right of fixation. Such a reduction could arise as attention must be deployed both to the left of the point of fixation in order to track the movement of each word effectively, and to the right in order to target each successive progressive saccade through the text. However, this explanation is complicated by the unexpected finding of increased skipping rates with the scrolling text format: skipping a word is usually assumed to indicate that all of the processing necessary to identify that word has occurred whilst fixating a previous word: therefore, the skipped word is presumed to be available within the parafoveal preview area (Drieghe et al., 2005). Increased skipping, then, might be taken as an indication of improved availability of upcoming information in the parafoveal area, rather than reduced availability as would be predicted (and to some extent supported, by the reduced progressive saccade amplitude). However, this seems unlikely given the increased complexity associated with attentional deployment during scrolling text reading. Consequently, an alternative explanation is required.

One possible explanation might be that there is difficulty with accurate saccadic targeting in scrolling text reading, and this may lead to higher levels of ‘accidental’ word skipping (i.e. skipping as a result of motor error; Reichle &

Drieghe, 2013). As noted earlier, a previous study of reading horizontally scrolling text has suggested that saccadic targeting accuracy is reduced for this format (Valsecchi et al., 2013). We found similarly that landing and launch sites were both modified to some degree by display format with a launch position slightly closer to the targeted word and landing position slightly further through a word, but these effects were quite small, and there was no increase in dispersion of launch sites and an increase of just 0.19 in the standard deviation of the landing site distribution. In view of the higher skipping rates seen with scrolling text, we may have in fact expected a leftward shift in landing positions with this format (cf. Krügel & Engbert, 2010), rather than the slight rightward shift that was actually recorded. This is not what we predicted given the findings of preserved saccadic targeting in non-text dynamic following tasks (Beers, 2001; Blohm et al., 2005; Havermann et al., 2012; Kaminiarz et al., 2009; Ohtsuka, 1994; Schlag, 1990; Schütz & Souto, 2011b), and suggests that the oculomotor system cannot completely compensate for the movement of text in this display format. This may be explained by the higher cognitive complexity of the reading situation compared to simpler dynamic following tasks. Nonetheless, the small margin of effects (less than half a character) would indicate that high levels of accidental skipping is very unlikely; particularly when combined with findings that refixation probability and the percentage of skipped words that are later regressed to for direct fixation are reduced with scrolling compared to static text.

We posit that a more likely explanation for the increased skipping rate is that it occurs as part of a riskier reading strategy (O'Regan, 1990; O'Regan & Jacobs, 1992), similar to (although clearly distinct from) that adopted by older readers of English (Rayner, Reichle, Stroud, Williams, & Pollatsek, 2006; Risse & Kliegl, 2011). As we believe is the case for reading scrolling text, older readers are suggested to adopt a risky reading strategy (including higher levels of word skipping) in response to a reduced, rather than increased, capacity for parafoveal processing. We suggest, therefore, that in order to maintain a swift reading speed comparable to that for static text (indeed, actually very slightly faster, as the total sentence reading times for the global measures show), readers employ a riskier reading strategy for scrolling text, skipping words more frequently in order to make efficient progress through the sentence in order that they reach the end before it exits the screen to the left. This is supported by the termination status of the stimulus: in both experiments, on average trials were terminated when a little over half of the sentence remained on the screen. This means that participants were successfully making progress through the sentence to finish reading before the text became unavailable, but were left unable to make long-range regressions back to the first portion of the text to re-examine it. It should be acknowledged here that we would of course assume that the oculomotor strategy may be altered to some extent if the rate of presentation of the text was made considerably faster or slower. However, for this study we have chosen a speed that is comparable to the average reading speed for static text (with less than 200 ms difference in the total reading time between the two formats across Experiments 1 and 2). Furthermore, analysis of the data to compare participants who read scrolling text faster to those who read both formats at around the same rate indicated very little difference in the oculomotor strategy of these groups, with only a faster scrolling sentence reading time and decreased fixation count for the former group.

Local Analyses: Experiment 1, Word Length and Frequency Effects.

Results.

To investigate the effects of word length and word frequency in scrolling compared to static text, standard eye movement measures for reading were compared for the target (manipulated) adjective. These were: first fixation duration, single fixation duration, gaze duration, go-past time, total time, skipping probability, and total number of fixations. First fixation duration was defined as the duration of the first fixation on a word. Single fixation duration was the duration of the fixation when readers made only one fixation on the word during the first pass. Gaze duration was defined as the sum of all fixations from the first fixation on the target word until a saccade to another word in the sentence. Go past time was defined as the sum of all fixations from the first fixation in a word until a fixation was made to the right of that word. Skipping probability was the likelihood that a word would be skipped during first pass. The number of first pass fixations is the number of fixations made during first pass reading of the target, and the total number of fixations is the number of fixations made during total reading time for the word. Finally, the total time for the target was defined as the sum of all fixations on the word. Each measure was analysed with repeated measures three-way ANOVAs (2x2x2 for display format, word length, and word frequency), with F_1 (for results across participants) and F_2 (for results across items) measures generated.

One participant was excluded from the analyses due to poor comprehension scores (less than 75% correct on both display formats), and 7 more excluded due to poor data quality, leaving 75 participants. Following the removal of these participants, mean comprehension scores were 88.8% (SD 12.0) for scrolling text and 91.8% (SD 8.3) for static text. A Wilcoxon signed ranks test showed no significant difference in comprehension levels between the two display formats (p = 0.187). A further 5.4% of trials were excluded due to poor calibration and participant error.

Table 2.

Local reading measures for the target word: skipping probability (%), first and single fixation duration, gaze duration (ms), go-past time, and total time. Standard errors are shown in parentheses.

Word length	Word frequency	Display format	Skipping probability (%)	First fixation duration (ms)	Single fixation duration (ms)	Gaze duration (ms)	Go-past time (ms)	Total time (ms)
Long	High	Scrolling	7.37 (1.56)	227.02 (5.45)	237.93 (7.98)	261.58 (6.80)	281.40 (8.91)	291.44 (9.16)
		Static	6.40 (1.43)	219.60 (4.54)	222.72 (5.73)	264.94 (8.17)	317.36 (21.07)	329.11 (16.27)
	Low	Scrolling	7.76 (1.76)	243.25 (5.91)	257.76 (10.22)	296.58 (9.66)	344.18 (14.85)	339.97 (11.83)
		Static	4.91 (1.22)	236.17 (7.21)	249.78 (10.71)	297.83 (11.39)	355.97 (19.52)	389.83 (16.94)
Short	High	Scrolling	38.60 (2.77)	221.77 (6.70)	215.10 (8.92)	240.77 (8.21)	268.05 (12.09)	253.07 (7.61)
		Static	34.91 (2.61)	221.58 (6.55)	214.26 (9.13)	233.00 (7.30)	287.36 (15.30)	275.37 (11.62)
	Low	Scrolling	35.69 (2.70)	225.15 (6.42)	231.45 (12.24)	236.60 (7.38)	261.40 (10.71)	249.83 (6.93)
		Static	30.02 (2.46)	224.36 (5.70)	238.48 (10.07)	234.98 (6.61)	282.97 (15.41)	281.49 (11.73)

Three-way within-subjects and within-items ANOVAs (2 x 2 x 2 for Word Length, Word Frequency, and Display Format) were carried out for a series of eye movement measures as follows (see Table 2 for means).

A standard effect of word length was found for word skipping, with short words being 28% more likely to be skipped than longer words ($F_1(1, 74) = 283.32$, $p < 0.001$, $\eta^2 = 0.37$, $F_2(1, 47) = 307.64$, $p < 0.001$, $\eta^2 =0.51$). There was no reliable effect of word frequency for word skipping ($F_1(1, 74) = 3.43$, $p = 0.07$, $\eta^2 = 0.004$, $F_2(1,47) = 2.21$, $p = 0.14$, $\eta^2 =0.004$), although there was a numerical trend towards more word skipping for higher than lower frequency words. This pattern of results replicated that obtained by Pollatsek et al. (2008). In relation to display format we found that, contrary to our prediction, target words were skipped 3% more frequently when reading scrolling than static text ($F_1(1, 74) = 2.40$, $p = 0.03$, $\eta^2 = 0.01$, $F_2(1, 47) = 5.17$, $p = 0.03$, $\eta^2 =0.02$). This effect did not interact with word length ($F_1(1, 74) = 1.24$, $p = 0.27$, $\eta^2 = 0.001$, $F_2(1, 74) = 1.24$, $p = 0.21$, $\eta^2 = 0.003$), nor word frequency ($F_1(1, 74) = 0.50$, $p = 0.48$, $\eta^2 = 0.001$, $F_2(1, 47) = 0.98$, $p = 0.33$, $\eta^2 =0.002$), suggesting that it was a generalised effect relating to an overall change in oculomotor behaviour, rather than indicating increased difficulty in word processing (as supported by our analyses of global oculomotor behaviour,).

Early fixation duration measures (single fixation duration *SFD*, first fixation duration *FFD*, and gaze duration *GD*) all mirrored previous results, finding the same pattern in scrolling text as established by Pollatsek et al. for static text. Long words took significantly longer to be processed than short words (SFD: 17 ms longer ($F_1(1, 27) = 14.96$, $p < 0.001$, $\eta^2 = 0.03$, $F_2(1, 46) = 13.69$, $p = 0.001$, $\eta^2 = 0.04$; FFD: 8 ms longer ($F_1(1, 56) = 6.36$, $p = 0.01$, $\eta^2 = 0.01$, $F_2(1, 47) = 10.86$, $p = 0.002$, $\eta^2 = 0.03$); GD: 44 ms longer ($F_1(1, 63) = 84.58$, $p < 0.001$, $\eta^2 = 0.10$, $F_2(1, 47) = 60.98$, $p < 0.001$, $\eta^2 = 0.20$)). Low frequency words elicited significantly longer durations than high frequency words (SFD: 22ms longer ($F_1(1, 27) =$

14.68, $p < 0.001$, $\eta^2 = 0.05$, $F_2(1, 46) = 3.09$, $p = 0.09$, $\eta^2 = 0.01$); FFD: 10 ms longer ($F_1(1, 56) = 10.25$, $p = 0.002$, $\eta^2 = 0.01$, F_2 $(1, 47) = 6.91$, $p = 0.01$, $\eta^2 = 0.02$); GD: 16 ms longer ($F_1(1, 63) = 14.73$, $p < 0.001$, $\eta^2 = 0.02$, $F_2(1, 47) = 12.21$, $p < 0.001$, $\eta^2 =0.04$)). For all but single fixation duration, the factors of word length and word frequency interacted, with t-tests indicating that the frequency effect was significant for long but not short words (FFD: $F_1(1, 56) = 4.18$, $p < 0.05$, $\eta^2 = 0.01$, $F_2(1, 47) = 4.04$, $p = 0.05$, $\eta^2 = 0.01$; GD: $F_1(1, 63) = 16.98$, $p < 0.001$, $\eta^2 = 0.02$, $F_2(1, 47) = 17.65$, $p < 0.001$, $\eta^2 = 0.04$).

Very importantly there was no effect of display format on any of these fixation time measures (SFD: $F_1(1, 27) = 0.47$, $p = 0.47$, $\eta^2 = 0.002$, $F_2(1, 46) = 3.55$, $p = 0.07$, $\eta^2 = 0.009$; FFD: $F_1(1, 56) = 1.40$, $p = 0.24$, $\eta^2 = 0.002$, F_2 $(1, 47) = 1.23$, $p = 0.27$, $\eta^2 =0.003$; GD: $F_1(1, 63) = 0.05$, $p = 0.82$, $\eta^2 < 0.001$, $F_2(1, 47) = 0.10$, $p = 0.75$, $\eta^2 < 0.001$), and no interaction of either word length (SFD: $F_1 = 2.85$, $p = 0.10$, $\eta^2 = 0.005$, $F_2(1, 46) = 0.90$, $p = 0.35$, $\eta^2 = 0.003$; FFD: $\mathrm{F}_1(1, 56) = 1.22$, $p = 0.27$, $\eta^2 = 0.001$, $F_2(1, 47) = 0.49$, $p = 0.49$, $\eta^2 = 0.001$; GD: $F_1(1, 63) = 0.72$, $p = 0.40$, $\eta^2 < 0.001$, $F_2(1, 47) = 0.09$, $p = 0.77$, $\eta^2 < 0.001$) or frequency (SFD $F_1 = 0.70$, $p = 0.41$, $\eta^2 = 0.001$, $F_2(1, 46) = 0.10$, $p = 0.76$, $\eta^2 < 0.001$; FFD $\mathrm{F}(1, 56) = 0.001$, $p = 0.98$, $\eta^2 < 0.001$, $F_2(1, 47) = 0.08$, $p = 0.78$, $\eta^2 < 0.001$; GD $F_1(1, 63) = 0.06$, p 0.80, $\eta^2 < 0.001$, $F_2(1, 47) = 0.07$, $p = 0.79$, $\eta^2 < 0.001$), suggesting that lexical processing was relatively unaffected by horizontal movement of the text during reading. This result is in line with our predictions.

Later fixation duration measures did show some effect of display type. Go-past time showed effects of word length ($F_1(1, 66) = 28.34$, $p < 0.001$, $\eta^2 = 0.02$, $F_2(1, 47) = 23.63$, $p < 0.001$, $\eta^2 = 0.02$), with longer go-past times for longer words, and display format ($F_1(1, 66) = 4.44$, $p = 0.04$, $\eta^2 = 0.08$, $F_2(1, 47) = 122.56$, $p < 0.001$, $\eta^2 = 0.11$), with longer go-past times for static than scrolling text, the same pattern as observed for earlier measures. There was no effect of frequency ($F_1(1, 64) = 3.24$, $p = 0.08$, $\eta^2 = 0.001$, $F_2(1, 47) = 1.27$, $p = 0.27$, $\eta^2 =$

0.001), and no interaction of word length and frequency ($F_1(1, 64) = 4.06$, $p = 0.05$, $\eta^2 = 0.003$, $F_2(1, 47) = 1.25$, $p = 0.27$, $\eta^2 = 0.001$). Go-past times were not reported for the target word by Pollatsek et al. (2011), however other investigations of the word frequency effect have similarly shown no effect on this measure (e.g. Ashby, Rayner, & Clifton, 2005). Finally, the total times produced effects of word length ($F_1(1, 64) = 109.81$, $p < 0.001$, $\eta^2 = 0.14$, $F_2(1, 47) = 66.98$, $p < 0.001$, $\eta^2 = 0.22$) and word frequency ($F_1(1, 64) = 13.23$, $p < 0.001$, $\eta^2 = 0.01$, $F_2(1, 47) = 9.40$, $p = 0.004$, $\eta^2 = 0.03$). These effects were qualified by an interaction between word length and word frequency ($F_1(1, 64) = 12.47$, $p < 0.001$, $\eta^2 = 0.01$, $F_2(1, 47) = 11.73$, $p = 0.001$, $\eta^2 = 0.03$, with the frequency effect being greater for long than short words ($t(64) = -3.46$, $p < 0.001$, $d = 0.43$; for short words $t(64) = -0.14$, $p = 0.888$, $d = 0.02$). This is once again in line with previous findings showing that readers exhibited particular difficulty identifying long low frequency words (as compared with words in the other conditions), likely due to the interaction of increased letter crowding in longer words with the reduced frequency. There was also an effect of display format ($F_1(1, 64) = 18.59$, $p < 0.001$, $\eta^2 = 0.04$, $F_2(1, 47) = 45.63$, $p < 0.001$, $\eta^2 = 0.07$), with longer total times for static compared to scrolling text formats. Both this and the similar finding of increased go-past times with static compared to scrolling text are likely reflective of the reduction of long-range regressive saccades with the latter format, as seen in our analyses of global oculomotor behaviour.

Discussion

Experiment 1 compared word frequency and word length manipulations on oculomotor behaviour when reading static and scrolling text. Both word frequency and word length effects were replicated in static and scrolling text, with increased fixation durations seen for longer words and for lower frequency words, and an increased probability of skipping for shorter words. No effect of display format (static or scrolling text) was found for any first pass fixation duration measure, which, when taken with the replication of the word length and word frequency effects, indicates that processing at the lexical level of word characteristics is preserved despite the movement of the text.

Measuring the effects of word length and word frequency on oculomotor behaviour provides an index of two aspects of lexical processing during reading. Word length effects provide an index of perceptual, and to some extent orthographic processing: that is to say, effects associated with processing the physical extent of the stimulus as determined by its constituent characters. Word frequency effects provide an index of the ease with which a word is uniquely identified within the mental lexicon. Experiment 1 replicated both effects in the static text conditions (as would have been expected), and also revealed similar effects for scrolling text conditions, with no interaction with display format (static or scrolling text) for first pass fixation duration measures (first fixation duration, single fixation duration, or gaze duration). Thus, there was no apparent additional cost associated with processing long and low frequency words when reading scrolling compared to static text. It seems reasonable to conclude that the perceptual and linguistic processes that take place during lexical identification occur with a similar time course under scrolling and static text conditions.

An aspect of the results that might, at first sight, appear somewhat surprising was the lack of an effect of the text presentation manipulation across many of the local measures. This might be particularly surprising given the clear patterns of altered oculomotor behaviour in the analysis of the global reading measures. However, it should be noted that the effects that occurred in the global measures were quite small. For example, there was an increase in average fixation duration in the order of approximately 10 ms for scrolling text. Thus, it seems likely that the effects were distributed across the entire sentence. In support of this suggestion, it can be seen from Table 1 that fixation durations for scrolling text are consistently slightly longer than for static text. The first pass measures also necessarily exclude reinspection fixations made after inter-word regressions, which occur more frequently when reading static text, again contributing to a reduction in the average fixation duration for this format (see global analyses). One of the few measures where an effect of display format was found was in word skipping probability. This effect did not interact with either word length or word frequency, and this appears to be a change in global oculomotor strategy as discussed previously.

There were some differences between static and scrolling text reading beyond the first pass measures that are worth highlighting. Longer go-past times were seen with static than scrolling text, which will reflect increased re-reading times after longer-range regressive saccades for the static text. Static text also elicited longer total reading times for the target words, which may again be explained by the changes in regression behaviour and loss of availability of the text.

Local Analyses: Experiment 2, Predictability Effect

Results

Of the 81 participants, 9 were excluded due to poor data quality or reading comprehension scores below 75%. There was no difference in reading comprehension for these final 72 participants (Wilcoxon signed rank test $p = 0.537$), with mean comprehension accuracy of 96.5% (SD 5.5) for scrolling text and 96.8% (SD 5.4) for static text. In addition to this, 3.2% of trials were removed from analysis due to loss of calibration or participant error (i.e. making a premature button press response to end the trial). We analysed the same local measures for the target word manipulated for predictability as those analysed in Experiment 1. Each measure was analysed with repeated measures two-way ANOVA (2x2 for display format and word predictability), with F_1 (for results across participants) and F_2 (for results across items) measures generated. Mean values are presented in Table 3.

Table 3.

Local reading measures for the target word: skipping probability (%), first and single fixation duration, gaze duration (ms), go-past time, and total time. Standard errors are shown in parentheses.

Predictability	Display format	Skipping probability (%)	First fixation duration (ms)	Single fixation duration (ms)	Gaze duration (ms)	Go-past time (ms)	Total time (ms)
High	Scrolling	33.08 (2.25)	213.05 (3.94)	214.12 (4.28)	231.71 (5.10)	264.92 (10.46)	251.74 (6.04)
	Static	29.21 (2.25)	196.84 (4.19)	201.20 (4.81)	220.36 (6.17)	270.95 (10.35)	263.61 (10.35)
Neutral	Scrolling	28.90 (2.15)	214.59 (3.97)	216.13 (4.12)	233.12 (5.03)	267.66 (8.08)	266.07 (7.33)
	Static	24.88 (2.02)	211.07 (4.88)	215.98 (5.74)	238.85 (6.88)	286.29 (12.54)	283.38 (10.90)

As in previous literature, highly predictable words were significantly more likely to be skipped than neutral words (by 4%; $F_1(1, 71) = 6.78$, $p = 0.01$, $\eta^2 = 0.01$, $F_2(1, 47) = 4.72$, $p = 0.03$, $\eta^2 = 0.02$). Word skipping was also 4% higher in reading of scrolling than static text ($F_1(1, 70) = 4.26$, $p = 0.04$, $\eta^2 = 0.01$, $F_2(1, 47) = 3.59$, $p = 0.06$, $\eta^2 = 0.01$). There was no interaction between these variables ($F_1(1, 71) = 0.001$, $p = 0.94$, $\eta^2 < 0.001$, $F_2(1, 47) < 0.001$, $p = 0.98$, $\eta^2 < 0.001$).

A predictability effect was found for single fixation durations, with 8 ms longer single fixations for neutral than highly predictable words ($F_1(1, 68) = 5.73$, $p = 0.02$, $\eta^2 = 0.01$, $F_2(1, 47) = 5.56$, $p = 0.02$, $\eta^2 = 0.02$), qualified by an interaction between predictability and display format showing that the effect of predictability was only present for static text reading ($F_1(1, 68) = 4.47$, $p = 0.04$, $\eta^2 = 0.01$, $F_2(1, 47) = 3.88$, $p = 0.05$, $\eta^2 = 0.02$). A similar pattern was found for first fixation duration, with effects of predictability ($F_1(1, 70) = 7.39$, $p = 0.008$, $\eta^2 = 0.01$; $F_2(1, 47) = 7.45$, $p = 0.009$, $\eta^2 = 0.03$) and display format ($F_1(1, 70) = 8.01$, $p = 0.006$, $\eta^2 = 0.02$, $F_2(1, 47) = 2.80$, $p = 0.1$, $\eta^2 = 0.02$), qualified by an interaction indicating that the predictability effect was present in reading of static text only ($F_1(1, 70) = 4.21$, $p = 0.04$, $\eta^2 = 0.01$, $F_2(1, 47) = 3.99$, $p = 0.05$, $\eta^2 = 0.02$). Gaze duration showed an effect of predictability only, with significantly longer durations in the neutral than high predictability condition (by 10 ms; $F_1(1, 70) = 5.60$, $p = 0.02$, $\eta^2 = 0.01$, $F_2(1, 47) = 4.53$, $p = 0.04$, $\eta^2 = 0.02$; display format *ns* $F_1(1, 70) = 0.34$, $p = 0.56$, $\eta^2 = 0.001$, $F_2(1, 47) = 0.57$, $p = 0.46$, $\eta^2 = 0.002$; interaction *ns* $F_1(1, 70) = 2.89$, $p = 0.09$, $\eta^2 = 0.01$, $F_2(1, 47) = 1.58$, $p = 0.21$, $\eta^2 = 0.006$). These findings replicate previous findings for static text, that highly predictable words produce shorter fixation durations than words that are not predictable. However, the interactions between predictability and display format in the earlier measures (single fixation duration and first fixation duration) show that the predictability effects did not occur to the same degree for scrolling text, suggesting that preceding sentential context did not exert as immediate a facilitatory influence over processing under scrolling text conditions as under static text conditions. This finding supports our hypothesis that predictability effects would be reduced when sentences were presented in scrolling text format.

There were no reliable effects of predictability or display type on go-past times, although there was a trend towards longer static text go-past times as seen previously in Experiment 1 (significant here in F_2 analyses only; $F_1(1, 70) = 2.04$, $p = 0.16$, $\eta^2 = 0.002$, $F_2 = 8.08$, $p = 0.01$, $\eta^2 = 0.03$). Total time was modulated by predictability, with significantly higher durations for neutral predictability target words ($F_1(1, 70) = 5.45$, $p = 0.02$, $\eta^2 = 0.01$, $F_2(1, 47) = 4.45$, $p = 0.02$, $\eta^2 = 0.04$). There was also a marginal effect of display format (significant across items only), with longer total gaze durations seen in static text reading ($F_1(1, 70) = 3.58$, $p = 0.06$, $\eta^2 = 0.01$, $F_2(1, 47) = 4.45$, $p = 0.04$, $\eta^2 = 0.03$). These patterns support previous findings suggesting that, overall, highly predictable words are processed quicker than neutral words. As in Experiment 1, the longer durations seen with static text for these late fixation duration measures likely reflect the reduction in long-range regressive saccades with scrolling text seen in our global oculomotor pattern analysis.

Discussion

Experiment 2 investigated the effect of a predictability manipulation (high or neutral predictability) in static and scrolling text display formats, in order to examine how well readers could integrate information from preceding sentential context, thereby facilitating word identification. This effect is well established for reading of static text (e.g. Balota, Pollatsek, & Rayner, 1985). The predictability effect was replicated in reading of static text, however, when reading scrolling text, readers' ability to construct and use sentence context information was compromised. Evidence for this comes from the interactions of predictability and display format in the early fixation duration measures (single fixation duration and first fixation duration), indicating that whilst facilitation of processing occurred for highly predictable words in static text, a similar effect did not occur for scrolling text at this point in the eye movement record. Note, though, that readers' ability to form expectations for lexical identity on the basis of preceding context is not entirely impaired, as the interaction with display format was not present in later processing measures including gaze duration, go-past time, and total gaze duration (although for gaze duration there was a non-significant trend towards the same pattern, with a 2 ms facilitation effect for higher predictability words with scrolling text compared to an 18 ms effect with static text). However, at least for total time measure this interaction does not seem to be so clear in the data, indicating that overall there is still an advantage for highly predictable words in scrolling as in static text, but that the time course of the effect is different in the different formats. This may indicate that increased predictability of a target word in scrolling text reduces the need for attempts to make regressive saccades a) to previous parts of the sentence once the initial fixations on this word have been made, and b) back to the target word once the rest of the embedding sentence has been read; as opposed to in static text, where the initial identification of the word is also facilitated.

The final aspect of the results that requires consideration is the word skipping data. Here, as in Experiment 1, we found increased skipping for scrolling than for static text. This presumably reflects the same risky reading strategy for text presented in scrolling format. There was no interaction of predictability with the text presentation format, though we did obtain a main effect of predictability such that predictable words were more likely to be skipped than neutral words, that is, in the direction that would be expected. It is possible that any interactive effect may have been obscured by changes in global skipping behaviour more generally, that is a greater prevalence of skipping behaviour for scrolling text. In line with this, note that the skipping rates for neutral target words under static text conditions are quite high (approximately 25%) compared to Fitzsimmons and Drieghe, 2013 (17%).

General Discussion

The present study explored the impact of the dynamic horizontally scrolling text format on oculomotor and linguistic processing during reading. By investigating the “Big Three” (Clifton et al., 2016) of reading research – word length, word frequency, and predictability – we aimed to assess whether text displayed in this way could be successfully read to the same degree as normal static text. In doing so, we also sought to understand which levels of processing were affected and to suggest which limiting factors were likely to be the cause of any performance decrement. We conducted two experiments: in Experiment 1, word length and word frequency (Inhoff & Rayner, 1986; Rayner & McConkie, 1975; Rayner, Sereno, & Raney, 1996) were manipulated to explore perceptual parsing of the text into meaningful subunits and word identification; in Experiment 2, target word predictability (Balota, Pollatsek & Rayner, 1985; Fitzsimmons & Drieghe, 2013) was manipulated to explore the integration of text into the sentence representation during reading.

The results from Experiment 1 show that when reading scrolling text, lexical effects on eye movement behaviour are comparable to those observed when reading static text. That is, increasing word length increased first pass fixation durations, while high frequency words had shorter first pass fixation durations compared to low frequency words. There was no interaction between these factors and the display format (i.e., static versus scrolling text): the effects were comparable for both static and scrolling text, suggesting that word identification was unaffected by the horizontal movement of the text during reading. However, in Experiment 2, we did find evidence that the scrolling text format impaired reading performance at the sentence level. When reading static text, the expected facilitation effect for identification of highly predictable words (Erlich et al., 1981; Fitzsimmons & Drieghe, 2013; Rayner et al., 2004, 2001; Rayner & Well, 1996) occurred for the very first fixation on the target word, as well as the single fixation and gaze duration measures. No such effect occurred for the first fixation or single fixation duration measures under scrolling text conditions, with only a weak (less than 2 ms) effect on gaze duration, but there was a clear, if reduced, predictability effect on total time for scrolling text. This overall pattern of results suggests that the scrolling text format did have a negative impact on sentence integration, slowing this process down and therefore reducing the effect of word predictability compared to when reading static text.

The present study is the first to examine specific aspects of linguistic processing in a scrolling text format. Others (Buettner et al., 1985; Valsecchi et al., 2013) have explored eye movements and reading generally, but none have considered eye movement behaviour in relation to specific linguistic manipulations. These previous studies have therefore been limited to analysing eye movement behaviour at a global oculomotor level only, giving no insight into how scrolling text influences the nature of different aspects of linguistic processing directly. Whilst investigations of the general characteristics of reading are informative about basic aspects of oculomotor behaviour, they are very limited in the extent to which they can relate specific patterns of eye movements to particular linguistic characteristics of sentences. For example, to date, it has been shown that periods of smooth pursuit replace the fixation periods seen in static text reading (Buettner et al., 1985; Valsecchi et al., 2013), that there are longer fixation durations on average in scrolling versus static text (Buettner et al., 1985; Valsecchi et al., 2013), and consequently, reading times are slower (Buettner et al., 1985). However, in both of these studies it is unclear which aspects of linguistic processing are disrupted to produce the increased reading times. The present experiments are therefore novel in the sense that they comprise the first efforts to tap specifically into linguistic processing to evaluate how words are identified and then integrated into the sentence representation during reading of scrolling text as compared with static text.

We began our analyses at the global level, replicating the approach taken in previous studies of scrolling text. Based on previous research (Buettner et al., 1985; Valsecchi et al., 2013), we expected that when reading scrolling text, participants would make longer fixation durations coupled with less word skipping and slower reading times, reflecting the added difficulty of reading text that was moving from right to left. We found longer average fixation durations, more regressive saccades and shorter forward saccade lengths for scrolling compared with static text. All of these differences are indicative of increased reading difficulty. However, readers also made fewer fixations, skipped words more frequently, and in fact, on average, total sentence reading times were slightly (but significantly) shorter for scrolling text than for static text. It is clear that there are trade-offs within reading behaviour, and participants appear to have made strategic changes to their reading behaviour in order to deal with the demands imposed by the scrolling text format. Particularly striking is the change in regression function, with half of saccades made with scrolling text found to be regressive (compared to less than a quarter of saccades in static text).

Next we turn to the local analyses focused on specific target words within each sentence. In Experiment 1, as expected, we replicated word frequency and word length effects in static text conditions. We also obtained comparable effects under scrolling text conditions. There was no modulatory influence of the scrolling text format on these factors, suggesting that word identification was not hindered by the scrolling text format. It appears, therefore, that despite the striking changes to global eye movement behaviour that arise as a consequence of reading scrolling text, word frequency and word length effects are not amplified or reduced. This in turn suggests that lexical identification proceeded unhindered: it appears that lexical identification is no more difficult when reading text that scrolls from right to left (at least for text moving at the speed used in the present experiments) than when reading static text.

In Experiment 2, we conducted a partial replication of a previous study (Fitzsimmons & Drieghe, 2013) wherein participants read static sentences where the target word was either highly predictable based on the previous context, or where the target word was neutral based on the preceding context. Again, we directly compared the effects of this manipulation when reading static and scrolling sentences. Consistent with Fitzsimmons & Drieghe (2013), for static text we found that highly predictable target words had shorter fixation durations compared to neutral target words. However, in the scrolling text condition, there was a clear negative influence of the dynamic format upon reading behaviour. When examining the interactions of predictability and display format in the early fixation duration measures, we found that facilitation of processing occurred for highly predictable relative to neutral words in static text but in the scrolling text condition this facilitation did not emerge until later in the eye movement record.

There are a number of reasons why effects of word frequency and word length were similar to those observed in static text reading, whilst effects of predictability were delayed. Initially, we suggested that the most important of these were likely compromised saccadic targeting accuracy, a less stable fixation position, a reduced attentional window, and diminished opportunity and ease of making long-range regressive saccades to reinspect the text. We will now consider these in turn.

Based on previous studies of oculomotor control during reading, it seemed sensible to consider the contribution that saccadic targeting makes to the effects. Previous research (Valsecchi et al., 2013) has suggested that one of the key challenges in reading scrolling text may be to maintain accuracy with respect to targeting saccades to an optimal location within a word such that it can be identified most efficiently. However, although this may be true to some extent, with an increased number of shorter regressive saccades in scrolling compared with static text, in fact an analysis of landing positions on words showed only a small difference between static and scrolling text. Given that display type was found to have no interactive effect with factors of word length or word frequency (indexing word identification) on any measure, the impact of this slight decrement in targeting accuracy would appear to be minimal.

Following the initial targeting, we also considered how stably readers followed this landing position through their pursuit of the word. Whereas for static text it seems relatively simple for a stable fixation to be held, to achieve this with scrolling text would require close matching of eye velocity to target velocity. This was not the case, with a small lag in eye velocity resulting in an effective shift of almost a character through the word during the pursuit period. This may have increased processing difficulty slightly, helping to account for the increase in average fixation duration seen with the scrolling format, however the preservation of the word length and word frequency effects would suggest that this reduction in fixation stability does not have any considerable impact on lexical processing.

We did find that readers made shorter forward saccades with scrolling text, which is consistent with a reduction in the amount of information that is available to the reader beyond the area immediately around the point of fixation. Two theoretical constructs are often discussed in relation to this attentional window: first, the perceptual span, a larger area of parafoveal vision approximately 14 or 15 characters to the right of fixation (and about 5 to the left) from which global word shape and spacing information is extracted (Rayner & McConkie, 1975); and second, the word identification span, in which individual letters may be recognised and identified (Underwood & McConkie, 1985). A directional conflict may exist for allocation of attention in a way that it does not during reading of static text. It seems reasonable to suggest that this contributes to increased difficulty observed when scrolling text is read. In typical reading of static text, the extent of the word identification span is known to correspond to the average length of a saccade (both around 7 characters, though this may vary slightly depending on factors such as text difficulty, where increased reduces attentional resources available to be deployed for processing in this window; Jacobs, 1986; Rayner, 1998). The reduced saccade length for scrolling text, then, may be taken as initial evidence for a constrained attentional window relative to that observed in reading of static text: likely attributable to the directional conflict introduced for the deployment of attention. This may contribute to an overall reduction in processing efficiency, which would again help to explain why average fixation duration is raised overall with scrolling text. As noted previously, the magnitude of this effect is sufficiently small not to be reflected in word length and frequency effects, but may plausibly contribute to the additional difficulty in integrating individual words with the sentence context (as seen in the delayed predictability effect). Further studies using the gaze-contingent and boundary techniques are required to examine the asymmetry of the attentional window under scrolling text conditions.

The final factor to consider is the reader's ability to make long-range saccades to reinspect text. In order for readers to maintain coherence within their discourse representation, they often need to re-read portions of text in order to deal with any temporary ambiguities or misinterpretations that have occurred. Such re-reading is not always possible in a scrolling text format, since creating a spatial memory representation of position of each part of the text for guiding such regressive saccades (see Kennedy, 1982; Murray & Kennedy, 1988) is likely more complicated, and in addition the relevant text may have disappeared to the left of the screen. As such, it is likely difficult for the reader to establish complete coherence in the discourse representation. Further evidence in support of this suggestion comes from the reduced extent of regressive eye movements under scrolling compared with static text conditions. Critically, in order for a predictability effect to occur at all, the reader necessarily must have a clear and unambiguous interpretation of sentential context. If the reader's ability to attain this level of interpretation is compromised, for example, due to the visual format with which the text is presented, then any predictability effect that might have occurred will be attenuated.

At the outset of this work, based on existing research, we may have reasonably adopted a default hypothesis that scrolling text format would cause less efficient linguistic processing at all levels. It is very clear from the results that this was not the case. Instead, we have shown that certain aspects of linguistic processing are unhindered, even when the text presentation is dynamic and therefore the nature of the visual sampling is different (i.e. involved a pursuit movement rather than a static fixation), so long as the eyes are able to adequately visually sample the information necessary for that processing to occur. In relation to lexical processing, this is very likely because word identification during reading is achieved most often via one or two fixations on that word. Clearly, given the rate at which the text scrolled in the current experiments, this period of time was sufficient for readers to undertake such sampling and processing and successfully complete lexical identification.

A somewhat different situation exists if we consider the processing required in order for a word to be integrated into the preceding context. It must first be lexically identified, and then incorporated into the syntactic structure of the sentence, after which its meaning in relation to the existing sentence and discourse representation must be computed. This takes longer to achieve than simply identifying a word lexically. Reduced processing efficiency and limited text availability combined therefore result in a disruption of sentence-level integration.

In summary, we found that reasonable reading performance is achievable with scrolling text. However, we propose that readers adopt a riskier oculomotor strategy, including increased rates of word skipping, as readers take into account the limited window of temporal availability of the text and thus prioritise completing word-level processing during the first pass on the sentence. In line with this, we showed that word identification is as efficient and effective with scrolling text as with static text, and we suggest that this occurs because the period of time that a word is available to be fixated and pursued in our scrolling text format was sufficiently long to allow for full identification to occur. In contrast, scrolling text did impair the reader's ability to rapidly form a clear interpretation of the text. The delayed predictability effects indicate that readers were less effective in forming an interpretation of sentential context and using this to evaluate the likelihood of words downstream in the sentence. We suggest that this is because, in prioritising word-level processing, readers have less opportunity to reinspect text that has disappeared from the screen in order to resolve temporary ambiguities and deal with initial misinterpretations. Finally, the present study demonstrates clearly the importance of considering different aspects of linguistic processing in relation to changes in global reading behaviour. Through manipulation of specific linguistic variables it is possible to understand how different aspects of linguistic processing are affected by changes in visual sampling that arise as a result of the format of the text that is being processed.

References

Acha, J., & Perea, M. (2008a). The effect of neighborhood frequency in reading: Evidence with transposed-letter neighbors. *Cognition*, *108*, 290–300.

Acha, J., & Perea, M. (2008b). The effects of length and transposed-letter similarity in lexical decision: Evidence with beginning, intermediate, and adult readers. *British Journal of Psychology*, *99*, 245–264.

Ashby, J., Rayner, K., & Clifton, C. (2005). Eye movements of highly skilled and average readers: differential effects of frequency and predictability. *The Quarterly Journal of Experimental Psychology. A, Human Experimental Psychology*, *58*(6), 1065–1086. http://doi.org/10.1080/02724980443000476

Balota, D., Pollatsek, A., & Rayner, K. (1985). The interaction of contextual constraints and parafoveal visual information in reading. *Cognitive Psychology*, *17*(3), 364–90.

Beers, R. Van. (2001). Sensorimotor integration compensates for visual localization errors during smooth pursuit eye movements. *Journal of Neurophysiology*, *85*(5), 1914–1922.

Blohm, G., Missal, M., & Lefèvre, P. (2005). Processing of retinal and extraretinal signals for memory-guided saccades during smooth pursuit. *Journal of Neurophysiology*, *93*(3), 1510–22. http://doi.org/10.1152/jn.00543.2004

Buettner, M., Krischer, C., & Meissen, R. (1985). Characterization of gliding text as a reading stimulus. *Bulletin of the Psychonomic Society*, *23*(6), 479–482.

Clifton, C., Ferreira, F., Henderson, J. M., Inhoff, A. W., Liversedge, S. P., Reichle, E. D., & Schotter, E. R. (2016). Eye movements in reading and information processing: Keith Rayner's 40 year legacy. *Journal of Memory and Language*, *86*, 1–19. http://doi.org/10.1016/j.jml.2015.07.004

de Brouwer, S., Missal, M., Barnes, G. R., & Lefevre, P. (2002). Quantitative Analysis of Catch-Up Saccades During Sustained Pursuit. *J Neurophysiol*, *87*(4), 1772–1780.

de Brouwer, S., Yuksel, D., Blohm, G., Missal, M., & Lefevre, P. (2002). What Triggers Catch-Up Saccades During Visual Tracking? *J Neurophysiol*, *87*(3), 1646–1650.

Deubel, H., & Schneider, W. X. (1996). Saccade target selection and object recognition: Evidence for a common attentional mechanism. *Vision Research*, *36*(12), 1827–1837. http://doi.org/10.1016/0042-6989(95)00294-4

Drieghe, D., Rayner, K., & Pollatsek, A. (2005). Eye movements and word skipping during reading revisited. *Journal of Experimental Psychology: Human Perception and Performance*, *31*(5), 954–9.

Duggan, G. B., & Payne, S. J. (2011). Skim Reading by Satisficing : Evidence from Eye Tracking. In *CHI* (pp. 1141–1150).

Erlich, S. F., Rayner, K., Ehrlich, S., & Rayner, K. (1981). Contextual Effects on Word Perception and Eye Movements during Reading. *Journal of Verbal Learning and Verbal Behaviour*, *20*, 641–655.

Fischler, I., & Bloom, P. A. (1980). Rapid processing of the meaning of sentences. *Memory & Cognition*, *8*(3), 216–225. http://doi.org/10.3758/BF03197609

Fitzsimmons, G., & Drieghe, D. (2013). How fast can predictability influence word skipping during reading? *Journal of Experimental Psychology Learning Memory and Cognition*, *39*(4), 1054–63. http://doi.org/10.1037/a0030909

Fitzsimmons, G., Weal, M. J., & Drieghe, D. (2014). Skim Reading : An Adaptive Strategy for Reading on the Web. In *WebSci '14* (pp. 1–9). Bloomington: ACM.

Gellman, R. S., & Fletcher, W. A. (1992). Eye position signals in human saccadic processing. *Experimental Brain Research*, *89*(2), 425–434. http://doi.org/10.1007/BF00228258

Harrison, J. J. (2014). *Volition and Automaticity in the Interactions of Optokinetic Nystagmus , Infantile Nystagmus , Saccades and Smooth Pursuit*. Cardiff University.

Hautala, J., Hyönä, J., & Aro, M. (2011). Dissociating spatial and letter-based word length effects observed in readers' eye movement patterns. *Vision Research*, *51*(15), 1719–27. http://doi.org/10.1016/j.visres.2011.05.015

Havermann, K., Volcic, R., & Lappe, M. (2012). Saccadic adaptation to moving targets. *PloS One*, *7*(6), e39708. http://doi.org/10.1371/journal.pone.0039708

Henderson, J. M., & Ferreira, F. (1990). Effects of foveal processing difficulty on the perceptual span in reading: implications for attention and eye movement control. *Journal of Experimental Psychology. Learning, Memory, and Cognition*, *16*(3), 417–29.

Hutton, S. B., & Tegally, D. (2005). The effects of dividing attention on smooth pursuit eye tracking. *Experimental Brain Research*, *163*(3), 306–13. http://doi.org/10.1007/s00221-004-2171-z

Inhoff, A. W. (1984). Two stages of word processing during eye fixations in the reading of prose. *Journal of Verbal Learning and Verbal Behavior*, *23*(5), 612–624.

Inhoff, A. W., & Rayner, K. (1986). Parafoveal word processing during eye fixations in reading: Effects of word frequency. *Perception & Psychophysics*, *40*(6), 431–439.

Jacobs, A. M. (1986). Eye-movement control in visual search: how direct is visual span control? *Perception & Psychophysics*, *39*(1), 47–58.

Johnson, R. (2009). The quiet clam is quite calm: Transposed-letter neighborhood effects on eye movements during reading. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *35*(4), 943–969.

Johnson, R., Perea, M., & Rayner, K. (2007). Transposed-letter effects in reading: Evidence from eye movements and parafoveal preview. *Journal of Experimental Psychology: Human Perception and Performance*, *33*(1), 209–229.

Jordan, T. R., Almabruk, A. A. A., Gadalla, E. A., McGowan, V. A., White, S. J., Abedipour, L., & Paterson, K. B. (2013). Reading direction and the central perceptual span: Evidence from Arabic and English. *Psychonomic Bulletin and Review*, *21*(2), 505–511. http://doi.org/10.3758/s13423-013-0510-4

Just, M. A., & Carpenter, P. A. (1980). A theory of reading: from eye fixations to comprehension. *Psychological Review*, *87*(4), 329–354.

Kaminiarz, A., Konigs, K., & Bremmer, F. (2010). The main sequence of human optokinetic nystagmus. *Journal of Vision*, *9*(8), 405–405. http://doi.org/10.1167/9.8.405

Kaminiarz, A., Königs, K., & Bremmer, F. (2009). Task influences on the dynamic properties of fast eye movements. *Journal of Vision*, *9*(13), 1.1-11. http://doi.org/10.1167/9.13.1

Kennedy, A. (1982). Eye movements and spatial coding in reading. *Psychological Research*, *44*, 313–322.

Kerzel, D., & Ziegler, N. E. (2005). Visual short-term memory during smooth pursuit eye movements. *Journal of Experimental Psychology: Human Perception and Performance*, *31*(2), 354–72. http://doi.org/10.1037/0096-1523.31.2.354

Khan, A. Z., Lefèvre, P., Heinen, S. J., Blohm, G., Lefevre, P., Heinen, S. J., & Blohm, G. (2010). The default allocation of attention is broadly ahead of smooth pursuit. *Journal of Vision*, *10*(13), 1–17. http://doi.org/10.1167/10.13.7

Kliegl, R., Grabner, E., Rolfs, M., & Engbert, R. (2004). Length, frequency, and predictability effects of words on eye movements in reading. *European Journal of Cognitive Psychology*, *16*(1–2), 262–284. http://doi.org/10.1080/09541440340000213

Krauzlis, R. J. (2004). Recasting the smooth pursuit eye movement system. *Journal of Neurophysiology*, *91*, 591–603. http://doi.org/10.1152/jn.00801.2003

Krauzlis, R. J., Basso, M. A., & Wurtz, R. H. (2000). Discharge properties of neurons in the rostral superior colliculus of the moneky during smooth-pursuit eye movements. *Journal of Neurophysiology*, *84*, 876–891.

Krügel, A., & Engbert, R. (2010). On the launch-site effect for skipped words during reading. *Vision Research*, *50*(16), 1532–9. http://doi.org/10.1016/j.visres.2010.05.009

Kucera, H., & Francis, W. (1982). *Frequency analysis of English usage: Lexicon and grammar*. Boston: Houghton Mifflin.

Liversedge, S. P., Rayner, K., White, S. J., Vergilino-Perez, D., Findlay, J. M., & Kentridge, R. W. (2004). Eye movements when reading disappearing text: is there a gap effect in reading? *Vision Research*, *44*(10), 1013–24. http://doi.org/10.1016/j.visres.2003.12.002

Lovejoy, L. P., Fowler, G., & Krauzlis, R. J. (2009). Spatial allocation of attention during smooth pursuit eye movements. *Vision Research*, *49*(10), 1275–1285. http://doi.org/10.1016/j.visres.2009.01.011

Lowell, R., & Morris, R. K. (2014). Word length effects on novel words: Evidence from eye movements. *Attention, Perception & Psychophysics*, *76*(1), 179–189. http://doi.org/10.3758/s13414-013-0556-4

Ludvigh, E., & Miller, J. W. (1958). Study of visual acuity during the ocular pursuit of moving test objects. I. Introduction. *Journal of the Optical Society of America*, *48*(11), 799–802. http://doi.org/10.1364/JOSA.48.000799

Miellet, S., O'Donnell, P. J., & Sereno, S. C. (2009). Parafoveal magnification: visual acuity does not modulate the perceptual span in reading. *Psychological Science, 20*(6), 721–8. http://doi.org/10.1111/j.1467-9280.2009.02364.x

Murray, W. S., & Kennedy, A. (1988). Spatial coding in the processing of anaphor by good and poor readers: Evidence from eye movement analyses. *The Quarterly Journal of Experimental Psychology Section A*, *40*(4), 693–718. http://doi.org/10.1080/14640748808402294

O'Regan, J. K. (1990). Eye movements and reading. In E. Kowler (Ed.), *Reviews of Oculomotor Research: Vol 4. Eye movements and their role in visual and cognitive processes.* (pp. 395–453). Amsterdam: Elsevier.

O'Regan, J. K., & Jacobs, A. M. (1992). Optimal Viewing Position Effect in Word Recognition : A Challenge to Current Theory. *Journal of Experimental Psychology: Human Perception and Performance*, *18*(I).

Ohtsuka, K. (1994). Properties of memory-guided saccades toward targets flashed during smooth pursuit in human subjects. *Invest. Ophthalmol. Vis. Sci.*, *35*(2), 509–514.

Paterson, K. B., McGowan, V. a, White, S. J., Malik, S., Abedipour, L., & Jordan, T. R. (2014). Reading direction and the central perceptual span in Urdu and English. *PloS One, 9*(2), e88358. http://doi.org/10.1371/journal.pone.0088358

Pollatsek, A., Juhasz, B., Reichle, E. D., Machacek, D., & Rayner, K. (2008). Immediate and delayed effects of word frequency and word length on eye movements in reading: a reversed delayed effect of word length. *Journal of Experimental Psychology: Human Perception and Performance*, *34*(3), 726–50. http://doi.org/10.1037/0096-1523.34.3.726

R Core Team. (2014). R: A language and environment for statistical computing. Vienna: R Foundation for Statistical Computing.

Rayner, K. (1977). Visual attention in reading: Eye movements reflect cognitive processes. *Memory & Cognition*, *5*(4), 443–448.

Rayner, K. (1998). Eye movements in reading and information processing: 20 years of research. *Psychological Bulletin*, *124*(3), 372–422.

Rayner, K., Ashby, J., Pollatsek, A., & Reichle, E. D. (2004). The effects of frequency and predictability on eye fixations in reading: implications for the E-Z Reader model. *Journal of Experimental Psychology: Human Perception and Performance*, *30*(4), 720–32. http://doi.org/10.1037/0096-1523.30.4.720

Rayner, K., Binder, K. S., Ashby, J., & Pollatsek, A. (2001). Eye movement control in reading: word predictability has little influence on initial landing positions in words. *Vision Research*, *41*(7), 943–54.

Rayner, K., & Duffy, S. (1986). Lexical complexity and fixation times in reading: Effects of word frequency, verb complexity, and lexical ambiguity. *Memory & Cognition*, *14*(3), 191–201.

Rayner, K., & Fischer, M. H. (1996). Mindless reading revisited: eye movements during reading and scanning are different. *Perception & Psychophysics*, *58*(5), 734–47.

Rayner, K., Fischer, M. H., & Pollatsek, A. (1998). Unspaced text interferes with both word identification and eye movement control. *Vision Research*, *38*(8), 1129–1144. http://doi.org/10.1016/S0042-6989(97)00274-5

Rayner, K., & Liversedge, S. P. (2011). Linguistic and cognitive influences on eye movements during reading. In S. Liversedge, I. Gilchrist, & S. Everling (Eds.), *The Oxford Handbook of Eye Movements* (pp. 751–766). Oxford: OUP.

Rayner, K., Liversedge, S. P., & White, S. J. (2006). Eye movements when reading disappearing text: the importance of the word to the right of fixation. *Vision Research*, *46*(3), 310–23. http://doi.org/10.1016/j.visres.2005.06.018

Rayner, K., Liversedge, S. P., White, S. J., & Vergilino-Perez, D. (2003). Reading disappearing text: Cognitive Control of Eye Movements. *Psychological Science*, *14*, 385–388. http://doi.org/10.1111/1467-9280.24483

Rayner, K., & McConkie, G. W. (1975). What guides a reader's eye movements? *Vision Research*, *16*, 829–837.

Rayner, K., & Raney, G. E. (1996). Eye movement control in reading and visual search: Effects of word frequency. *Psychonomic Bulletin & Review*, *3*(2), 245–8. http://doi.org/10.3758/BF03212426

Rayner, K., Reichle, E. D., Stroud, M. J., Williams, C. C., & Pollatsek, A. (2006). The effect of word frequency, word predictability, and font difficulty on the eye movements of young and older readers. *Psychology and Aging*, *21*(3), 448–465. http://doi.org/10.1037/0882-7974.21.3.448

Rayner, K., Sereno, S. C., & Raney, G. E. (1996). Eye movement control in reading: a comparison of two types of models. *Journal of Experimental Psychology: Human Perception and Performance*, *22*(5), 1188–1200. http://doi.org/10.1037/0096-1523.22.5.1188

Rayner, K., Slattery, T. J., & Drieghe, D. (2011). Eye movements and word skipping during reading: Effects of word length and predictability. *Journal of Experimental Psychology: Human Perception and Performance*, *37*(2), 514–28.

Rayner, K., & Well, A. D. (1996). Effects of contextual constraint on eye movements in reading: A further examination. *Psychonomic Bulletin & Review*, *3*(4), 504–9. http://doi.org/10.3758/BF03214555

Reichle, E. D., & Drieghe, D. (2013). Using E-Z Reader to examine word skipping during reading. *Journal of Experimental Psychology: Learning, Memory and Cognition*, *39*(4), 1311–20. http://doi.org/10.1037/a0030910

Risse, S., & Kliegl, R. (2011). Adult age differences in the perceptual span during reading. *Psychology and Aging*, *26*(2), 451–460.

Rizzolatti, G., Riggio, L., Dascola, I., & Umilta, C. (1987). Reorienting attention across the horizontal and vertical meridians: Evidence in favour of a premotor theory of attention. *Neuropsychologia*, *25*(1A), 31–40.

Rizzolatti, G., Riggio, L., & Sheliga, B. (1994). Space and selective attention. In C. Umilta & M. Moscovitch (Eds.), *Attention and Performance XV* (pp. 231–265). Cambridge MA: MIT press.

Robinson, D. A. (1965). The mechanics of human smooth pursuit eye movement. *The*

Journal of Physiology, *180*(3), 569–91.

Schlag, J. (1990). Saccades can be aimed at the spatial location of targets flashed during pursuit. *Journal of Neurophysiology*, *64*(2), 575–581.

Schotter, E. R., Bicknell, K., Howard, I., Levy, R., & Rayner, K. (2014). Task effects reveal cognitive flexibility responding to frequency and predictability: Evidence from eye movements in reading and proofreading. *Cognition*, *131*(1), 1–27. http://doi.org/10.1016/j.cognition.2013.11.018

Schotter, E. R., Tran, R., & Rayner, K. (2014). Don't believe what you read (only once): Comprehension is supported by regressions during reading. *Psychological Science*, *25*(6), 1218–1226. http://doi.org/10.1177/0956797614531148

Schütz, A. C., & Souto, D. (2011). Adaptation of catch-up saccades during the initiation of smooth pursuit eye movements. *Experimental Brain Research*, *209*(4), 537–549. http://doi.org/10.1007/s00221-011-2581-7

Seya, Y., & Mori, S. (2012). Spatial attention and reaction times during smooth pursuit eye movement. *Attention, Perception & Psychophysics*, *74*(3), 493–509. http://doi.org/10.3758/s13414-011-0247-y

Sharmin, S. (2015). Dynamic text presentation in print interpreting - an eye movements study of reading behaviour. *International Journal of Human-Computer Studies*, *78*, 17–30.

Sheliga, B., Riggio, L., Craighero, L., & Rizzolatti, G. (1995). Spatial attention-determined modifications in saccade trajectories. *NeuroReport*, *6*, 585–588.

Sheliga, B., Riggio, L., & Rizzolatti, G. (1994). Orienting of attention and eye movements. *Experimental Brain Research*, *98*, 507–522.

So, J. C. Y., & Chan, A. H. S. (2013). Effects of display method, text display rate and observation angle on comprehension performance and subjective preferences for reading Chinese on an LED display. *Displays*, *34*(5), 371–379. http://doi.org/10.1016/j.displa.2013.09.006

Szinte, M., Carrasco, M., Cavanagh, P., & Rolfs, M. (2015). Attentional tradeoffs maintain the tracking of moving objects across saccades. *Journal of Neurophysiology*, *113*(7), 2220–2231. http://doi.org/10.1152/jn.00966.2014

Tanaka, T., Sugimoto, M., Tanida, Y., & Saito, S. (2014). The influences of working memory representations on long-range regression in text reading: an eye-tracking study. *Frontiers in Human Neuroscience, 8*, 765–772. http://doi.org/10.3389/fnhum.2014.00765

Ter Braak, J. (1936). Untersuchungen über optokinetischen Nystagmus. *Arch Neerl Physiol*, *21*, 309–376.

Underwood, N. R., & McConkie, G. W. (1985). Perceptual span for letter distinctions during reading. *Reading Research Quarterly*, *20*(2), 153–162.

Valsecchi, M., Gegenfurtner, K. R., & Schütz, A. C. (2013). Saccadic and smooth-pursuit eye movements during reading of drifting texts. *Journal of Vision*, *13*(10:8), 1–20.

Van Donkelaar, P., & Drew, A. S. (2002). The allocation of attention during smooth pursuit eye movements. *Progress in Brain Research*, *140*, 267–77. http://doi.org/10.1016/S0079-6123(02)40056-8

Vitu, F. (2011). On the role of visual and oculomotor processes in reading. In S. Liversedge, I. Gilchrist, & S. Everling (Eds.), *The Oxford Handbook of Eye Movements* (pp. 731–750). Oxford: OUP.

Walker, R. (2013). An iPad app as a low-vision aid for people with macular disease. *British Journal of Ophthalmology*, *97*(1), 110–112.

White, S. J., Rayner, K., & Liversedge, S. P. (2005). Eye movements and the modulation of parafoveal processing by foveal processing difficulty: A reexamination. *Psychonomic Bulletin & Review*, *12*(5), 891–896. http://doi.org/10.3758/BF03196782