The Characteristics And Application Of Reading Dynamic Horizontally Scrolling Text

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Declaration of authorship

I, Hannah Harvey, hereby declare that this thesis and the work presented in it is entirely my own. Where I have consulted the work of others, this is always clearly stated.

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Abstract

The dynamic horizontally scrolling text format is theoretically interesting, providing a challenging reading situation with an unusual profile of difficulties: reduced sustained availability of text, increased difficulty in creating a spatial map of the text, and a conflict in the deployment of attention. It also has a range of possible applications, both in digital media and as a potential reading aid for populations with certain visual impairments. Despite this, comparatively little research has considered how the processes involved in successful reading are affected by this format. This investigation aimed to provide a more detailed overview of some of these key processes: the global oculomotor pattern employed to read the text, word-level and sentence-level linguistic processing, the deployment of attention, and text comprehension. Experiments demonstrated that word-level processing was unaffected by the scrolling format, with successful replication of the word-length and word-frequency effects, but that establishing and using sentence-level context information appeared to be compromised. One factor that may play a role in this processing deficit is the reduced extent of the perceptual span, with the effective preview ahead of the point of fixation seemingly compressed from 12 characters to the right of fixation with static text to 8 characters to the right with scrolling text. Together, these changes produced a reduction in levels of text understanding, with a particular deficit in inference-based comprehension. This finding and the elimination of the predictability effect were both apparent regardless of display speed. Overall, these studies provide a basis for further investigation of reading horizontally scrolling text: this may produce insights into factors which limit successful reading with any text display format, and allow optimization of its application in digital media and as a reading aid (the latter of which is also briefly investigated in the final experimental chapter, providing support for its utility).

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Chapter 1: Background And Overview

Reading is an important skill that fundamentally relies on the basic characteristics of vision to allow absorption of information via the written word. However, although reading of normal static text is increasingly well characterised both in terms of the oculomotor and cognitive (specifically attentional and linguistic) processes involved (Clifton et al., 2016; Rayner, 1998, 2009; Vitu, 2011), the impact of less commonly used dynamic presentation formats, such as horizontally scrolling text, on these processes is relatively less well understood. This is despite reasonably common usage of these formats in digital media to display unlimited text in a restricted window. Horizontally scrolling text in particular is encountered quite frequently in everyday life, for example on train information displays, on news tickers, and for presenting text in limited presentation windows on mobile devices such as mobile phones and smart-watches (e.g. Chien, Chen, & Wei, 2008; Lin & Shieh, 2006). It has also been suggested to have potential as an aid to help improve reading performance in populations with visual impairments including central vision loss (e.g. Bowers, Woods, & Peli, 2004; Walker, Bryan, Harvey, Riazi, & Anderson, 2016; Walker, 2013).

Normal Reading

The oculomotor processes involved in normal reading of static text can be briefly characterised as consisting of a series of fixations to inspect most words, interspersed with short saccades to move between words in the text. These saccades largely drive attention forwards through the text (i.e. in English moving across from the left to right of lines of text), although they may also be made to regress backwards in the text in order to inspect skipped words or reinspect previously read words in around 10 - 15% of cases (modulated by text characteristics such as complexity and familiarity; Rayner, 1998, and by reader characteristics, such as age; Rayner, Reichle, Stroud, Williams, & Pollatsek, 2006). This pattern is optimised to use the layout of the early visual system (specifically the retina and primary visual cortex) to best advantage, with each fixation allowing the text to be inspected at the highest acuity portion of vision (see Figure 1).

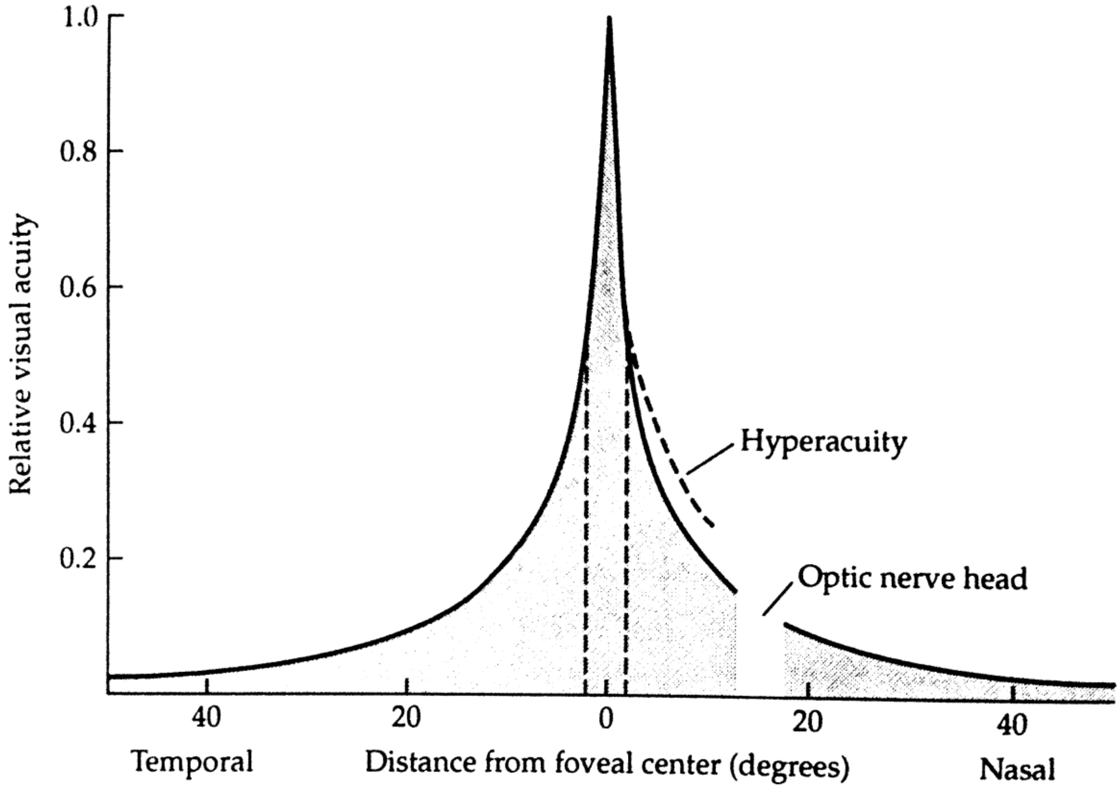

Figure 1. Plot demonstrating the decline in relative visual acuity (in the left eye) with increasing eccentricity from the fovea (delineated by dashed lines around 0. The blind spot occurring at the optic nerve head is shown as the gap in the plotted line (from Oyster, 1999, p. 666; based on Wertheim, 1894).

This zone consists of approximately the central 5° of the retina known as the macula lutea, and in particular the foveal pit in the central 2° of this area (Drieghe, 2011; Wertheim, 1980). Visual acuity is at its peak here as this is the region at which cone photoreceptors (the class of photoreceptor able to provide the highest level of spatial detail) have the highest density, with a lower level of convergence to retinal ganglion cells leading to small receptive fields; the representation of this area in the primary visual cortex is therefore disproportionate to its size in the retina (Azzopardi & Cowey, 1993). These factors underlie the increased spatial resolution of the retinal image focused on the foveal area, with a reasonably steep drop-off of acuity into the periphery (halving at 1° eccentricity from the centre of the fovea and again at 5° eccentricity; Wertheim, 1980). However, although the best and most detailed information is therefore typically taken from this central region (Rossi & Roorda, 2010), that is not to say that this is the only functional part of the retina in the reading process:

research has confirmed the important role of a parafoveal preview region (i.e. information falling on the retinal area just outside of the fovea) in effective reading, with evidence suggesting that information about word length and form is taken from a *perceptual span* of up to around 12 - 15 characters to the right and 4 characters to the left of the character at fixation during reading (McConkie & Rayner, 1975; with a more focused *word identification span* of up to around 8 characters to the right and 4 to the left from which characters may actually be identified; Underwood & Mcconkie, 1985).

From this parafoveal preview area, research suggests that enough information about upcoming words may be gleaned to either reduce the amount of time needed to be spent fixating them, or even allow following saccades to be programmed to skip some words altogether: word skipping is estimated to occur on average around 20 - 30% of the time (with certain kinds of words being more – e.g. very short and frequently encountered words such as, function words - or less – e.g. longer, less frequently encountered words - likely to be skipped; e.g. Drieghe, Rayner, & Pollatsek, 2005). Equally, characteristics of the information attended to in the foveal area may constrain parafoveal processing (i.e. with more challenging foveal information requiring more attention, therefore reducing the cognitive resources available for forward processing and correspondingly the size of the effective parafoveal window; Henderson & Ferreira, 1990; Schroyens, Vitu, Brysbaert, & D'Ydewalle, 1999; White, Rayner, & Liversedge, 2005). Many factors have been identified which are suggested to impact on processing time, word skipping probability, and the likelihood of making intra-word refixations and inter-word regressions. These include (but are not limited to) factors at both the level of individual words, such as word length, word frequency, and familiarity, and of whole sentences, such as predictability and syntactic complexity (Clifton et al., 2016; Drieghe, Brysbaert, Desmet, & De Baecke, 2004; Drieghe et al., 2005; Rayner & Liversedge, 2011). For example, long words are generally fixated for longer and are less likely to be skipped than shorter words, and a regression to a previously skipped word is more likely to be made if the skipped word was of low than high frequency in a language (Rayner & McConkie, 1975; Vitu, McConkie, & Zola, 1998). Investigations of the effect of these factors on such measures have therefore been commonly used to provide an index of the depth, time course, and success of processing during reading.

A number of attempts have been made to develop a theoretical model which can account for all of these nuances of the oculomotor approach to reading (Engbert, Nuthmann, Richter, & Kliegl, 2005; Just & Carpenter, 1980; Kowler & Anton, 1987; Morrison, 1984; Reichle, Rayner, & Pollatsek, 2003; Reilly & O'Regan, 1998; Salvucci, 2001; Suppes, 1990; Yang & McConkie, 2001). Over the past twenty years, these attempts have been largely condensed into two major alternative computational models: the E-Z Reader model (Pollatsek, Reichle, & Rayner, 2006; Reichle et al., 2003), which proposes that attention is deployed serially during reading; and SWIFT (Saccade-generation With Inhibition by Foveal Targets; Engbert, Longtin, & Kliegl, 2002; Engbert et al., 2005), which takes the opposing view that attention is deployed to process multiple words in parallel. According to the E-Z Reader model, processing progresses one word at a time as identification of each is completed, with saccadic shifts being programmed to the next word following completion of the first stage of lexical processing of the fixated word. Execution of the actual saccade is planned so as to coincide with the successful completion of the 2nd stage of processing of the foveal word *n* in most cases. If this shift occurs too early (i.e. so that processing of word *n* is not completed when the eyes move to the subsequent word) a regressive saccade may be programmed to return to this word at a later stage. Conversely, if full processing of word *n* is completed prior to the saccade execution, processing of word *n* + 1 will begin; if the first stage is also completed, the original saccade programme will be cancelled and a new programme initialised with word *n* + 2 as its target (Reichle et al., 2003; Reichle, Warren, & McConnell, 2009; Reichle, 2011). SWIFT, on the other hand, argues that words around the point of fixation are activated to different extents, dependent on early low-level processing which is carried out for multiple words in parallel, with saccadic shifts programmed at random intervals to the word within this area receiving the highest level of activation. The programmed saccade may be delayed up to a point by higher processing difficulty associated with the foveated word *n*, but this temporary delay may not be sufficient to complete processing; this would increase activation of this word and may lead to a later regressive saccade (Engbert & Kliegl, 2011;

Engbert et al., 2005). Both models provide a useful framework to understand how the complex task of reading may be executed, although neither has been able thus far to comprehensively account for all experimental findings (Engbert & Kliegl, 2011; Reichle, 2011). Consideration of how different reading situations alter processing may therefore help to inform further development in order to better distinguish which of these models is able to provide the better conceptualisation of the real-world reading process.

Other common measures (apart from eye movements) that have been used to investigate reading are reading speed, comprehension, accuracy, and recall. These are interrelated (e.g. comprehension may fall if reading speed is forced beyond a certain optimal rate; Kang & Muter, 1989; Rayner, Schotter, Masson, Potter, & Treiman, 2016), and may be affected by factors such as the complexity and familiarity of the text (e.g. comprehension and reading speed may both be increased if the text is familiar; Shimoda, 1993). However, although these are valuable measures, some care should be taken in their interpretation, as a low reading speed does not necessarily result in poor comprehension (e.g. Legge, Ross, Maxwell, & Luebker, 1989), and comprehension may be poor even in accurate reading (e.g. Nation & Clarke, 2004); it may therefore be important to use some of these measures in conjunction with each other or with other measures (such as eye movement patterns) to clarify their true functional significance with regards to reading quality.

Horizontally Scrolling Text

‘Scrolling’ text is used here to mean a single line of text moving horizontally from the right to the left of a screen in a smooth, pixel-stepped presentation. This format has previously been referred to in the literature by a number of terms including leading text (e.g. Öquist & Lundin, 2007), Times Square format (e.g. Kang & Muter, 1989), tickers (e.g. Maglio & Campbell, 2000), and drifting text (e.g. Valsecchi, Gegenfurtner, & Schütz, 2013; although some of these, in particular Times Square format, have been more commonly used to refer to text moved in steps of one or even several characters at a time, rather than the smooth pixel-stepped motion investigated here). It also holds a certain degree of similarity to the RSVP-with-flankers (or *passive reading*) paradigm used in some EEG studies of reading, where words are presented in a horizontal single line and are shifted to the left one word at a time in order to allow participants to read whilst holding a central fixation (important in EEG research in order to avoid processing artefacts associated with an eye movement rather than the neural signal; see e.g. Croft & Barry, 2000); this presentation similarly produces an apparent leftward motion of the text (e.g. Kornrumpf, Niefind, Sommer, & Dimigen, 2016).

Scrolling text is of theoretical interest, providing a challenging reading situation with scope to investigate the effect of factors including reduced sustained availability of text on successful text processing. This format also has a number of possible applications, including those which can be broadly divided into presenting unlimited text in limited spaces (for normal reading) and encouraging better reading practices (and thus resulting in an improvement in reading performance and ease) in cases of disordered vision resulting from damage, disease, or abnormality at various stages of the visual hierarchy. Both of these areas have been considered in research before (e.g. Bowers et al., 2004; Lin & Shieh, 2006): however, there are still considerable gaps in the understanding of this format compared to that established for reading of normal static text.

Whereas normal reading of static text has been well characterised, with detailed investigations into the oculomotor and cognitive processes involved as outlined above, little work has been carried out to investigate processing during reading of scrolling text. The demands for reading with this format are altered from the normal reading situation, as the movement of the text provides an additional dimension that must be considered by the oculomotor system in planning saccades, and also likely impacts on the online deployment of attention (cf. Kornrumpf, Niefind, Sommer, & Dimigen, 2016), with implications for cognitive processing. Neither of the key eye movement models of reading introduced previously (E-Z Reader or SWIFT; Engbert et al., 2005; Reichle et al., 2003) has attempted to consider what the effect of such a dynamic presentation of text would have on oculomotor control, meaning that it is not possible to derive specific predictions from these models regarding reading with this format.

However, according to the prominent 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, relying on the same neural circuitry. Essentially, shifts of attention are proposed to be part of the motor planning stage of an eye movement, which may subsequently be executed (resulting in an overt shift of attention and gaze) or terminated (resulting in a covert shift attention only). 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 enabling the simultaneous processing of a target at a spatially separate location (Deubel & Schneider, 1996). Under this paradigm, scrolling text would produce a conflict in the attentional system, with smooth pursuit programs to track the text as it moves leftwards conflicting with saccadic programmes planned and executed along the line of text from left to right as normal. It would seem likely that this would have some impact on other facets of cognitive processing, with this conflict possibly impacting both on the spatial deployment of attention and the cognitive load of the task. It may also complicate the production and maintenance of a spatial map of the text (cf. Kennedy, 1982), particularly given the reduced sustained availability of the text: both of which factors may reduce the feasibility of making long-range regressive saccades thought to play an essential supportive role in text comprehension (Schotter, Tran, & Rayner, 2014).

So far, much of the work on normal reading of scrolling text has come from a technological perspective, with focus only on performance measures such as the speed (e.g. Teramoto, Nakazaki, Sekiyama, & Mori, 2016), accuracy (e.g. Lin & Shieh, 2006), and comprehension (e.g. Kang & Muter, 1989) achievable when reading text presented in this way compared to in other formats (often on small screens such as wristwatches; e.g. Chien, Chen, & Wei, 2008; So & Chan, 2013). These studies have also largely been carried out in languages using a logographic writing system (as opposed to the alphabetic writing system of English; relevant because of differences in reading of normal static text which have been recorded with these different systems e.g. Jackson, Lu, & Ju, 1994;

Rayner, 1998). Furthermore, given that the target of this research has most often been to find an optimal way to present text in constrained windows, many of these studies have not included a comparison with normal reading of static text, but rather other dynamic presentation methods such as rapid serial visual presentation (RSVP; where words are presented sequentially for a short duration). Some findings from these comparisons have suggested that scrolling text allows better comprehension (Kang & Muter, 1989) and more accurate memory than RSVP, with this improved reading quality maintained better at increasing reading speeds and being reflected in a subjective preference for scrolling compared to RSVP text (Lin & Shieh, 2006). However, others have found no difference on such measures (e.g. Chien et al., 2008) or even worse performance with scrolling text (Juola, Tiritoglu, & Pleunis, 1995; although this study used 1 - 3 character jumps rather than a smooth pixel-scrolling method as is more typically used particularly in more recent studies, and will be investigated here), and some have suggested that the optimal presentation method is dependent on speed (with scrolling text recommended for speeds over 320 characters per minute in a comparison with RSVP and whole paged scrolling methods by So & Chan, 2013) and presentation window size.

The lack of consensus, and of appropriate comparisons, in the literature presented in this section up to this point therefore does not give rise to a particularly clear understanding of how reading is affected by the scrolling text format. One methodological tool which has been instrumental perhaps over all others in the investigation of the processes involved in reading static text has been eye tracking, with the study of the eye movements made during reading allowing inferences about the underlying cognitive basis of this task to be drawn. There has been very little discussion of eye movements during scrolling text to this point (with the notable exceptions of investigations by Buettner, Krischer, & Meissen, 1985 and Valsecchi et al., 2013). The primary finding from these studies which have investigated the oculomotor pattern employed for reading text presented in this way is that periods of smooth pursuit (a slow tracking movement employed to stabilise the retinal motion induced by a moving target; Krauzlis, 2004; Robinson, 1965) replace the fixation periods seen in reading of static text. 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 250 wpm; Rayner, 1998), dynamic visual acuity is comparable to that for static targets (Ludvigh & Miller, 1958).

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). 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). Voluntary nystagmus in particular is employed to stabilise an image at a selected location in a dynamic array (van den Berg, 1988); as is required to identify individual words in a moving sentence. 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. Buettner et al.’s suggestion that the changes can be attributed to difficulty in making these transitions may therefore 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 on-going 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).

With findings of a similar level of comprehension achievable as with static text, this perhaps suggests that the cognitive processes involved in reading scrolling text are relatively unchanged from normal reading, with differences only in the oculomotor processes as necessitated by the movement of the text. Valsecchi and colleagues (2013) propose an explanation for this effect, suggesting that the shift in preferred landing position is attributable to less precise saccadic targeting of words with scrolling text. However, although little research has looked at the processing of moving text, oculomotor tracking of other moving objects has been investigated, and this possibility may be supported by comparing retinal error in saccade tasks with moving and static targets, which appears to be similar in both cases; for instance reported as 1.71 ± 0.54^{o} in a static target task (Collins & Wallman, 2012) and as ranging from 0.32 - 1.6^{o} (SD 1.3 - 3.6 ^{o}) in a moving target task (Kim, Thaker, Ross, & Medoff, 1997), suggesting that the oculomotor system is able to program saccades as accurately to a moving as to a static target as long as it receives sufficient information about the speed of movement of the target (as would be the case of scrolling text with a constant presentation rate and possibly also in user-controlled text). In addition to this, it is suggested that good pursuit gain (the relationship between gaze and target position, where 1 is perfect tracking) is possible, with perfect tracking achievable with speeds up to around 10 ^{o}/s (Rashbass, 1961; Robinson, 1965; Young, 1971), and gain of around 0.9 - 1 achievable during smooth pursuit of targets with constant velocity under 20 ^{o}/s (Barnes, 2011; encompassing the comfortable range of text movement speeds e.g. as in Valsecchi et al., 2013). There is even some evidence to suggest that ocular tracking may be improved if the target requires additional processing (as is needed for reading; Shagass, Roemer, & Amadeo, 1976). This suggests that an explanation of saccadic targeting alone is unlikely to be sufficient to account for the shift in landing position seen by Valsecchi et al. (2013).

Two possible alternative explanations for their findings rely on the idea that attention may be deployed in a different way when reading scrolling text than in normal reading of static text, in order to accommodate the movement of the text. Firstly, there is some evidence that attention is focussed slightly ahead of the pursuit target during ocular pursuit (Van Donkelaar & Drew, 2002), and the shift in landing position recorded by Valsecchi et al. may therefore be needed to allow this. Alternatively, the shift could reflect an attentional conflict produced by the movement of the text as described previously, which may explain the extended processing time (reflected in longer fixation durations) seen by Valsecchi and colleagues (2013), with the shift in landing position possibly reflecting a compensatory mechanism to preserve some parafoveal preview. Fine and Peli (1996) investigated perceptual span in reading of scrolling text and found that this was shrunken compared to the normal extent established for static text (Rayner, 1998). However, the effect of the movement of text on the asymmetry of the span was not investigated, and their use of an ageing sample (median age 71, some with a degree of central vision loss; Fine & Peli, 1996) may have confounded their findings. These potential problems may be supported to some degree by a finding of no significant difference in span between this group and a low vision comparison group in this study, although a later study (Fine, Woods, & Peli 2001) replicated this effect with a sample with no reported visual impairment (but again with an aging sample). Studies focused specifically on establishing any differences in perceptual and visual span length for normal reading scrolling text, including looking for differences in the asymmetry of the spans (which was not considered in either previous study; Fine & Peli, 1996; Fine et al., 2001), would be useful to corroborate and extend these findings.

It is also possible that the added challenge of the strong cognitive component of text processing may lead to increased complexity in following scrolling text compared to other types of moving stimuli. In particular, the division of attention required to follow the text moving from right to left across the screen whilst also reading words as usual left to right may cause some additional difficulty (although it would be useful to characterise the effect of this on attention more precisely). Research into the effect of dividing attention on other cognitive tasks has suggested that performance is generally worsened for multiple tasks performed within one modality (e.g. Watter, Geffen, & Geffen, 2001; i.e. as opposed to cross-modality tasks), although it is uncertain how applicable these results are for reading scrolling text as there is typically a clearer division of attention to two separate tasks than this: while it is necessary to perform an oculomotor tracking task in parallel with the typical reading process, the task should be relatively simple assuming that the text is scrolled at a steady rate. However, it may also be more difficult to remember text once it has been read initially, as it subsequently moves out of the screen: a factor that also prevents regressions onto previous parts of the text, as is an important component of typical reading. Prevention of regressions (using a masking technique) in reading of static text has been shown to lead to a significant decrease in comprehension (Schotter, Tran, et al., 2014). This could be overcome by allowing user-control over the speed and direction of the text (allowing the text to be brought back into view as necessary), however this may be expected to increase the complexity of the tracking task, and has been shown previously to lead to worse comprehension levels (Chen & Chan, 1990).

This overview demonstrates the considerable gaps in understanding of reading with the horizontally scrolling format. A large part of this investigation is therefore dedicated to producing a more detailed overview of how presenting text in this way influences some of the key processes involved in reading: oculomotor (Chapter 2), linguistic (Chapter 3), and attentional (Chapter 4); and quantifying the effect of how changes in these aspects of processing affect text comprehension (Chapter 5).

Scrolling Text And Central Vision Loss

The other broad aim of this investigation is to explore the viability of scrolling text as a potential reading aid for individuals with central vision loss. One of the most prominent conditions involving central vision loss is age-related macular degeneration, which is the most common cause of legal blindness in individuals over the age of 65 (Friedman et al., 2004), affecting 4.8% of this age group in the UK (a figure which is projected to rise by a third by 2020; Owen et al., 2012). In age-related macular degeneration (AMD), cells in the high acuity macular area of the retina become inefficient in visual processing and eventually undergo degeneration. The early stages of the disease (prior to degeneration) are characterised by the build-up of a deposit known as drusen, in the photoreceptor layer and between the retinal pigment epithelium layer and the blood-retina barrier (Bruch’s membrane; Ambati & Fowler, 2012; Hoh Kam, Lenassi, & Jeffery, 2010; Johnson et al., 2002). This accumulation of drusen can lead to a form of AMD termed ‘dry’ AMD, in which RPE and photoreceptor cells degenerate, progressing in some cases to the more severe ‘wet’ AMD, consisting of overgrowth of blood vessels from the layer of vasculature behind the retina (choroidal vascularization; Ambati & Fowler, 2012) and possible rupture of Bruch’s membrane (Mousa, Lorelli, & Campochiaro, 1999). Either of these forms result in a loss of central vision of varying size and distribution (i.e. the impairment may be focused over part of or the whole of the central part of vision, and may either be absolute or more diffuse; Ergun et al., 2003; Nazemi, Fink, Lim, & Sadun, 2005; Sunness, Massof, Johnson, Finkelstein, & Fine, 1985). Wet AMD may also include some degree of visual distortion (metamorphopsia; Lim, Mitchell, Seddon, Holz, & Wong, 2012). Despite promising advances in gene and stem cell therapies (e.g. Carr et al., 2013; Evans & Syed, 2013), an effective cure still seems unlikely to become clinically viable for some years, and the importance of finding nonclinical interventions to help improve the quality of life of people with such conditions in the meantime is evident.

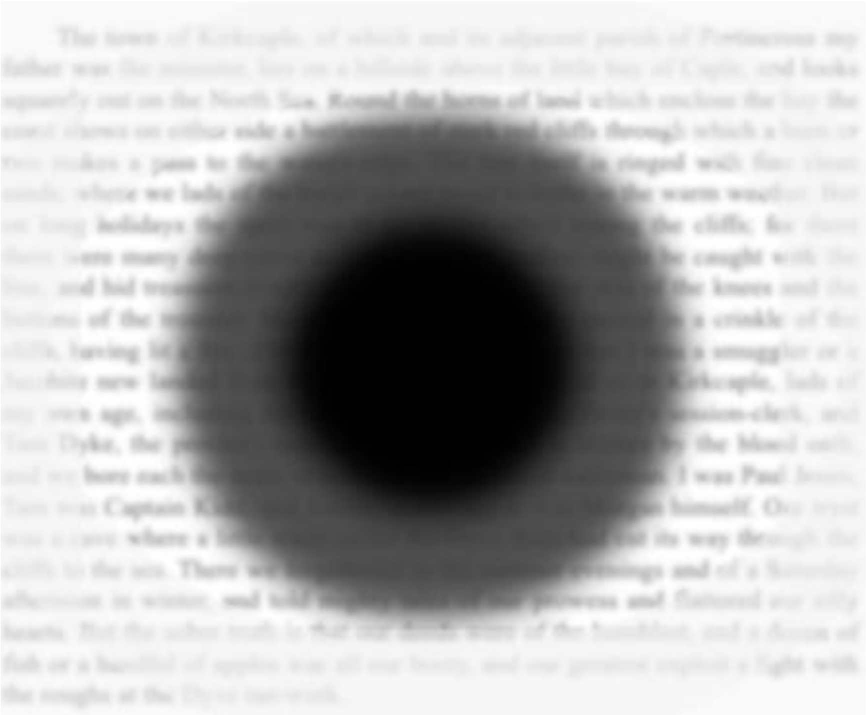

Figure 2. Representation of reading typical print with a central scotoma, such as in age-related macular degeneration.

The devastating effect of central vision loss on reading (such as represented in Figure 2) may be inferred from the earlier account of the reliance of reading on the high acuity centre of the retina, and difficulty reading is, accordingly, one of the most commonly reported problems in these conditions (Hazel, Petre, Armstrong, Benson, & Frost, 2000). The damage or loss of this part of the retina causes the typical overlearned pattern of eye movements employed in reading to become counterproductive, leading to an erratic pattern of saccades in a drive to continue foveating words (with around 54% of the variation in change in reading speed estimated to be explained by this factor; Crossland, Culham, & Rubin, 2004). Deruaz et al. (2004) have further proposed that the abnormal oculomotor behaviour seen in this population may also partly be deliberately manufactured, with saccades being made frequently between multiple PRLs in order to prevent Troxler fading, a perceptual effect whereby items in the periphery (as text is seen if fixated using a PRL under conditions of central vision loss) fade from conscious perception until the a movement of the scene or the eye is made, changing the pattern of light on the retina (Clarke, 1960): this occurs as fixation durations become longer (reflecting the increased difficulty in recognising words; Bullimore & Bailey, 1995), creating an additional obstacle in word identification. It has also been suggested that the forced shift to the peripheral part of vision results in a reduction in the perceptual span by around 4.5 characters (the shrinking perceptual span hypothesis; (Crossland & Rubin, 2006; Rubin & Turano, 1994), with evidence suggesting that this explains some of the decrease seen in reading speed independently to changes in saccadic behaviour (Crossland & Rubin, 2006); possibly via a need for an increase in the number of fixations required for successful reading (Calabrèse, Bernard, Faure, Hoffart, & Castet, 2014).

Two reading strategies in particular have been advocated (e.g. by the Macular Society who coordinate a peer training programme for these; Macular Society, 2014) to help reduce this difficulty: the Eccentric Viewing technique and Steady Eye strategy. The eccentric viewing (EV) technique involves making fixations at some position away from a target, deliberately using an area of the preserved peripheral retina known as the preferred retinal locus (PRL) to inspect it and therefore functionally replacing the fovea (Timberlake, Peli, Essock, & Augliere, 1987; Whittaker, Budd, & Cummings, 1988). Although this cannot overcome the loss of acuity, it is thought to improve reading performance via increased fixational stability (e.g. Nilsson & Nilsson, 1986; Palmer, Logan, Nabili, & Dutton, 2009; Palmer, 2009), helping individuals to establish a more functional PRL (i.e. directing stimuli to the most useful preserved part of vision) than they may establish without guidance (Gaffney, Margrain, Bunce, & Binns, 2014). The Steady Eye strategy is a related technique, advocated for use in conjunction with EV (although in some cases i.e. with a ring scotoma where there is some central sparing it may also be used without EV), which attempts to improve fixational stability even further, with the eyes being fixed at a particular position and a stimulus (such as text) being moved through the PRL to allow its inspection in the absence of saccades (Watson & Berg, 1983).

Training in the eccentric viewing technique has been shown to have some effectiveness in increasing reading speed, decreasing comfortable text size, and improving the comprehension and comfortable duration of reading static text (Palmer et al., 2009). Two recent reviews of EV training evaluation studies (including combined training with components such as steady eye strategy or saccadic targeting exercises) indicated that, although there were methodological issues (such as no control group, non-random assignment to groups, or assessors who were not blinded to the treatment group) in all studies reviewed, there was reasonable evidence for improvement and in various measures including near visual acuity, reading speed following EV training, and quality of life scales, with some suggestion of better maintenance of these gains than with common alternative techniques such as magnification alone (Gaffney et al., 2014; Hong, Park, Kwon, & Yoo, 2014). These improvements have even been shown to be possible even in relatively short training periods, with one study using auditory biofeedback based on recorded eye position (i.e. sounding a tone when the eye moves out of an eccentric position to encourage more conscious control of eye movements) showing increases of 22% in reading speed in a relatively short training period of only 1.5 hours (Hall & Ciuffreda, 2001).

Less attention has been paid to the effectiveness of encouraging use of steady eye strategy, although, as noted, some reports have shown some success with a low vision reading intervention incorporating EV and steady eye training (e.g. Palmer, 2009). A similar approach has also been investigated for RSVP, where words are presented sequentially in one place. This has been shown to allow a reduction in eye movements needed to read text in a sample with central visual impairment, resulting in an increase in reading speed (Rubin & Turano, 1994). However other studies have not replicated the reading speed improvement, and there is some evidence from studies which have collected subjective ratings that RSVP is not always a particularly well-liked text format for reading (e.g. Bowers, Woods, & Peli, 2004; Harland, Legge, & Luebker, 1998). RSVP may also be less than ideal as a reading aid as it eliminates the parafoveal preview, shown to have an important role in fluent reading (Schotter, Angele, & Rayner, 2012). Scrolling text, on the other hand, preserves this preview, and has fared better in subjective ratings (Bowers et al., 2004; Harland et al., 1998; Walker et al., 2016; Walker, 2013). This format could also theoretically allow use of the steady eye strategy, with all text scrolling past a fixed viewing point subverting the need for eye movements altogether. Given that reading speed in participants with central vision loss has been found to be positively correlated with number of fixations needed for reading (Calabrèse et al., 2014), this may even allow potential for improved reading speed beyond that of static text.

Although clearly far from ideal (i.e. due to the additional attentional demands discussed previously in terms of normal reading, and also the loss of useful structural information conveyed by the layout of static text such as paragraphs), previous research has highlighted the usefulness of a scrolling text presentation format for other visual disorders such as hemianopia (e.g. Ong et al., 2012), and the possibility of using this format as a reading aid with central field loss has been explored before (see e.g. Bowers et al., 2004; Legge et al., 1989; Walker et al., 2016; Walker, 2013). In theory the movement of the text may also prevent problematic Troxler fading which has been suggested to be a factor in necessitating frequent saccades (Deruaz et al., 2004). However, although there have been some positive results supporting its use, there remains a lack of consensus over whether or not this format is helpful. Research has previously investigated the usefulness of scrolling text as an aid for central vision loss, although often these studies have not reported asking for or determining adherence to the strategies described in the previous paragraphs (although one simulated scotoma study showed increased fixational stability via enhanced adherence to EV and improved reading accuracy with scrolling text when participants were specifically asked to try to use the steady eye strategy, and adherence was monitored; Harvey & Walker, 2014), and some have investigated a low vision sample where all participants have a visual impairment but not necessarily one affecting central vision (e.g. participants may have conditions such as glaucoma, primarily affecting more peripheral vision, or cataracts, where the lens becomes blurred; e.g. Legge, Ahn, Klitz, & Luebker, 1997). This former point is largely as a result of a different approach to scrolling text as a potential aid, where it has been hoped that the movement of the text would entrain the oculomotor system into the relatively more automatic (as opposed to the normal reading saccades) optokinetic nystagmus-like pattern described previously in terms of normal reading of scrolling text, overriding in this way the problematic erratic saccades (Fine & Peli, 1996).

Despite this, several studies have shown a benefit of this format. For instance, Legge and colleagues found reading speed to be 15% faster with scrolling than static text in a low vision sample (Legge, Ross, Luebker, & Lamay, 1989), and that comparable comprehension levels to controls with normal vision were achievable with scrolling text if the movement of the text was sufficiently slow (Legge, Ross, Maxwell, et al., 1989). Walker et al. (2016) furthermore reported improved reading accuracy with scrolling text (compared to single lines of static text). Other studies comparing scrolling text to a number of other formats (including static text and RSVP) have variably showed some or no reading speed benefit, but with a subjective preference for this over other formats regardless (Bowers et al., 2004; Harland et al., 1998). This preference has also been replicated with an AMD sample in a report of a novel reading application for iPad using scrolling text (with 8 of 12 participants rating the reading with scrolling text more favourably; Walker, 2013), and may feasibly underlie the popularity of aids such as CCTV devices and stand magnifiers (Ahn & Legge, 1995), which require text to be moved manually under the device creating a similar effect to horizontally scrolling text as described here. This may be able to be explained by an effect shown for example by Brown (1972) and Bex, Edgar, and Smith (1995), where there is a small degree of sharpening in the perception of moving stimuli above that of static stimuli in peripheral vision for velocities under 10^{o}/s; identified as a reasonable presentation speed for reading horizontally scrolling text with normal vision (e.g. Valsecchi et al., 2013; i.e. presentation speed with central visual impairment can be expected to be comfortably lower than this).

One possible issue to consider with reading using eccentric viewing technique is visual crowding. Crowding is a perceptual effect wherein objects may not be distinguished in the periphery if they are placed too closely together (Whitney & Levi, 2011). The critical distance between elements increases with increasing eccentricity of the stimuli (Bouma, 1970), meaning that it may not be sufficient just to enlarge text for eccentric reading, with adjustments to other aspects of the text such as the word and line spacing (the latter for multiline text only) could be important to optimise reading ability. Although Bouma’s findings were based on letter spacing in particular, the task used to establish this was a letter identification task: for improving eccentric reading, word spacing in particular rather than letter spacing is likely to be useful, as reading is generally thought to be aided by whole-word form information (as evidenced by findings such as increased cost for non-similar than similar visually similar parafoveal preview substitution and the decrement of reading performance when word spacing information is eradicated; Epelboim, Booth, Ashkenazy, Taleghani, & Steinman, 1997; Hyönä, Bertram, & Pollatsek, 2004; Rayner, 1998). This information may be lost to some extent with increased letter spacing, likely explaining the decrement in reading performance when letter spacing is increased much above typical spacing, both in normal and eccentric reading (e.g. Chung, 2002). However the benefit of increased word and line spacing has been shown in a study of reading of static text with central vision loss, showing improved reading performance with static text under these conditions (Blackmore-Wright, Georgeson, & Anderson, 2013). This may have to be an even greater consideration for scrolling text, with evidence that crowding is increased during smooth pursuit for information in the opposite direction to the pursuit (Harrison, Remington, & Mattingley, 2014); i.e. in the case of reading for the upcoming text which in normal reading would be the region of text in the parafoveal preview, from which readers may begin processing words and planning subsequent saccades. It may therefore be helpful to have even slightly wider word spacing than for static text to overcome this; although it is not clear what impact implementation of the steady eye strategy would have on this effect, or at what level increased word spacing might become counterproductive. Investigation of such display factors is clearly needed to optimise the use of the scrolling text format as a reading aid for this population.

Thesis Plan

To address the issues identified by the overview of the literature presented in this chapter, this thesis consists of two sections, with Chapters 2 - 5 providing an account of investigations into normal reading of scrolling text, and Chapter 6 considering the application of this format as a reading aid.

Chapter 2 examines global changes in the oculomotor pattern required for reading scrolling text at two different speeds: a comparable speed to the average for reading static text, and half this speed. To do this, data is pooled from Experiments 1 - 3, which are presented in full in Chapter 3.

Chapter 3 investigates three key linguistic effects that have previously been established using oculomotor investigation in normal static reading: Experiment 1 investigates two lexical processing effects, the word length and word frequency effects; and Experiments 2 and 3 investigate a sentence-level processing effect, the predictability effect (Experiment 2 comparing the faster scrolling rate with static text, and Experiment 3 comparing across the two scrolling rates). These latter two experiments are also combined to compare the predictability effect across all three text display conditions.

Chapter 4 discusses the impact of the horizontal movement of text during reading on the deployment of attention via the well-established gaze-contingent window method, using a variety of different window extents to characterise how this changes (Experiments 4 and 5).

Chapter 5 continues to look at the functional impact of the changes reported in previous chapters on reading comprehension, with Experiment 6 comparing scrolling (both faster and slower rates) and static text on deeper measures of comprehension than are typically used in reading research using oculomotor measures to investigate linguistic processing, such as is reported in Chapter 3. This experiment also considers whether working memory load might provide an explanation for a decrement in text comprehension with scrolling text.

Finally Chapter 6 moves away from normal reading to investigate the scrolling text format with a view to it being applied as a reading aid for populations with central vision loss (CVL). To this end, Experiments 7 and 8 use a gaze-contingent paradigm to investigate scotoma size and inter-word spacing (Experiment 7), and reading comprehension (Experiment 8) with a simulated central scotoma. In particular, Experiment 7 considers some factors that may help to optimise the presentation of scrolling text for use to improve reading with a CVL, whilst Experiment 8 compares scrolling and static text on a sustained reading task.

The conclusions and implications of all the experiments are discussed in Chapter 7.

Aims

The aims of this investigation are therefore:

- To characterise some of the linguistic and attentional processes involved in normal reading of scrolling text; to understand how and why these differ from reading of static text, and to assess the functional impact of these changes on understanding.
- To investigate the possibility of implementing scrolling text as a reading aid for individuals with conditions including central visual impairment such as age-related macular degeneration, when used in conjunction with the established techniques of eccentric viewing and steady eye strategy.

Hypotheses

The hypotheses are correspondingly that:

- Word-level lexical processing (reflected by the word length and word frequency effects) will be similar for reading of scrolling text to those seen in reading of static text.
- Sentence-level integration of information will be negatively affected by the presentation of text in this way.

- Attentional processes will be affected by the additional demand of tracking the movement of the text in the opposite direction to that of reading (and this will be reflected in measures such as the perceptual span).
- Comprehension in a sustained reading task will be reduced with scrolling text.
- Optimisation of the presentation of the scrolling format will improve measures of reading performance under conditions of a simulated loss of central vision.
- Scrolling text will result in improvements to sustained reading comprehension under these viewing conditions, compared to paragraph-form static text.

Chapter 2: Characterisation Of Changes To The Global Oculomotor Pattern When Reading Scrolling Text

Introduction

As introduced in Chapter 1, the organisation of the visual system necessitates an active oculomotor approach to reading, with saccades made to bring text into the high-acuity foveal region for identification of individual words at fixation; and the exact properties of these saccades and fixations are also influenced by characteristics of the text to be read (Clifton et al., 2016; Rayner & Liversedge, 2011; Rayner, 1998; Reichle, Pollatsek, Fisher, & Rayner, 1998). Extensive work has been carried out to examine the oculomotor and cognitive processes that take place during reading of static text (see Rayner & Liversedge, 2011; Rayner, 1998; 2009; Vitu, 2011 for reviews). However, as noted in Chapter 1, to date, there has been very little research to investigate reading behaviour when text is presented in the dynamic horizontally scrolling format.

This format poses an additional 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. 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. The scrolling format can therefore be expected to have a significant impact on oculomotor behaviour at a global level (i.e. the average pattern seen across the whole text stimulus; this chapter) and a local level (i.e. looking at oculomotor behaviour elicited by specific ‘target’ words manipulated for particular characteristics; explored in Chapter 3).

Only a small number of studies have investigated the oculomotor changes induced by scrolling text thus far (notably Buettner, Krischer, & Meissen, 1985; Valsecchi, Gegenfurtner, & Schütz, 2013), with the key finding from these studies being that the typical ocular fixations made on most words in the text for identification must be replaced with periods of smooth pursuit, to track each ‘fixated’ word as it moves during the identification period. These episodes of oculomotor pursuit are employed to stabilise the retinal image of the moving words and to maintain the reader’s current position within the text stimulus whilst processing of the currently tracked word is completed. 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, they will hereafter be referred to as fixations, reflecting their similar functional role.

As reviewed in more detail in Chapter 1, Buettner et al. (1985) provided a brief overview of changes to the oculomotor strategy with scrolling text, recording longer fixation durations, lower fixation count, shorter average saccade amplitude, and a slower reading speed. Valsecchi et al.’s (2013) report of oculomotor behaviour with scrolling text was more detailed in this regard, corroborating the finding of an increase in average fixation durations with scrolling compared to static text, but additionally reporting an accompanying small increase in the dispersion of saccade landing positions. This was interpreted as reflecting the increased difficulty in saccadic targeting for the dynamic stimulus, accounting for the increase in fixation duration. There is some support from pursuit tasks with non-text dynamic stimuli for a reduction in the accuracy of saccadic targeting (Gellman & Fletcher, 1992), but other studies (e.g. Beers, 2001; Blohm et al., 2005; Havermann et al., 2012; Ohtsuka, 1994; Schlag, 1990) suggest that the oculomotor system is able to adjust well to a shift in target position during the interval between saccade launch and landing if the target speed is constant. These findings suggest that any loss of targeting accuracy during reading of scrolling text (as suggested by Valsecchi et al., 2013) should be minimal, with a correspondingly minor impact on text processing. Furthermore, the interpretation of this finding as explaining the rise in average fixation duration does not take into account Buettner et al.’s (1985) finding of reduced fixation count, which would indicate that a more likely explanation of this inflation in processing time would be a reduction in refixation probability.

One way in which the movement of the text might have an impact on text processing and reading performance is via altered demands on the visuospatial attention system. The conflict in attentional deployment that occurs when reading scrolling text as outlined in Chapter 1 may contribute to 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 et al., 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 ahead of the direction of movement of the target. 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. This would suggest that the available preview in scrolling text may be reduced, as the equivalent fixation durations are indicative of a similar level of preprocessing having occurred prior to fixation, whereas if the preview was equivalent with both formats a higher degree of preprocessing would be assumed for the shorter saccade lengths seen with scrolling text and therefore relatively shorter fixation durations to complete processing would be expected.

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 reading of scrolling text, where the demands of linguistic processing occur concurrently with pursuit of the scrolling text. This may therefore also contribute to higher levels of foveal processing load.

A final consideration for scrolling text is that the words eventually move out of the limits of the screen, 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 as achievable with scrolling as with static text by Valsecchi et al., 2013), readers may be forced to adopt a more careful reading strategy than they do when reading static text. Specifically, it may be important for readers to ensure that they identify and linguistically process words correctly during first pass inspection because the words 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 expected to be the case that they would make longer average fixation durations for scrolling compared to static text. This prediction is consistent both with the results of previous reports of reading scrolling text (Buettner et al., 1985; Valsecchi et al., 2013), and 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). A more detailed consideration of other aspects of the global oculomotor pattern is required to verify whether other adaptations (such as lower levels of word skipping and shorter saccade amplitudes) are also made which would be consistent with this proposed change in reading strategy.

In addition to these effects, a reduction in long-range regressive saccades might also be expected, 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 therefore be reasonably expected that regressive eye movement behaviour for reading of scrolling text may be similar to that observed in other reading paradigms where the opportunity for regressions is limited (e.g., Fischler & Bloom, 1980; Schotter, Tran, & Rayner, 2014).

Experiments

Two experiments were carried out to investigate the impact of horizontally scrolling text on these core oculomotor processes (as well as the ‘Big Three’ effects of linguistic processing [Clifton et al., 2016], which are discussed in detail in Chapter 3). These experiments therefore aimed in the first instance to further characterise aspects of global oculomotor behaviour during reading of scrolling text, comparing scrolling and static text read at approximately the same rate (with the scrolling text displayed at a rate close to 250 wpm, known to be around the average normal reading speed for static text; Rayner, 1998). This was similar to the rates investigated by Valsecchi et al. (2013) in their investigation of scrolling text. The rate used by participants in Buettner et al.'s (1985) investigation was set individually, but the average speed used was somewhat slower than this at 148 wpm.

In line with previous research (Buettner et al., 1985; Valsecchi et al., 2013), a pattern of periods of smooth pursuit to track the moving words that replace static periods of fixation in normal reading was expected. These periods were expected to be of longer duration than typical fixations, and a corresponding decrease in fixation count and refixation probability was predicted. Previous work has produced conflicting results with regards to saccade length during reading of scrolling text. However, as previously discussed, it was expected that slippage between the point of fixation and the scrolling word under fixation might occur, that there might be a reduction in the rightward extent of the perceptual span due to an attentional conflict, and that foveal processing difficulty might be increased for scrolling text (Henderson & Ferreira, 1990; Jacobs, 1986; Rayner, 1998; White et al., 2005). These factors were therefore predicted to reduce average saccade amplitudes compared to static text, and were also expected to result in a reduced level of word-skipping due to a reduced parafoveal preview. A particular reduction was also predicted for regressive saccades 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).

Launch and landing site distributions across words of different lengths for scrolling text were also investigated to assess the influence of the movement of the text on reader's ability to target words in a similar way to as with static 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), the impact of this format on launch and landing site distributions was expected to be minimal (cf. Valsecchi et al., 2013) when participants were reading scrolling as opposed to static text.

Methods

The methods for Experiments 1 and 2 are detailed below to preface the global oculomotor analyses across these studies presented subsequently.

Experiment 1

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, no reading or language impairments, and spoke British 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). These stimuli were chosen because they have been previously established to elicit robust effects of word length and word frequency on oculomotor behaviour: replication of these effects in the static text condition therefore provides a solid empirical basis from which to interpret the findings of the novel scrolling text comparison. 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 per million occurrences, compared to 5 per million occurrences for low frequency words (Kucera & Francis, 1982; Pollatsek et al., 2008); 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 $t(46) = -21.06$, $p < 0.001$). Overall, these sentences had on average 10.7 words (SD 1.6) and 63.9 characters (SD 8.3). Each participant read one version of any given sentence frame e.g. *The judge* *summoned the* [*thin / rude / popular / fabulous*] *solicitor to the bench*. Four files were prepared in which items were rotated across conditions according to a Latin Square design. Each file contained all of the 48 sentences with a quarter of the items appearing in each condition, and each item appeared in a different condition across files. No participant was presented with the same sentence frame twice. The files were each additionally split into two halves, with each participant shown one half (i.e. containing 24 experimental sentences) presented as scrolling text and the other half as static text.

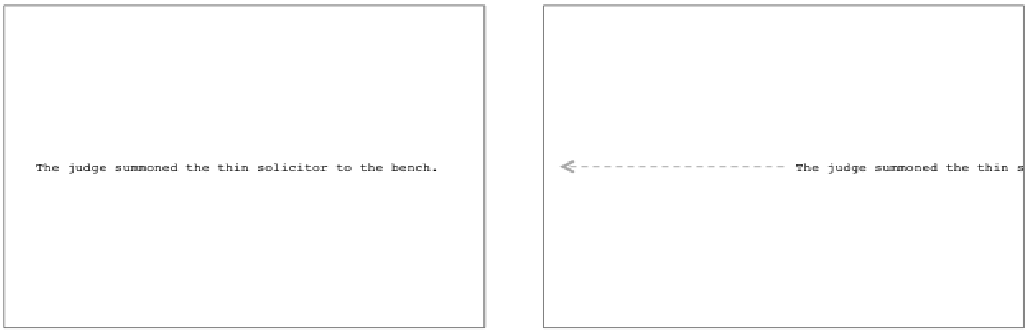

Figure 3. Presentation of static (L) and horizontally scrolling (R) sentences in Experiment 1. The arrow in the right pane indicates the motion of the text, and was not visible to participants.

All sentences were displayed in black Courier font (12 pt; horizontal character width 11 px, 0.4°) with a white background on a 1024 x 786 pixel (96 DPI) CRT monitor running at a refresh rate of 100 Hz. Each sentence was displayed centrally in the vertical axis (i.e. with a y coordinate of 384 pixels; see Figure 3). Static sentences were displayed in a single line, offset from the leftmost edge of the screen by 80 pixels. Scrolling sentences appeared at a position 80 pixels offset from the centre of the screen (i.e. with x-y screen coordinates (592, 384)), and began moving at the constant rate of 3 pixels per screen refresh after a delay of 12 screen refreshes. This delay was introduced following initial pilot studies (conducted with n = 18 participants who did not take part in the main experiment to confirm a comfortable display speed for the scrolling condition), where participants reported perceiving an initial blurring of the text stimulus if it started moving immediately as the trial started. The viewing distance was 70cm, sustained by 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 recorded 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 (i.e. low and high frequency long words and low and high frequency short words) 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 similar characteristics but no manipulated target word. 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 verify that participants were engaging with the task to a satisfactory level. A key press was required to end the trial as soon as reading of the sentence was complete. One participant was excluded from the analyses due to poor comprehension scores (less than 75% of the questions answered correct on both display formats), and 7 more excluded due to poor data quality, leaving 75 participants in the final analyses. 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 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 prior to the presentation of each sentence. 5.4% of trials were excluded due to poor calibration and participant error. Sentence onsets took less than 0.5 s to trigger on average. Text in the scrolling text condition moved from its starting position in the centre of the screen horizontally across the screen from right to left at a rate of 3 pixels per refresh, equating to around 240 words per minute for the sentences used. This rate was chosen as it is close to the normal reading rate for static text (around 250 wpm; Rayner, 1998), and was verified as a comfortable reading speed with 18 pilot participants allowed to set their own display speed from a range of speeds increasing from a minimum of 80 wpm (with no maximum available display speed).

Analytic Approach

All analyses were carried out using RStudio 0.98.953 running R 3.0.3 (R Core Team, 2014), with eyeTrackR and ez packages (Godwin, 2012; Lawrence, 2013). Scrolling and static text were analysed and processed in an identical fashion, with periods of smooth pursuit in scrolling text treated as fixations. This approach was taken in order to provide equivalent periods for analysis with both text formats, allowing the patterns of oculomotor behaviour in reading with scrolling text to be considered within the context of the existing literature based on static text. These periods were delineated as any time spent looking at the screen not flagged as a blink or a saccade (using a saccadic velocity criterion of 30 ^{o}/s). An in-depth characterisation of the velocity profile of such periods made in response to the scrolling text format, confirming these as consisting of smooth pursuit (as opposed for example to a series of microsaccades) was carried out by Valsecchi et al. (2013). As such, a similar profile was assumed for these periods in all studies presented in this investigation. 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. Multiple comparisons were corrected for using the Bonferroni criterion throughout.

For the local analyses (Chapter 3), a region of interest was drawn around each word in the sentence (with the space before the first letter of a word included with 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). When this occurred, if a fixation on one of the two words lasted 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 4. Following this procedure, fixations shorter than 80 ms and longer than 1200 ms were removed from the analysis (as is standard in eye movement experiments investigating reading).

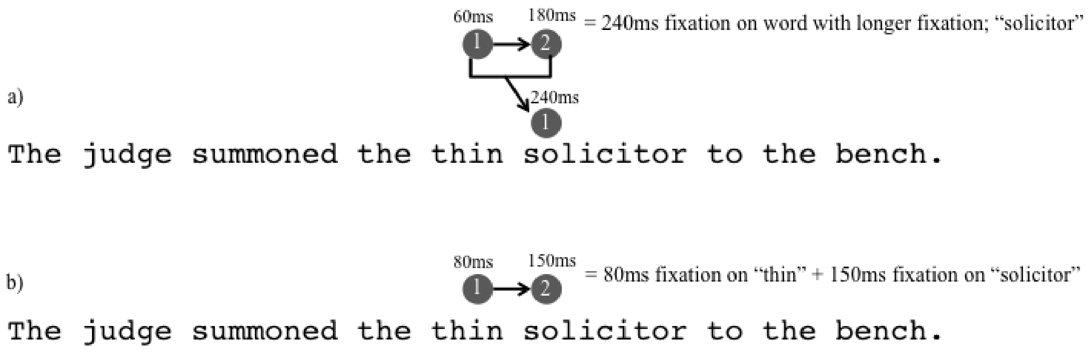

Figure 4. Allocation of split pursuit periods to a single word for scrolling text analysis: during pursuit period spanning two words, if the duration spent on one word was less than 80 ms (a), the duration of these were pooled onto the word where the majority of the pursuit period occurred (i.e. for this example, 60 ms spent at the end of the word 'thin' and 180 ms spent on the next word 'solicitor' would be allocated as a single fixation pursuit of 240 ms on 'solicitor'); however, if more than 80 ms was spent on each word (b), this was recorded as two separate fixations (i.e. for this example, an 80 ms fixation would be allocated to the word 'thin', and a separate 150 ms fixation allocated to the word 'solicitor').

Experiment 2

Participants

Eighty-one students from Royal Holloway University of London (mean age 21.2 years, SD = 1.9, 69 female) took part in Experiment 2. All participants had self-reported normal or corrected-to-normal vision, no reading or language impairments, and spoke British 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 [*a) Russell had hurt his hand in the door of the car./ b) 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 version *a)* of the first sentence, with possible candidate words to complete the second sentence being constrained by the semantic context of the word *hand*. This second (experimental) sentence contained on average 11.5 words (SD 2.6) and 53.7 characters (SD 15.2). Two files were constructed such that if a high predictable target word appeared in one file, the low predictable counterpart word appeared in the other file. 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 sentence pairs 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).

All sentences were displayed similarly to in Experiment 1 at a viewing distance of 70 cm in black, 12 pt Courier font (horizontal character width 11 px, 0.4^{o}) with a white background on a 1024 x 786 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 (250 Hz sample rate).

Design

This experiment employed a 2 (Display Format: static vs. scrolling) x 2 (Word Predictability: high vs. neutral) within-subjects and within-items design. This gave four conditions (with high and neutral predictability sentences displayed in both static and scrolling format). Predictability was rotated across files according to a Latin square design. Each participant saw each sentence pair in one condition only and the order of factors was counterbalanced across participants.

Procedure

Participants were asked to read 74 sentence pairs (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 (e.g. for the sentence pair *The weatherman warned people about going outside. He was worried about the wind knocking someone over*., participants were asked *Did the weatherman warn people about going outside?*). 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 5.35) 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). The procedure was otherwise as for Experiment 1.

Results

Global oculomotor measures were computed on the data pooled from Experiments 1 and 2 in order to maximise statistical power, giving 148 participants for this analysis. These measures were as follows: 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 (and the probability of regressing to these skipped words), the probability of making a regression, the probability of refixating a word, the average horizontal position of the eye on the screen during reading, the average velocity of the eye compared to the text velocity during reading of scrolling text, the resulting amount of position ‘slip’ during a fixation period, and landing and launch sites (for 3 - 9- letter words). Furthermore, for scrolling text only, the proportion of the text stimulus left on the screen at the termination of a trial was calculated.

Table 1. Main global reading measures for scrolling and static text: 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.

	Skipping probability (%)	**Average fixation duration (ms)**	**Number of fixations**	**Refixation probability (%)**	**Average saccade amplitude (chars)**			**Regression probability (%)**	**Total sentence reading time (ms)**
					Overall	**Forward**	**Regressive**		
Scrolling	27.06 (0.89)	220.65 (2.39)	12.36 (0.27)	23.61 (1.26)	5.18 (0.12)	4.56 (0.13)	6.18 (0.15)	49.65 (0.65)	2707.05 (66.78)
Static	25.70 (0.92)	209.99 (2.38)	13.89 (0.33)	27.95 (1.25)	7.98 (0.11)	6.85 (0.10)	12.54 (0.34)	24.19 (0.75)	2903.86 (77.09)
P value	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	0.002

Paired sample t-tests were computed for each of these 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 ($t(147) = -6.92$, $p < 0.001$, $d = 0.57$), with the average duration of these fixations increased by 11 ms with scrolling text relative to the duration of fixations made on static text ($t(147) = 6.27$, $p < 0.001$, $d = 0.52$). Relatedly, refixation probability was also reduced when reading scrolling text ($t(147) = -3.897$, $p < 0.001$, $d = 0.32$), 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 increase in average fixation duration seen for scrolling text.

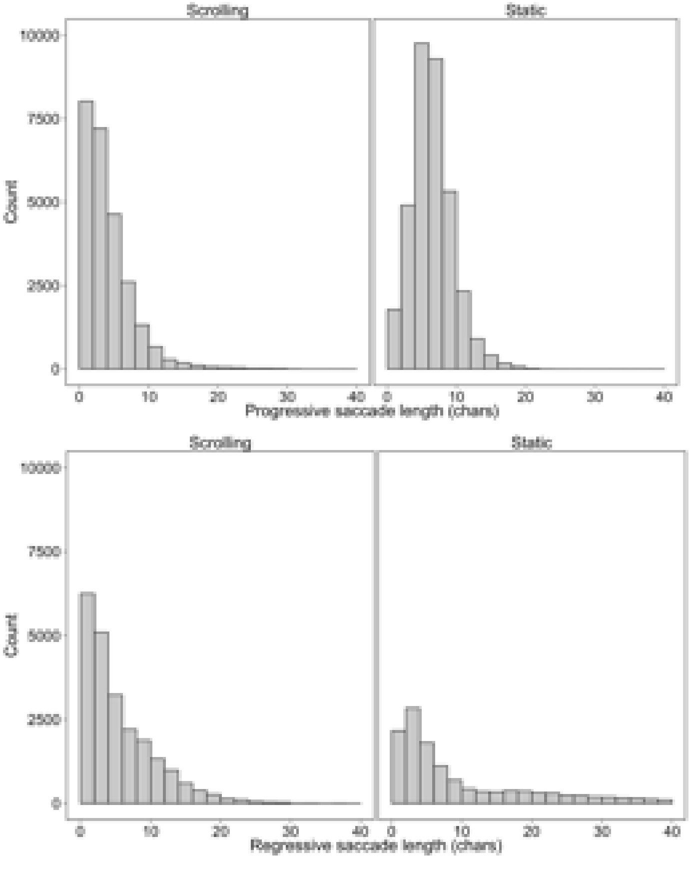

Figure 5. The frequency of saccade amplitudes (in characters) made by all participants during reading scrolling (left panes) and static (right panes): for progressive (upper pane) and regressive (lower pane) saccades.

Mean saccade length was reduced by 2.80 characters ($t(147) = -24.50$, $p < 0.001$, $d = 2.01$), and the probability that readers made a regression increased significantly ($t(147) = 23.88$, $p < 0.001$, $d = 1.97$) when they read scrolling compared with static text. The overall saccade data was also split to examine progressive and regressive saccades separately (see Figure 5). Regressions were 6.36 characters shorter for scrolling than for static text ($t(147) = -16.79$, $p < 0.001$, $d = 1.38$). Consistent with predictions, longer-range saccades were less common in the scrolling text format, 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 ($t(147) = -21.33$, $p < 0.001$, $d = 1.74$), 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.

Contrary to what was predicted, skipping rates were significantly higher with scrolling text (by 1.36%); $t(147) = 3.53$, $p < 0.001$, $d = 0.29$. This finding was unexpected, due to the hypothesised reduction in the effective parafoveal preview with this format, and is considered further in the Discussion. Furthermore, a lower percentage of skipped words were later returned to for direct fixation in scrolling than in static text ($t(147) = -7.17$, $p < 0.001$, $d = 0.59$; 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.

Total sentence reading time was on average 197 ms shorter, not longer as predicted, for scrolling compared to static text sentences. This comparison was significant; $t(147) = -3.19$, $p = 0.002$, $d = 0.26$. Although this effect differs from some of the previous research examining reading of scrolling text, it may be explained by the slightly 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 words per minute, compared to around 240 wpm here; comparison of total reading time 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%). This confirms that the slight decrease in reading duration with this format was not forced by the availability of the text. Furthermore, average horizontal position of the eye on the screen was also significantly different for the different display formats ($t(147) = 28.29$, $p < 0.001$, $d = 2.32$), with a sharp peak slightly to the right of the centre of the screen in reading of scrolling text compared to a relatively flat distribution of eye position across the full extent of the screen in reading of static text (as required to read along the extent of static sentences; see Figure 6). This further 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.

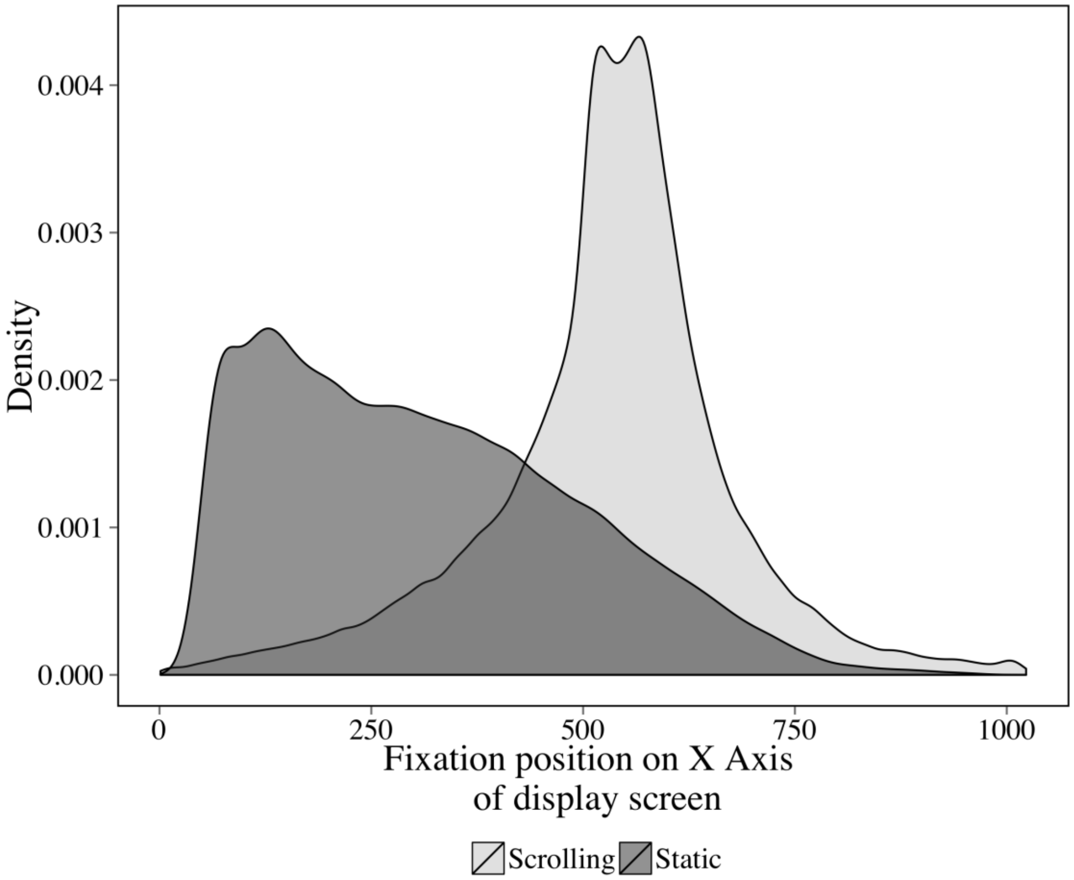

Figure 6. Density distribution of fixations made by all participants in the x-axis of the display screen during reading for scrolling and static text

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 ($t(147) = 21.52$, $p < 0.001$, $d = 1.77$; see *Figure 7*). This disparity resulted in a significant difference between the distance (in characters) the eyes travelled during a fixation period for scrolling and static text ($t(147) = -19.37$, $p < 0.001$, $d = 1.59$), with 0.9 (SE 0.03) characters travelled during a pursuit period in reading of scrolling text compared to 0.4 (SE 0.02) characters during a typical fixation in reading of static text.

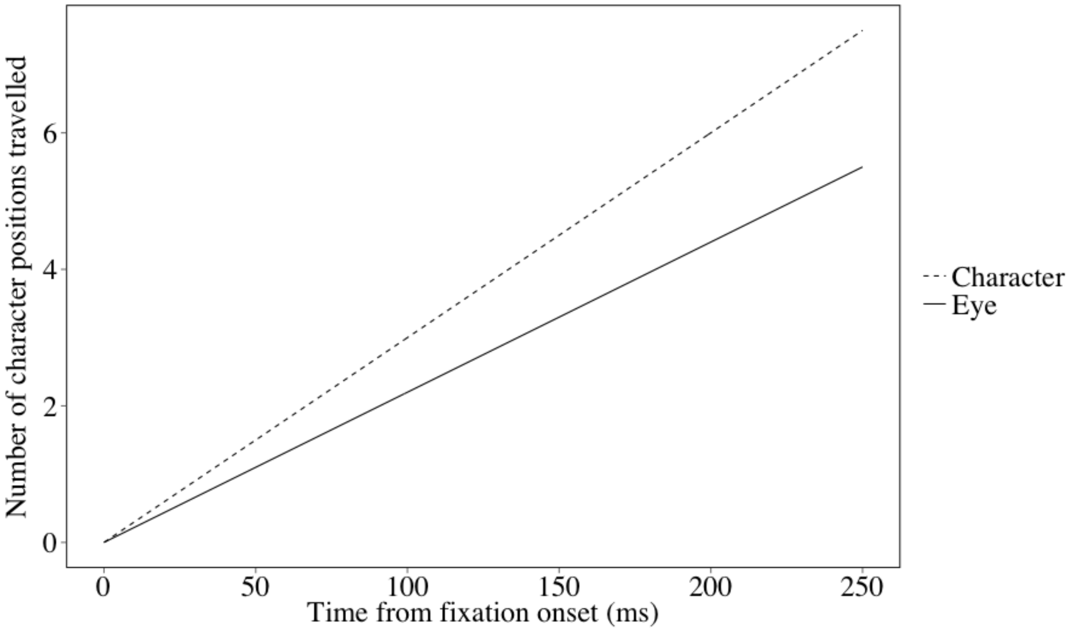

Figure 7. Comparison of the average number of character positions moved by an initially foveated scrolling character (dashed line) and the eye during pursuit fixation phases (full line) during an example pursuit fixation of 250 ms. Text velocity was constant at 0.3 pixels/ms. This comparison demonstrates 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, the landing position data for scrolling and static text conditions were grouped into single character bins for each constituent letter of words of the same length that appeared in the sentences (3 - 9 letter words). The resulting frequency distributions are shown in *Figure 8*. Mean landing positions were analysed with 2 (Display Format) x 7 (Word Length) ANOVAs. These analyses showed an effect of display format $F(1, 143) = 32.35$, $p < 0.001$, $\eta_G^2 = 0.02$, with the mean landing position shifted by 0.18 characters further into the targeted word for scrolling compared to static text (scrolling mean 3.04 SE 0.03, static mean 2.87 SE 0.03). Unsurprisingly, word length also had a significant effect on landing position $F(6, 858) = 278.72$, $p < 0.001$, $\eta_G^2 = 0.45$, showing a standard finding (Rayner, 1979) of the mean landing position advancing further into the word as length increased. These patterns of landing positions are very similar to those seen previously for static text. These factors were also found to interact $F(6, 858) = 6.28$, $p < 0.001$, $\eta_G^2 = 0.01$, with pairwise comparisons indicating that the differences in landing positions across static and scrolling text were only significant for 3-, 7-, and 8- letter words. These results indicate that the movement of text in the scrolling text format did not reduce the accuracy with which participants targeted their saccades to upcoming words, as a more consistent difference in landing positions across word lengths would be expected if this was the case. Furthermore, there was no evidence of an increased dispersion of landing positions; see *Figure 8*. This suggests that under scrolling text conditions readers were largely able to compensate for the movement of the text in order to target saccades to an optimum position within a word (Rayner, 1979). Readers were able to do this as effectively under scrolling text conditions as they could when reading static text.

The effects of word length and display format on launch site were also investigated (see Figure 9). Display format had a significant effect on launch site $F(1, 140) = 6.44$, $p = 0.01$, $\eta_G^2 = 0.005$, with saccades launched from 0.1 characters closer to the subsequently fixated word in scrolling text than static text (scrolling mean 3.09 SE 0.02, static mean 3.19 SE 0.02). This is likely due to the slippage in fixation position through the word and reduced saccade length seen when participants read scrolling text. Word length again also had an effect on launch site, $F(6, 840) = 31.82$, $p < 0.001$, $\eta_G^2 = 0.08$, as found previously for static text, with closer launch sites for longer than shorter words. These two factors also interacted, $F(6, 840) = 2.84$, $p = 0.009$, $\eta_G^2 = 0.01$, with significant differences between static and scrolling text only for 3- and 7- letter words indicating that, as for landing position, this was not a consistent effect across all word lengths and therefore would seem to further support the conclusion that saccadic targeting of words was relatively unaffected by the movement of text.

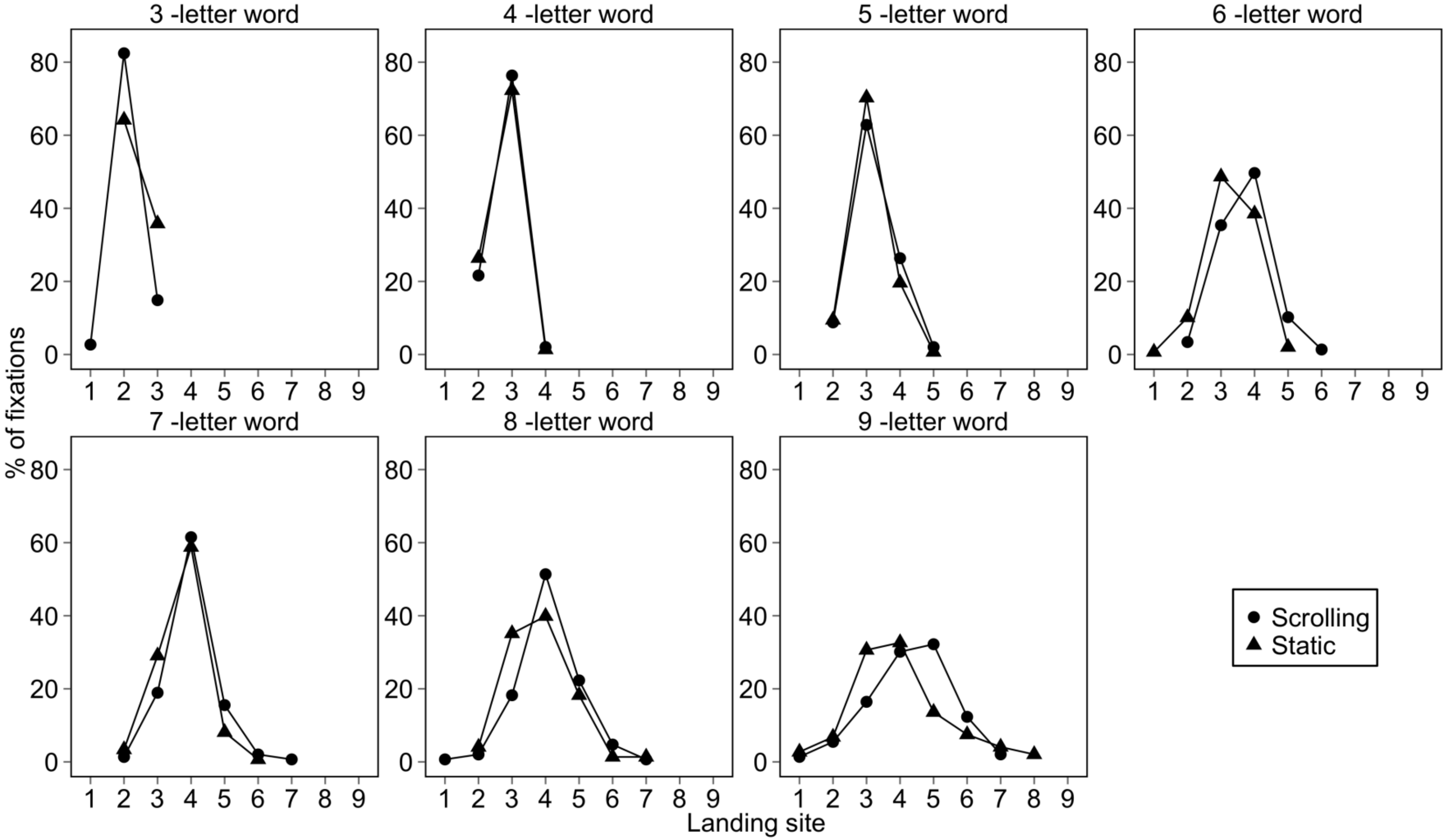

Figure 8. Landing position distributions split by word length (3 - 9 letter words) presented under static and scrolling text conditions.

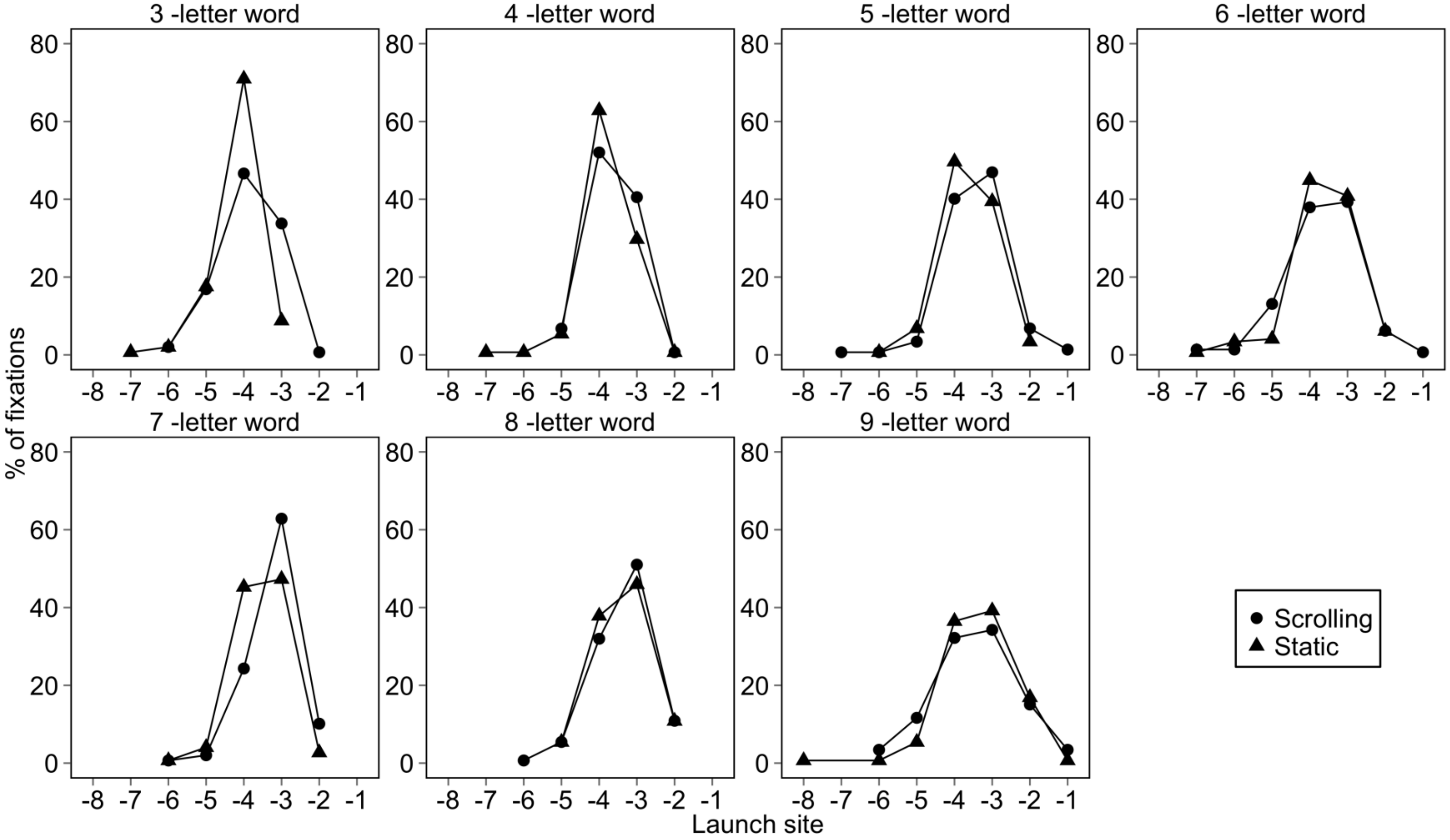

Figure 9. Launch site distributions split by word length (3 - 9 letter words) presented under static and scrolling text conditions.

Discussion

These analyses compared the global oculomotor reading pattern employed to read scrolling and static text read at comparable rates of around 250 wpm (the approximate average static reading speed; Rayner, 1998). A distinct pattern of changes was observed with the scrolling format as readers adapted to the continual horizontal movement and associated limited availability of the text.

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 a reduced number of fixations employed in reading of scrolling text. The average saccade amplitude was also reduced for reading scrolling text. The alternating pattern of pursuit periods and saccades can be interpreted as an adoption of an OKN-like oculomotor pattern for reading scrolling text. 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 dynamic stimulus in this way).

To investigate the reduction in saccade length further, separate comparisons of forward and regressive saccade amplitudes were computed. This indicated that saccades made in both directions were shorter than the comparable movements seen in reading of static text. However, the margin of this difference was greater for regressive saccades than for 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, it was hypothesised that regressions require the maintenance of some kind of positional representation of words in a memory buffer (similar to that suggested for example by Murray & Kennedy, 1988 in their Spatial Coding Hypothesis). 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 (word) 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.

The amount of information outside of the point of fixation available to the reader, characterised in reading research as an attentional window, may be split to two concepts: the perceptual span, a larger area from which global word shape and spacing information may be taken ahead of the point of fixation (Rayner & McConkie, 1975); and the word identification span, in which individual letters may be recognised and identified (Underwood & McConkie, 1985). In typical reading of static text, the extent of the word identification span is known to correspond to the average length of saccade (both around 7 characters, within the understanding that this may vary slightly depending on factors such as text difficulty, where increasing difficulty may be assumed to reduce the attentional resources available for deployment in this window; Jacobs, 1986; Rayner, 1998). The reduced saccade length may then be evidence for a constrained attentional window relative to static text, likely attributable to the directional conflict introduced for the deployment of attention, with oculomotor tracking of the text required as it moves leftwards across the screen simultaneous to rightward shifts of attention for progression through the text as in typical reading of static text. More detailed characterisation of this deployment of attention, as has been carried out for reading of static text using gaze-contingent window (McConkie & Rayner, 1975, 1976; Rayner & McConkie, 1975), is required to corroborate these inferences. This is attempted subsequently, in Chapter 4. However, an explanation of a reduced attentional window with scrolling text is complicated by the unexpected finding of increased skipping rates with this display 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 reading of scrolling text. Consequently, an alternative explanation is required.

One possible explanation might be that there is difficulty with accurate saccadic targeting in reading of scrolling text, 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). However, although 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, these effects were not consistent across word lengths. In view of the higher skipping rates seen with scrolling text, it may in fact even have been expected that there would be a leftward shift in landing positions with this format (cf. Krügel & Engbert, 2010), rather than the slight rightward shift that was actually recorded. This shift was contrary to the null effect that was 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). 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), and the inconsistency of this effect across word lengths, 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.

A more likely explanation for the increased skipping rate is that it occurs as part of a riskier reading strategy (O’Regan & Jacobs, 1992; O’Regan, 1990), similar to (although clearly distinct from) that adopted by older readers of English (Rayner, Reichle, et al., 2006; Risse & Kliegl, 2011). As seems to be 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. In order to maintain a swift reading speed comparable to that for static text (indeed, actually slightly faster, as the total sentence reading times for the global measures show), readers would therefore appear 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.

Changes To The Global Oculomotor Pattern For Reading Scrolling Text At A Slower Rate

One key caveat to the conclusions about the global oculomotor pattern adopted to read scrolling text drawn from the analyses presented previously is that this pattern could undoubtedly be influenced to some extent by the speed at which the text is displayed. The finding of a seemingly ‘risky’ reading strategy adopted to read this format may therefore reasonably be expected to be somewhat different if the time pressure for reading the text was reduced: i.e. if the text was presented at a slower rate.

Experiment 3 therefore compared the oculomotor strategy for scrolling text presented at a rate of around 240 wpm (as in Experiments 1 and 2) with text presented at half this speed (120 wpm). It was expected that the slower presentation speed would result in a less risky strategy, with a reduction in the word skipping rate and a slower reading speed. The reduction in the presentation speed was also predicted to make it easier for participants to match their eye velocity to the text velocity, resulting in less position ‘slip’ through the word during pursuit periods and consequently fewer very short regressions (functioning as catch-up saccades). Aside from these measures, the broad profile of the global oculomotor pattern was expected to be very similar when reading scrolling text display at either presentation speed.

The data from this experiment is also compared with that from Experiment 2, which used the same stimuli (from Fitzsimmons & Drieghe, 2013), in order to contrast the oculomotor patterns employed for both scrolling display rates with the pattern recorded for static text. The differences between scrolling and static formats were expected to be similar for both scrolling rates (i.e. although it was expected that regression probability may be lower with the slower scrolling format due to a reduction in the number of short catch-up saccades, this was still expected to be higher than in static text).

As for Experiments 1 and 2, Experiment 3 is also discussed further in terms of the local analysis of a linguistic manipulation (the predictability effect) in Chapter 3.

Experiment 3: Methods

Participants

Participants were 32 students (6 male, mean age 23.3) from RHUL, who had not taken part in the previous experiments. All participants reported normal or corrected-to-normal vision, no language or reading impairments, and English as their first language. All gave informed consent prior to taking part as approved by departmental ethical review.

Stimuli And Apparatus

Stimuli were as for Experiment 2 (48 neutrally and gradually predictable sentence pairs from Fitzsimmons & Drieghe, 2013). All sentences were displayed as before at 70 cm in black, 12 pt Courier font with a white background on a 1024 x 786 pixel CRT monitor running at 100 Hz. Eye movements were recorded during reading using an SR EyeLink 1000 eye tracker collecting one sample of eye position (pupil and corneal reflection) every millisecond (1000 Hz sample rate).

Procedure

Similarly to the procedure employed in Experiment 2, participants read 24 experimental sentence pairs including a manipulated target word plus 13 filler sentences for each speed condition. All sentences were presented using the scrolling text format, moving either at the same rate as in Experiment 2 (3 pixels per screen refresh; faster speed condition) or at half this speed (i.e. 3 pixels per 2 screen refreshes; slower speed condition). Participants reported no perceivable difference in the smoothness of presentation between these two speeds. Comprehension questions (2AFC yes/no) were asked after half of the sentences as in Experiment 2, to ensure task engagement. There was no difference in reading comprehension between the two display speed conditions (Wilcoxon signed rank test $p = 0.52$; faster display rate mean comprehension score 97.6% SD 3.9, slower rate mean 97.2% SE 4.3). No participants were excluded from the analysis, but a similar number of trials (3.9%) were removed due to loss of calibration or participant error as in Experiment 2.

Results

All global oculomotor measures presented for Experiments 1 and 2 were computed as previously (see Table 3).

There were significantly more fixations made during reading with text moving at the slower rate $t(31) = -11.03$, $p < 0.001$, $d = 1.95$, with around 4.5 more fixations made than at the faster rate. However, there was no significant difference in average fixation duration between the two scrolling speeds ($t(31) = -0.23$, $p = 0.82$, $d = 0.04$). This indicated that, unsurprisingly, there was no difference in ease of word identification with the slower rate. This combination of effects accounted for the significantly (1087.9 ms) longer total reading time seen with the slower scrolling rate, as was expected; $t(31) = -6.63$, $p < 0.001$, $d = 1.17$. Overall saccade length was significantly longer when reading with text at a slower rate $t(31) = -4.21$, $p < 0.001$, $d = 0.74$, with this reflecting an increase in saccade length with both progressive and regressive saccades ($t(31) = -5.12$, $p < 0.001$, $d = 0.91$ and $t(31) = -3.40$, $p = 0.002$, $d = 0.60$ respectively; see Figure 10 for frequency histograms).

Table 2. Global reading measures for faster (~240 wpm) and slower (~120 wpm) scrolling text: 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.

	Skipping probability (%)	**Average fixation duration (ms)**	**Number of fixations**	**Refixation probability (%)**	**Average saccade amplitude (chars)**			**Regression probability (%)**	**Total sentence reading time (ms)**
					Overall	**Forward**	**Regressive**		
Faster scrolling	37.42 (0.96)	229.06 (6.57)	14.94 (0.49)	15.52 (1.69)	5.10 (0.22)	4.37 (0.19)	6.40 (0.33)	44.55 (1.90)	3411.72 (161.34)
Slower scrolling	32.52 (0.69)	230.14 (6.59)	19.50 (0.57)	22.29 (1.86)	5.89 (0.24)	5.05 (0.18)	7.69 (0.42)	33.73 (2.08)	4499.56 (196.44)
P value	< 0.001	0.82	< 0.001	< 0.001	< 0.001	< 0.001	0.002	< 0.001	< 0.001

As predicted, the probability of skipping any given word during reading the sentence on the first pass over the sentence was significantly reduced (by around 5%) when reading text moving at the slower scrolling rate. There was also a significantly higher probability of making a regression to inspect a skipped word with this slower format, $t(31) = -5.54$, $p < 0.001$, $d = 1.12$ (2.0% for faster compared to 7.1% for slower speed). The probability of making an immediate refixation on a word following initial fixation was also increased (by 6.2%) when participants read the slower moving text; $t(31) = -5.93$, $p < 0.001$, $d = 0.98$.

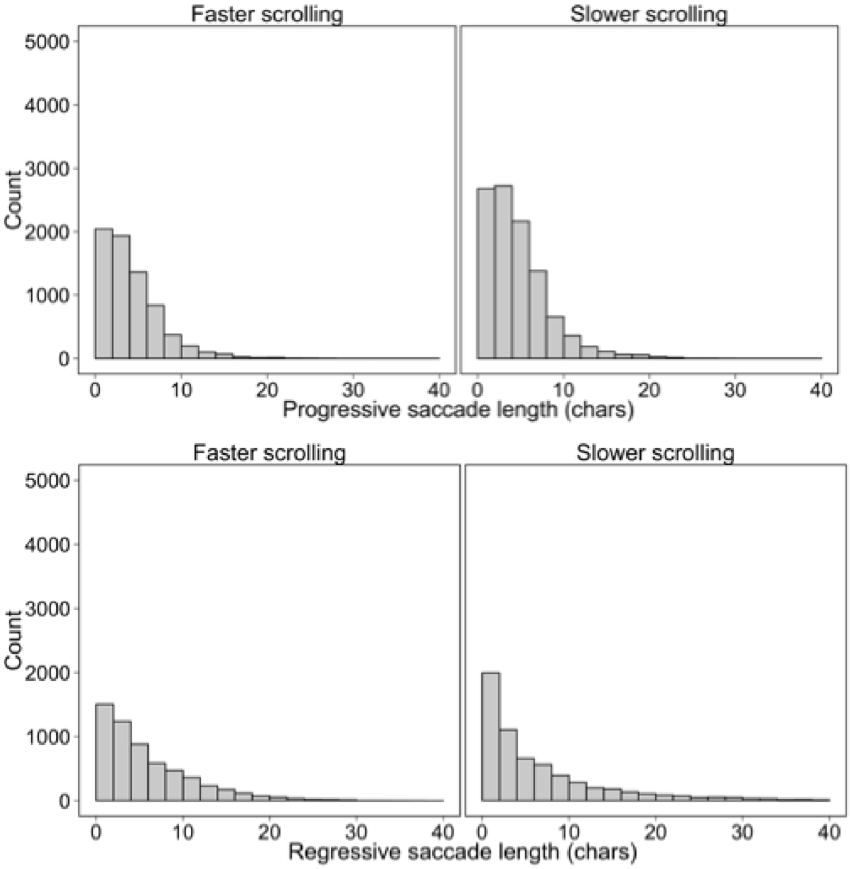

Figure 10. Frequency histograms for the lengths of progressive (upper pane) and regressive (lower pane) saccades for faster (left panes) and slower (right panes) scrolling text.

Regression probability was decreased by a margin of around 10% with the slower text display speed $t(31) = 3.83$, $p < 0.001$, $d = 0.68$. This may be interpreted as being due to a reduced need for leftward catch-up saccades at this speed, as, unlike for the faster scrolling speed, there was no significant difference in the average velocity of the eye during pursuit (fixation) periods and the velocity of the text at the slower speed ($t(31) = -1.59$, $p = 0.12$, $d = 0.39$; cf. $t(31) = -2.22$, $p = 0.03$, $d = 0.28$ for faster speed). This resulted in a significant difference in the amount of position 'slip' from the initial landing position on a word between the two speeds, with significantly less movement through the word with the slower speed $t(31) = 3.89$, $p < 0.001$, $d = 0.69$ (0.6 for the faster scrolling speed compared to 0.3 for the slower speed). Congruent with a reduction of the proportion of leftward catch-up and correctional saccades required, analysis of the pattern of consecutive saccade directions (see Table 4) indicated significant effects of display rate $F(1, 31) = 4.59$, $p = 0.04$, $\eta_G^2 = 0.003$ and of saccade pattern $F(3, 93) = 201.95$, $p < 0.001$, $\eta_G{}^2 = 0.82$. Exploration of an interaction of these factors $F(3, 93) = 26.50$, $p < 0.001$, $\eta_G^2 = 0.17$ indicated that a significantly great proportion of analysed saccade pairs were both progressive with the slower display speed (49.87% compared to 41.99% for the faster speed; $t(31) = -4.95$, $p < 0.001$, $d = 0.87$), with a corresponding decrease in the proportion of each of the other three saccade patterns compared to the faster rate (two regressive saccades $t(31) = 6.15$, $p < 0.001$, $d = 0.86$; a regressive saccade followed by a progressive saccade $t(31) = 4.88$, $p < 0.001$, $d = 1.09$; a progressive saccade followed by a regressive saccade $t(31) = 4.00$, $p < 0.001$, $d = 0.71$).

Table 3. Proportion of saccade pairs following each of four possible direction patterns made during reading of faster and slower scrolling text. Standard errors are shown in parentheses.

Display format	**Left - Left**	**Left - Right**	**Right - Left**	**Right - Right**
Faster	18.19 (0.81)	23.66 (0.53)	23.94 (0.46)	41.99 (1.77)
Slower	14.00 (0.45)	19.94 (0.65)	21.63 (0.56)	49.87 (1.54)

The average horizontal position of the eye on the screen (see Figure 11) was significantly further to the right of the screen for the slower scrolling rate (at 704.9 pixels as opposed to 543.6 pixels, of a 1024 pixel display screen; $t(31) = -15.63$, $p < 0001$, $d = 2.76$). This suggests that participants may have been spending more time at the rightward edge of the screen, waiting for text to become available for inspection; in contrast to the faster scrolling rate, where participants were largely fixating around the centre of the screen throughout (replicated from Experiments 1 and 2). In combination with the finding that the average proportion of the stimuli remaining on the screen at termination of a trial was significantly increased for the slower scrolling rate $t(31) = -10.74$, $p < 0.001$, $d = 1.90$ (44.9% of the stimuli remaining at the faster rate [SE 4.3] vs. 79.1% [SE 2.6] at the slower rate), this verifies that the reduced reading speed seen for the slower reading rate was forced by the rate of presentation.

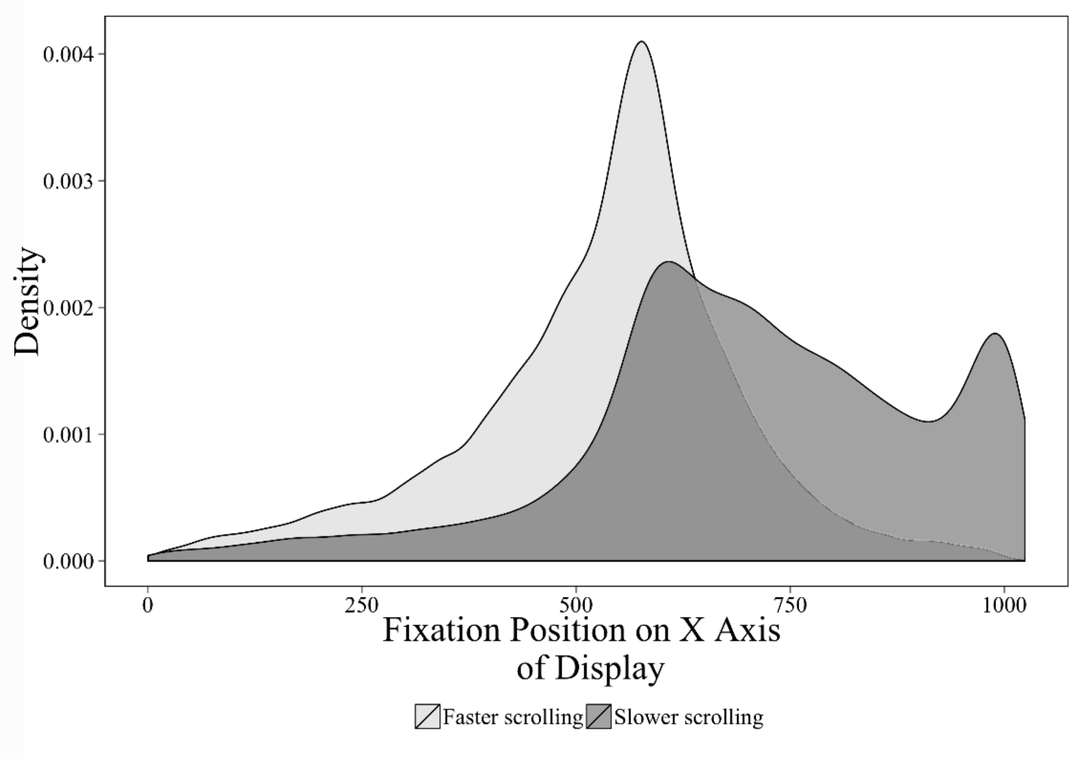

Figure 11. Density distribution of fixations made by all participants in the x-axis of the display screen during reading for faster and slower scrolling text.

There was no significant difference in landing position ($p = 0.48$, $d = 0.13$; faster rate mean landing position 2.92 characters through the targeted word SE 0.05, slower rate 2.96 characters SE 0.04) or launch site ($p = 0.25$, $d = 0.21$; faster rate mean launch position 3.18 characters away from the targeted word SE 0.06, slower rate 3.13 characters SE 0.04) between the two display rates. This suggests that saccadic targeting was affected similarly by the scrolling format, regardless of display speed.

Comparison To Experiment 2

There were no significant differences on any global oculomotor measure between the scrolling text condition in Experiment 2 and the comparable (faster condition) scrolling speed in this experiment, indicating that this is a reliable oculomotor pattern employed for reading scrolling text displayed at this speed (approximately 240 wpm). The slower scrolling rate was also compared with the results for static text in Experiment 2. All measures as computed previously were compared across these conditions with Welch Two Sample t-tests.

Comparing static text (Experiment 2) and the slower scrolling speed, the average fixation duration was significantly longer for scrolling text ($t(45.5) = 3.76$, $p < 0.001$, $d = 0.91$; as with the faster scrolling speed), but there were more rather than fewer fixations made on the sentence in addition to this ($t(65.9) = 5.20$, $p < 0.001$, $d = 1.06$). As would be expected, this resulted in significantly longer total reading durations for the scrolling text at this speed (1293 ms longer; $t(49.5) = 5.81$, $p < 0.001$, $d = 1.34$). The average saccade length made was still significantly shorter with the scrolling format, as it was at the faster display speed ($t(59.6) = -9.27$, $p < 0.001$, $d = 1.97$), and this comparison was significant for both progressive ($t(84.0) = -11.18$, $p < 0.001$, $d = 2.07$) and regressive ($t(72.8) = -8.08$, $p < 0.001$, $d = 1.58$) saccades when these were analysed separately. A higher regression probability with scrolling text ($t(41.3)$, $= 2.58$, $p = 0.01$, $d = 0.66$) suggests that there remains a much higher proportion of short, correctional or catch-up regressive saccades with scrolling text, although, as is clear from the comparison of the two scrolling speeds reported above, these occur to a lesser extent with the slower format.

The average horizontal position of the eye was again significantly different to that with static text ($t(33.2) = 35.21$, $p < 0.001$, $d = 10.57$), with the average position when reading the slower scrolling rate closer to the right screen edge of the screen (705 / 1024 pixels) and closer to the left screen edge (280 / 1024 pixels) with static text.

In contrast to the faster scrolling rate, the probability of skipping a word was not significantly different between the scrolling and static text formats at the slower rate; and in fact there was a numerical trend in the opposite direction, with slightly lower skipping rates seen with scrolling text (2.1% lower; $t(100.9) = -1.81$, $p = 0.07$, $d = 0.30$). Furthermore, a significantly higher proportion of skipped words were regressed to with scrolling text at this speed than with static text ($t(45.4) = 3.00$, $p = 0.004$, $d = 0.73$; compared to a lower proportion of skipped words being returned to with the faster rate than with static text). Finally, a further difference in pattern from that seen with the faster scrolling rate was a finding of no significant difference in refixation probability (*p* = 0.90; compared to significantly lower refixation probability with faster scrolling text).

Discussion

The data from Experiment 3 were examined to investigate the effect of the different display speeds on the oculomotor strategy used to read scrolling text, and compared to the static text data from Experiment 2. As expected, many of the measures analysed were altered by the slowing of the text, with more fixation periods recorded, longer progressive and regressive saccade length, a higher rate of refixations, and lower rates of regressions and word skipping, compared to the faster format. However, the average duration of fixation periods was not significantly different, indicating that word identification was no more difficult with the faster speed. Furthermore, the relationship between results with the scrolling formats and the static text results from Experiment 2 was very similar for both display speeds, with differences only in fixation count, word skipping, and refixation behaviour: for the slower format, more rather than fewer fixations were made on the sentence over the entire sentence reading; the skipping rate was not significantly different from that seen with static text, whereas significantly more word skipping took place in the faster scrolling format; and the probability of making a refixation was not significantly different than with static text for the slower format, whereas a significantly smaller proportion of words were refixated when the text was moving faster.

This pattern of results suggests that the oculomotor strategy adopted for reading scrolling text has some core features, such as the substitution of steady fixations for periods of pursuit, which are longer than typical fixations made with static text, and shorter progressive saccades (perhaps attributable to a reduced perceptual span), and a greater number of shorter regressive saccades (attributable to a functional shift from long-range re-inspection of previously read text towards correctional or catch-up saccades). However, it is clear that the rate of text display does have some impact on how readers approach scrolling text, as would be expected. Whereas with a faster scrolling rate participants seemed to adopt a riskier reading strategy, with high levels of word skipping and a slightly quicker reader speed (despite the fact that display speed and the availability of text at the point of trial termination clearly would have allowed for their speed to be equal or even slightly reduced to the average speed for static text), with a slower display rate they were able to abandon this strategy, with comparable skipping rates to as with static text and an overall slower reading speed. Further evidence for can be seen in the difference in regressive saccade length and frequency between the two scrolling speeds, with significantly longer and fewer regressions with the slower speed indicating perhaps that fewer correctional or catch-up saccades were required at this pace: with this interpretation corresponding to a finding of better matching of pursuit velocity during ‘fixation’ periods to the text velocity with the slower display rate.

Chapter Conclusion

Chapter 2 largely confirms and builds on findings from previous reports on the scrolling text format (Buettner et al., 1985; Valsecchi et al., 2013), to provide a more in-depth characterisation of the changes to the global oculomotor pattern employed for reading text displayed in this way (compared to text displayed in the more typical static format). These results demonstrate some core features of oculomotor behaviour elicited by the horizontal movement of the text stimulus during reading, such as the substitution of a classic alternating fixation-saccade pattern for a nystagmus-like pursuit-saccade pattern, with longer pursuit/fixation periods and shorter saccade amplitudes (with this latter finding lending some support to the idea of a reduced attentional ‘window’ when reading with this format, explored further in Chapter 4). However they also highlight how changing the display rate of the text impacts the strategy taken to approach the reading task, with a higher skipping probability indicating that a riskier reading strategy is adopted with a faster display rate, in order to ensure that all of the text is read before it becomes unavailable. These findings form the basis for an investigation of the impact of this format on linguistic processing of the text, reported next in Chapter 3.

Chapter 3: Linguistic Processing With Scrolling And Static Text

Analysis of changes to the global oculomotor pattern in Chapter 2 demonstrated a number of significant changes to eye movement behaviour with this format (compared to normal static reading). It may therefore be expected that some changes may also arise with regards to cognitive and linguistic processing when reading text presented in this way. Chapter 3 presents local analyses of manipulated target words to investigate this question.

At a simplified level, in addition to the basic oculomotor processing employed to navigate the text, there are three key processes that need to take place in order for us to read, all of which (if successfully completed) have an effect at a local (i.e. individual word or clause) level on oculomotor measures. These three processes are: perceptual parsing of the body of text to be read 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 (Clifton et al., 2016). This key triad of processes can be investigated by manipulating certain specific characteristics of the text and recording the affect of these manipulations on fixation durations, as an index of processing time: word length, word frequency, and predictability respectively (the ‘Big Three’; Clifton et al., 2016; Rayner & Liversedge, 2011). In addition to improving understanding of how (and how well) readers are able to carry out these processes with scrolling text in its own right, this more challenging reading task may also provide an insight into the limiting factors for successful reading of any text display format. This chapter therefore aims to investigate the effect of these changes on word- and sentence- level processing, by attempting to replicate the word length, word frequency, and predictability effects which have been found very robustly with normal static text.

Word Length And Word Frequency Effects

The word length and word frequency effects are two of the most well-established oculomotor effects in the literature, demonstrating two facets of word-level processing. 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 move their eyes across the stimuli 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 & Rayner, 1986; Inhoff, 1984; Just & Carpenter, 1980; Kliegl, Grabner, Rolfs, & Engbert, 2004; Pollatsek et al., 2008; Rayner, Ashby, Pollatsek, & Reichle, 2004; Rayner & Duffy, 1986; Rayner & Raney, 1996; Rayner, 1977). Furthermore, 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.

Predictability Effect

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 which has been developed up to that point. The word predictability effect is therefore 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 the context frame of *Russell had hurt his hand in the door of the car. He had trapped his finger while playing.* is semantically primed by the context of the *hand* in the first sentence. This manipulated target word (*finger*) is therefore much more easily predicted than when it is preceded by a neutral sentence (e.g. the word *finger* in the context frame of *Russell had to go to the hospital. He had trapped his finger while playing*.; Fitzsimmons & Drieghe, 2013). Such words are therefore processed more quickly when sentence context makes their occurrence highly predictable, compared to when they are not easy to predict, as indicated by shorter fixations and increased word skipping rates (see Balota, Pollatsek, & Rayner, 1985; Ehrlich & Rayner, 1981; Fitzsimmons & Drieghe, 2013; Inhoff, 1984; Kliegl et al., 2004; Rayner et al., 2004, 2011), and the presence of this effect during reading is a good indicator of successful integration and use of context information across sentences.

Experiment 1: Word-Level Processing When Reading Scrolling And Static Text (Word Length And Word Frequency Effects)

Introduction

Experiment 1 aimed to investigate word-level processing with scrolling text (when reading at a similar rate to an average static reading rate, i.e. the faster display speed considered in Chapter 2), via the word length and word frequency effects. 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 words being less likely to be skipped and eliciting longer reading times than high frequency words of comparable length (Rayner & Raney, 1996). Furthermore, 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. It was expected that these effects would be replicated in the static text reading condition.

Given the results of the oculomotor analyses (of the data from this and following Experiment 2) presented in Chapter 2, with little evidence of significant additional difficulties for accurate saccadic targeting with the scrolling text format, and reasonable matching of pursuit velocity to the text velocity during pursuit-fixation periods, it can be assumed that readers are able to maintain a stable fixation on each targeted word. This in turn means that efficiency of word identification can be expected to be preserved with the scrolling format. The interactive word length and word frequency effects were therefore predicted to be reflected in the fixation duration measures in scrolling text with a similar magnitude as expected (based on previous literature; notably Pollatsek et al., 2008) in static text. No interaction between display format and word length or frequency was expected for any measure.

Methods

See Chapter 2: Methods (*Experiment 1)* above.

Results: Local Analyses Of Word Length And Frequency Effects

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, total fixation duration, 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. Skipping probability was the likelihood that a word would be skipped during first pass. 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. Finally, the total fixation duration for the target was defined as the sum of all fixations on the word, across the full reading period (all passes on the sentence). Each measure was analysed using three-way (2 x 2 x 2) within-subject (F_1, for results across participants) and within-item (F_2, for results across items) ANOVAs, for Display Format (static vs. scrolling), Word Length (short vs. long), and Word Frequency (high vs. low).

Table 4. Local reading measures for the target word: skipping probability (%), first and single fixation duration (ms), gaze duration (ms), and total fixation duration (all passes; ms). 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)**	**Total fixation duration (ms)**
Long	High	Scrolling	7.37 (1.56)	227.02 (5.45)	237.93 (7.98)	261.58 (6.80)	291.44 (9.16)
		Static	6.40 (1.43)	219.60 (4.54)	222.72 (5.73)	264.94 (8.17)	329.11 (16.27)
	Low	Scrolling	7.76 (1.76)	243.25 (5.91)	257.76 (10.22)	296.58 (9.66)	339.97 (11.83)
		Static	4.91 (1.22)	236.17 (7.21)	249.78 (10.71)	297.83 (11.39)	389.83 (16.94)
Short	High	Scrolling	38.60 (2.77)	221.77 (6.70)	215.10 (8.92)	240.77 (8.21)	253.07 (7.61)
		Static	34.91 (2.61)	221.58 (6.55)	214.26 (9.13)	233.00 (7.30)	275.37 (11.62)
	Low	Scrolling	35.69 (2.70)	225.15 (6.42)	231.45 (12.24)	236.60 (7.38)	249.83 (6.93)
		Static	30.02 (2.46)	224.36 (5.70)	238.48 (10.07)	234.98 (6.61)	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 5 for means).

A standard effect of word length was found on word skipping probability, with short words being 28% more likely to be skipped than longer words ($F_1(1, 74) = 278.32$, $p < 0.001$, $\eta_G^2 = 0.37$, $F_2(1, 47) = 307.64$, $p < 0.001$, $\eta_G^2 = 0.51$). There was no reliable effect of word frequency for word skipping ($F_1(1, 74) = 3.43$, $p = 0.07$, $\eta_G^2 = 0.004$, $F_2(1,47) = 2.21$, $p = 0.14$, $\eta_G^2 = 0.004$), 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, target words were skipped 3% more frequently when reading scrolling than static text ($F_1(1, 74) = 2.40$, $p = 0.03$, $\eta_G^2 = 0.01$, $F_2(1, 47) = 5.17$, $p = 0.03$, $\eta_G^2 = 0.002$). This effect did not interact with word length, nor with word frequency, suggesting that it was a generalised effect relating to an overall change in oculomotor behaviour, rather than indicating increased difficulty in word processing. This is supported by analyses of global oculomotor behaviour, where significantly higher rates of word skipping were seen in reading of scrolling versus static text.

Single fixation durations on the target word were 17 ms longer for long than short words ($F_1(1, 27) = 14.96$, $p < 0.001$, $\eta_G^2 = 0.03$, $F_2(1, 46) = 13.69$, $p = 0.001$, $\eta_G^2 = 0.04$). There was also an effect of word frequency that was significant across participants and approached significance across items ($F_1(1, 27) = 14.68$, $p < 0.001$, $\eta_G^2 = 0.05$, $F_2(1, 46) = 3.09$, $p = 0.09$, $\eta_G^2 = 0.01$). Low frequency words elicited longer single fixation durations than high frequency words. This again mirrored the results of Pollatsek et al. First fixation durations were 8 ms longer for long than short words ($F_1(1, 56) = 6.36$, $p = 0.01$, $\eta_G^2 = 0.01$, $F_2(1, 47) = 10.86$, $p = 0.002$, $\eta_G^2 = 0.03$), and 10 ms longer for low than high frequency words ($F_1(1, 56) = 10.25$, $p = 0.002$, $\eta_G^2 = 0.01$, F_2 $(1, 47) = 6.91$, $p = 0.01$, $\eta_G^2 = 0.02$). There was a robust interaction of word length and frequency ($F_1(1, 56) = 4.18$, $p < 0.05$, $\eta_G^2 = 0.01$, $F_2(1, 47) = 4.04$ $p = 0.05$, $\eta_G^2 = 0.01$). Paired sample t-tests indicated that the frequency effect was significant for long words (16 ms difference; $t(56) = -2.80$, $p = 0.01$, $d = 0.37$), but not short words (3 ms difference; $t(56) = -0.41$, $p = 0.68$, $d = 0.05$). Again, the pattern of effects for first fixation duration was very similar to that obtained by Pollatsek et al., although in their study the word frequency effect and the interaction did not achieve significance. Longer words also elicited longer gaze durations than shorter words (by 44 ms;

$F_1(1, 63) = 84.58$, $p < 0.001$, $\eta_G^2 = 0.10$, $F_2(1, 47) = 60.98$, $p < 0.001$, $\eta_G^2 = 0.20$), as did lower than higher frequency words (by 16 ms; $F_1(1, 63) = 14.73$, $p < 0.001$, $\eta_G^2 = 0.02$, $F_2(1, 47) = 12.21$, $p < 0.001$, $\eta_G^2 = 0.04$). Once again, these effects were qualified by an interaction ($F_1(1, 63) = 16.98$, $p < 0.001$, $\eta_G^2 = 0.02$, $F_2(1, 47) = 17.65$, $p < 0.001$, $\eta_G^2 = 0.04$) indicating that the word frequency effect was present for long words ($t(63) = -3.32$, $p = 0.002$, $d = 0.41$), but not short words($t(63) = 0.13$, $p = 0.90$, $d = 0.02$). Very importantly there was no effect of display format on any of these fixation time measures (SFD: $F_1(1, 27) = 0.47$, $p = 0.47$, $\eta_G^2 = 0.002$, $F_2(1, 46) = 3.55$, $p = 0.07$, $\eta_G^2 = 0.009$; FFD: $F_1(1, 56) = 1.40$, $p = 0.24$, $\eta_G^2 = 0.002$, $F_2(1, 47) = 1.23$, $p = 0.27$, $\eta_G^2 =0.003$; GD: $F_1(1, 63) = 0.05$, $p = 0.82$, $\eta_G^2 < 0.001$, $F_2(1, 47) = 0.10$, $p = 0.75$, $\eta_G^2 < 0.001$), and no interaction of either word length (SFD: $F_1 = 2.85$, $p = 0.10$, $\eta_G^2 = 0.005$, $F_2(1, 46) = 0.90$, $p = 0.35$, $\eta_G^2 = 0.003$; FFD: $F_1(1, 56) = 1.22$, $p = 0.27$, $\eta_G^2 = 0.001$, $F_2(1, 47) = 0.49$, $p = 0.49$, $\eta_G^2 = 0.001$; GD: $F_1(1, 63) = 0.72$, $p = 0.40$, $\eta_G^2 < 0.001$, $F_2(1, 47) = 0.09$, $p = 0.77$, $\eta_G^2 < 0.001$) or frequency (SFD: $F_1 = 0.70$, $p = 0.41$, $\eta_G^2 = 0.001$, $F_2(1, 46) = 0.10$, $p = 0.76$, $\eta_G^2 < 0.001$; FFD: $F(1, 56) = 0.001$, $p = 0.98$, $\eta_G^2 < 0.001$, $F_2(1, 47) = 0.08$, $p = 0.78$, $\eta_G^2 < 0.001$; GD: $F_1(1, 63) = 0.06$, p 0.80, $\eta_G^2 < 0.001$, $F_2(1, 47) = 0.07$, $p = 0.79$, $\eta_G^2 < 0.001$), suggesting that lexical processing was relatively unaffected by horizontal movement of the text during reading. This result is in line what was predicted based on the existing literature and the global oculomotor analysis in Chapter 2.

Later fixation duration measures did show some effect of display type. Go-past time showed effects of word length ($F_1(1, 66) = 28.34$, $p < 0.001$, $\eta_G^2 = 0.02$, $F_2(1, 47) = 23.63$, $p < 0.001$, $\eta_G^2 = 0.02$), with longer go-past times for longer words, and display format ($F_1(1, 66) = 4.44$, $p = 0.04$, $\eta_G^2 = 0.08$, $F_2(1, 47) = 122.56$, $p < 0.001$, $\eta_G^2 = 0.11$), with longer go-past times for static than scrolling text, the same pattern as observed for earlier measures. There was no effect of frequency ($F_1(1, 64) = 3.24$, $p = 0.08$, $\eta_G^2 = 0.001$, $F_2(1, 47) = 1.27$, $p = 0.27$, $\eta_G^2 = 0.001$), and no interaction of word length and frequency ($F_1(1, 64) = 4.06$, $p = 0.05$, $\eta_G^2 = 0.003$, $F_2(1, 47)= 1.25$, $p = 0.27$, $\eta_G^2 = 0.001$). Finally, the total times produced effects of word length ($F_1(1, 64) = 109.81$, $p < 0.001$, $\eta_G^2 = 0.14$, $F_2(1, 47) = 66.98$, $p < 0.001$, $\eta_G^2 = 0.22$) and word frequency ($F_1(1, 64) = 13.23$, $p < 0.001$, $\eta_G^2 = 0.01$, $F_2(1, 47) = 9.40$, $p = 0.004$, $\eta_G^2 = 0.03$). These effects were qualified by an interaction between word length and word frequency ($F_1(1, 64) = 12.47$, $p < 0.001$, $\eta_G^2 = 0.01$, $F_2(1, 47) = 11.73$, $p = 0.001$, $\eta_G^2 = 0.03$, 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 ($F_1(1, 64) = 18.59$, $p < 0.001$, $\eta_G^2 = 0.04$, $F_2(1, 47) = 45.63$, $p < 0.001$, $\eta_G^2 = 0.07$), 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, again as seen in the 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 initially appear somewhat unexpected 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. It therefore 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 in Chapter 2). 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 reading of static and scrolling text 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.

Experiment 2: Sentence-Level Processing When Reading Scrolling And Static Text (Predictability Effect)

Introduction

Experiment 1 indicated that lexical processing appears to take place quite similarly when scrolling compared to static text was read. However, word length and word frequency are both intrinsic characteristics of a word: their influence comes about entirely 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, 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 predictability effects were examined for scrolling and static text (as in Experiment 1). This second experiment was based on a study by Fitzsimmons and Drieghe (2013) that used static text presentation only. As for Experiment 1, it was expected that the findings from Fitzsimmons and Drieghe would be replicated in the static text condition. However, in contrast to the findings of Experiment 1, it was expected that predictability effects would be reduced or lost completely when sentences were presented in scrolling text format: the global oculomotor analyses reported in Chapter 2 confirmed a reduction in the scope for long-range regressions with scrolling text due to a limited temporal window of text availability resulting from the continual movement of text through and out of range of the spatial limits of the display screen. When readers are prevented from making long-range regression to reinspect 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 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

See Chapter 2, *Experiments: Methods* above.

Results: Local Analyses Of Sentence-Level Processing Effect

The same local measures were analysed for the target word manipulated for predictability as for the target words (manipulated for length and frequency) in Experiment 1. Each measure was analysed with two-way (2 x 2) repeated-measures ANOVAs for Display Format (scrolling vs. static text) Predictability (high vs. neutral), with F_1 (for results across participants) and F_2 (for results across items) measures generated as before. Mean values are presented in Table 6.

Table 5. Local reading measures for the target word: skipping probability (%), first and single fixation duration (ms), gaze duration (ms), and total fixation duration (all passes; ms). Standard errors are shown in parentheses.

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

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

A predictability effect was found for single fixation durations, with 8 ms longer single fixations for neutral than highly predictable words ($F_1(1, 68) = 5.73$, $p = 0.02$, $\eta_G^2 = 0.01$, $F_2(1, 47) = 5.56$, $p = 0.02$, $\eta_G^2 = 0.02$), qualified by an interaction between predictability and display format showing that the effect of predictability was only present for reading of static text ($F_1(1, 68) = 4.47$, $p = 0.04$, $\eta_G^2 = 0.01$, $F_2(1, 47) = 3.88$, $p = 0.05$, $\eta_G^2 = 0.02$). A similar pattern was found for first fixation duration, with effects of predictability ($F_1(1, 70) = 7.39$, $p = 0.008$, $\eta_G^2 = 0.01$; $F_2(1, 47) = 7.45$, $p = 0.009$, $\eta_G^2 = 0.03$) and display format ($F_1(1, 70) = 8.01$, $p = 0.006$, $\eta_G^2 = 0.02$, $F_2(1, 47) = 2.80$, $p = 0.1$, $\eta_G^2 = 0.02$), qualified by an interaction indicating that the predictability effect was present in reading of static text only ($F_1(1, 70) = 4.21$, $p = 0.04$, $\eta_G^2 = 0.01$, $F_2(1, 47) = 3.99$, $p = 0.05$, $\eta_G^2 = 0.02$). Gaze duration showed an effect of predictability only, with significantly longer durations in the neutral than high predictability condition (by 10 ms; $F_1(1, 70) = 5.60$, $p = 0.02$, $\eta_G^2 = 0.01$, $F_2(1, 47) = 4.53$, $p = 0.04$, $\eta_G^2 = 0.02$), and no effect of ($F_1(1, 70) = 0.34$, $p = 0.56$, $\eta_G^2 = 0.001$, $F_2(1, 47) = 0.57$, $p = 0.46$, $\eta_G^2 = 0.002$) or interaction with ($F_1(1, 70) = 2.89$, $p = 0.09$, $\eta_G^2 = 0.01$, $F_2(1, 47) = 1.58$, $p = 0.21$, $\eta_G^2 = 0.006$) display format. 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, and a numerical trend towards the same pattern in gaze duration) show that the predictability effects did not occur to the same degree for scrolling text, suggesting that preceding sentential context did not exert a as immediate a facilitatory influence over processing under scrolling text conditions as under static text conditions. This finding supports the hypothesis that predictability effects would be reduced when sentences were presented in scrolling text format.

Total fixation duration was modulated by predictability, with significantly higher durations for neutral predictability target words ($F_1(1, 70) = 5.45$, $p = 0.02$, $\eta_G^2 = 0.01$, $F_2(1, 47) = 4.45$, $p = 0.02$, $\eta_G^2 = 0.04$). There was also a marginal effect of display format (significant across items only), with longer total gaze durations seen in reading of static text ($F_1(1, 70) = 3.58$, $p = 0.06$, $\eta_G^2 = 0.01$, $F_2(1, 47) = 4.45$, $p = 0.04$, $\eta_G^2 = 0.03$). 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 seen in the global oculomotor pattern analysis. There was no evidence of an interaction of predictability and display type in this measure ($F_1(1, 70) = 0.13$, $p = 0.72$, $\eta_G^2 < 0.001$, $F_2(1, 47) = 0.01$, $p = 0.91$, $\eta_G^2 < 0.001$).

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. It is worth noting however that the readers' ability to form expectations for lexical identity on the basis of preceding context does not seem to be entirely impaired, as the interaction with display format was not present in later processing measures including gaze duration 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. Nevertheless, at least for total fixation duration 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, increased skipping rates were seen for scrolling than for static text. There was no interaction of predictability with the text presentation format, though a main effect of predictability was seen 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%).

Experiment 3: Sentence-Level Processing (Predictability Effect) With Faster And Slower Scrolling Presentation Rates

Introduction

As discussed in Experiment 2, when a target word is established as highly predictable from previous sentence context during reading of static text, this produces a processing facilitation effect resulting in reduced fixation durations and increased word skipping for this target word (Balota et al., 1985; Erlich et al., 1981; Fitzsimmons & Drieghe, 2013; Inhoff, 1984; Kliegl et al., 2004; Rayner et al., 2004; Rayner, Slattery, & Drieghe, 2011). However, in Experiment 2 here, results indicated that this effect is diminished in scrolling text, with no evidence of facilitation in early processing measures such as single fixation duration. This indicates that a word being highly predictable from sentence context does not help with its initial processing when reading this format. The absence of this effect suggests some degree of failure to integrate information across sentences, and may at least in part be a result of a risky oculomotor strategy employed for the display speed used in Experiments 1 and 2. This strategy, outlined in the global oculomotor strategy comparison for scrolling and static text from the data collected combined from these two experiments (reported in Chapter 2), involves fewer and longer fixations, more word skipping, and fewer long-range regressions. This oculomotor strategy is altered with a slower display rate, with a higher proportion of longer regressions (although still significantly fewer than with static text), and less word-skipping (falling back to a comparable rate as seen with static text). If the difficulty with establishing sentence context information recorded in Experiment 2 was explained by the oculomotor strategy adopted with faster scrolling text, it would therefore be expected that this would be resolved with the slower display rate.

However, it has been demonstrated that for older readers, who are thought to employ a risky oculomotor reading strategy, the predictability effect is usually preserved (Rayner, Reichle, et al., 2006) . This may suggest that this alone is insufficient to explain why scrolling text would have such an effect. Little research has been carried out into reading situations where the predictability effect breaks down, however previous work has suggested that sustained text availability is an important factor in discourse processing, with RSVP text and static text where regressions are prevented by masking eliciting poorer comprehension scores than freely available static text (Fischler & Bloom, 1980; Schotter, Tran, et al., 2014). In typical reading, regressive saccades comprise around 15% of eye movements made to explore the text: the lack of text availability to make such reinspections may force readers to prioritise word identification, leaving fewer resources to integrate information into a coherent discourse across sentences. If these factors are the sole impediment to a level of discourse formation which could support the facilitation effect of predictable words, improving the sustained availability of the text via a slower presentation speed would be expected to reinstate the standard effect of predictability as seen in static text, at least to some extent. Conversely, if additional factors arising from the scrolling text situation such as increased working memory load resulting from following of the dynamic stimulus (cf. Kerzel & Ziegler, 2005) contribute to this finding, simply slowing down the speed of the text would not be expected to reinstate the effect.

Experiment 3 was therefore designed to address the question of whether allowing participants more time to read the text (reducing the need for a risky oculomotor strategy and improving sustained availability of the text), would allow readers to create a coherent discourse representation of the text and resulting in the reinstatement of the standard predictability effect in the early processing measures such as single fixation duration and first fixation duration. Experiment 3 therefore employed the same paradigm as Experiment 2, replacing the static text comparison condition with a slower scrolling presentation rate. It was expected that, as in Experiment 2, this early facilitation would be absent at the faster scrolling rate. If, then, the effect was present in the slower scrolling rate, this would indicate that the inability to effectively use sentence context seen with scrolling text in Experiment 2 was solely attributable to the text speed. On the other hand, if this effect was still absent, this would suggest that the discourse representation was limited by some other factor or factors associated with the scrolling text format, rather than simply the speed at which the text became unavailable.

Method

See Chapter 2 *Experiments: Methods* above.

Results

Local analyses were carried out as for Experiment 2, comparing the effect of predictability (high vs. neutral) on the time taken to process a target word at the two scrolling rates (see Table 7). There was no effect of predictability and no interaction of this factor with scrolling speed seen for any measure on the target word.

Reflecting the difference seen in the global oculomotor analyses (see Chapter 2), the target word was skipped significantly less frequently with the slower scrolling speed (8.6% less skipping; $F_1(1, 31) = 13.22$, $p < 0.001$, $\eta_G^2 = 0.08$, $F_2(1, 47) = 7.64$, $p = 0.008$, $\eta_G^2 = 0.02$; predictability *ns* $F_1(1, 31) = 0.82$, $p = 0.37$, $\eta_G^2 = 0.009$, $F_2(1, 47) = 1.06$, $p = 0.31$, $\eta_G^2 = 0.004$; interaction *ns* $F_1(1, 31) = 1.45$, $p = 0.24$, $\eta_G^2 = 0.01$, $F_2(1, 47) = 1.21$, $p = 0.28$, $\eta_G^2 = 0.004$). Single fixation durations were significantly longer (by 31 ms) with the slower scrolling speed $F_1(1, 30) = 14.80$, $p < 0.001$, $\eta_G^2 =$

0.10, $F_2(1, 46) = 28.32$, $p < 0.001$, $\eta_G^2 = 0.12$ (predictability *ns* $F_1(1, 30) = 1.95$, $p = 0.17$, $\eta_G^2 = 0.01$, $F_2(1, 46) = 2.00$, $p = 0.16$, $\eta_G^2 = 0.01$; interaction *ns* $F_1(1, 30) = 1.79$, $p = 0.19$, $\eta_G^2 = 0.009$, $F_2(1, 46) = 1.72$, $p = 0.20$, , $\eta_G^2 = 0.009$), as were first fixation durations (by 25 ms; $F_1(1,31) = 18.22$, $p < 0.001$, $\eta_G^2 = 0.09$, $F_2(1, 47) = 21.84$, $p < 0.001$, $\eta_G^2 = 0.12$; predictability *ns* $F_1(1, 31) = 1.99$, $p = 0.17$, $\eta_G^2 = 0.006$, $F_2(1, 47) = 2.71$, $p = 0.11$, $\eta_G^2 = 0.01$; interaction *ns* $F_1(1, 31) = 0.06$, $p = 0.82$, $\eta_G^2 < 0.001$, $F_2(1, 47) = 0.06$, $p = 0.81$, $\eta_G^2 < 0.001$). There was similarly an effect of display speed alone on gaze duration $F_1(1, 31) = 102.89$, $p < 0.001$, $\eta_G^2 = 0.25$, $F_2(1, 47) = 59.42$, $p < 0.001$, $\eta_G^2 = 0.23$ (duration 60 ms longer with the slower display speed; with no significant effect of predictability $F_1(1, 31) = 0.08$, $p = 0.79$, $\eta_G^2 < 0.001$, $F_2(1, 47) = 0.75$, $p = 0.39$, $\eta_G^2 = 0.004$; and no interaction $F_1(1, 31) = 0.48$, $p = 0.49$, $\eta_G^2 = 0.003$, $F_2(1, 47) = 0.92$, $p = 0.34$, $\eta_G^2 = 0.004$). These findings indicate that, as shown in Experiment 2 for the faster scrolling text, there was no early facilitation of word processing for highly predictable words (compared to neutrally predictable words) at either scrolling speed. This is again in contrast with the well-established finding of a facilitative effect of predictability with normal static text (including with the stimuli used here; Fitzsimmons & Drieghe, 2013).

Furthermore, total fixation duration also saw no effect of the predictability manipulation, but were an average of 114 ms longer with the slower scrolling speed $F_1(1, 31) = 51.47$, $p < 0.001$, $\eta_G^2 = 0.22$, $F_2(1, 47) = 49.09$, $p < 0.001$, $\eta_G^2 = 0.19$ (predictability *ns* $F_1(1, 31) = 0.74$, $p = 0.40$, $\eta_G^2 = 0.003$, $F_2(1, 47) = 0.65$, $p = 0.42$, $\eta_G^2 = 0.004$; interaction *ns* $F_1(1, 31) < 0.01$, $p = 0.98$, $\eta_G^2 < 0.001$, $F_2(1, 47) = 0.13$, $p = 0.72$, $\eta_G^2 < 0.001$). This indicates that, unlike in Experiment 2, there was no facilitative effect of predictability even at the later stages of processing, including regressive saccades and re-reading. The reasons for this are considered in the discussion.

There was no significant difference on any of these measures for the comparable scrolling speed condition between Experiments 2 and 3 (all comparisons $p \geq 0.2$), showing that this was a reliable pattern of results regarding the effects of the predictability manipulation on reading text displayed in this format.

Table 6. Local reading measures for the target word: skipping probability (%), first and single fixation duration (ms), gaze duration (ms), and total fixation duration (over all passes; ms). Standard errors are shown in parentheses.

Predictability	**Scrolling speed**	**Skipping probability (%)**	**First fixation duration (ms)**	**Single fixation duration (ms)**	**Gaze duration (ms)**	**Total fixation duration (ms)**
High	Faster	29.03 (2.91)	212.01 (5.75)	218.96 (6.52)	233.87 (8.06)	272.49 (13.34)
	Slower	18.82 (2.39)	235.58 (8.18)	241.10 (9.98)	299.43 (9.89)	389.18 (29.59)
Neutral	Faster	23.87 (2.37)	217.07 (5.92)	220.51 (6.12)	241.45 (8.69)	285.66 (12.95)
	Slower	18.91 (1.67)	243.18 (7.94)	259.86 (9.88)	296.63 (10.37)	401.32 (18.08)

Discussion

Experiment 3 aimed to extend the findings of Experiment 2, investigating whether the breakdown of the standard predictability effect seen in reading of static text with the scrolling text format was attributable solely to the text display speed. The results demonstrate that this is not the case, with no facilitative effect of higher predictability (established by the sentence context) on word processing seen at either display speed in this experiment (around 240 and 120 words per minute for the faster and slower rates investigated respectively).

Experiment 2 compared the predictability effect with static and scrolling text and found a marked reduction in the effect in the oculomotor measures reflecting early word processing for the scrolling format. Experiment 3 investigated the same effect (using identical stimuli) at a slower display rate, to understand whether this could be the primary reason for this decreased ability to use sentence context to facilitate processing at these initial stages, or whether some other fundamental characteristic of this dynamic format, such as the limited window of text availability and increased difficulty in producing and maintaining a spatial map of the text for making regressive saccades to revisit previously seen parts of the text to resolve ambiguities and consolidate understanding, or disruption of linguistic processing due to increased demand on available cognitive resources resulting from an attentional conflict.

The results of Experiment 3 showed that, whilst there were numerical trends in the correct direction (with a slightly higher skipping rate and lower fixation durations for highly than neutrally predictable target words) across all measures, there was no significant effect of predictability on any measure, and no interactions of this factor with display speed. Although this may seem initially contradictory, given the preservation of the predictability effect across all of the measures in Experiment 2, and evidence for eradication of this effect only in the early processing measures (of skipping probability, first fixation duration, and single fixation duration) for the scrolling text comparison in that study, examination of the data shows very similar margins of difference for the effect of predictability on comparable scrolling text condition in both experiments: 5.2% vs. 4.2% difference in skipping rate, 5.1 ms vs.

1.5 ms in first fixation duration, 1.6 ms vs. 2.0 ms difference in single fixation duration, 7.6 ms vs. 1.4 ms difference in (first-pass) gaze duration, and 13.2 ms vs. 14.3 ms difference in total gaze duration (each for Experiment 3 and Experiment 2 respectively). Furthermore, there was no significant difference between the comparable scrolling text conditions in each experiment on any of these measures. This suggests that the apparent difficulty in establishing and using sentential context information to make predictions about likely upcoming candidate words is a key feature of reading with scrolling text in general, and is not explained by a riskier oculomotor strategy adopted to read text when it is scrolled at a certain rate.

Chapter Discussion

Experiments 1 - 3 investigated three important manipulations of text characteristics that have been established in research using normal static text format (word length, word frequency, and predictability). Word length and word frequency effects seen when reading static text both occur comparably for scrolling text indicating that the perceptual and linguistic processes associated with lexical identification are relatively unaffected by horizontal text movement. However, in contrast, the sentence-level predictability effect does not seem to occur with the same time course when reading from scrolling text, or possibly at all. Experiment 2 showed that the predictability effects were not seen for the same early processing measures (probability of skipping the target word, and first and single fixation durations) as for static text, and Experiment 3 showed no significant predictability effect for any oculomotor measure with scrolling text moving at a rate of around 240 wpm as in Experiments 1 and 2, or at half this rate (around 120 wpm).

Experiments 1 and 2 deployed a comparison of static text and text scrolling at around 240 wpm to encourage reading at a similar rate (which was achieved across both experiments, with only a small increase in scrolling condition around the margin of around 200 ms). Previous research (Valsecchi et al., 2013) using a similar display speed suggested that one of the key challenges in reading scrolling text may be accuracy with respect to targeting saccades to an optimal recognition point in a moving word. If this was the case, it may have been expected that this would have a detrimental impact on word identification; however, although this may be true to some extent, with evidence for increased shorter regressive saccades in scrolling text (possibly functioning in part as short catch-up saccades as seen in other pursuit tasks; de Brouwer, Missal, Barnes, & Lefevre, 2002; de Brouwer, Yuksel, Blohm, Missal, & Lefevre, 2002), analysis of landing positions in Experiments 1 and 2 here showed very little difference between static and scrolling text. Accordingly, there was no impact of text format on either the word length or word frequency effects investigated in Experiment 1.

Overall, the present set of results, combined with previous studies of reading scrolling text, make it clear that the visual system is relatively robust when faced with the challenges presented by reading scrolling text. No reduction in efficiency for individual word processing in reading scrolling text was seen in Experiment 1, but the overall pattern of results did reveal that reading scrolling text came at a cost to performance. The distinct pattern of results across the three studies, with similar effects of word length and frequency as seen with static text found in Experiment 1 but a reduced predictability effect in Experiments 2 and 3 suggests that these results are reflective of changes in the cognitive processing undertaken during reading of scrolling text compared to static text, as opposed to being attributable only to altered oculomotor behaviour. These results indicate that, although the movement of text does not impede word identification at a perceptual or cognitive level, it does result in a more complicated oculomotor pattern and an increased foveal load. This seems to suggest that the challenges of reading scrolling text, notably the limited availability of the text as it constantly moves across and then off of the screen, encourages readers to adopt a risky reading strategy of increased word skipping in order to ensure that they finish reading the text before it is removed from view.

Distinct from other situations in which a risky reading strategy is adopted, where predictability effects may be preserved (or in the case of older readers, possibly even enhanced; Rayner, Reichle, et al., 2006), once words have been skipped in this format the potential cost of returning to them is large, and the difficulty of making such a return is high. Under this explanation, during reading of scrolling text, this strategy prioritises word identification, with less opportunity to integrate this information across sentences to develop a coherent discourse representation of the text (e.g. Kintsch, 1988, 1998); supported by findings of preserved word length and word frequency effects (Experiment 1) but an absence of early predictability effects with this format relative to in static text (Experiment 2).

An additional consideration in Experiment 3 was whether these results would hold true with a slower display speed (half of the pace chosen in Experiments 1 and 2). Oculomotor features associated with a ‘riskier’ strategy in these previous two experiments (in particular the increased rate of word skipping) were no longer seen with this reduced speed, with the probability of skipping a word was comparable (and even marginally reduced) to levels seen with static text for this slower scrolling rate. This supported the conclusion that the time pressure associated with the limited window of text availability was the main factor in encouraging participants to take this strategy. However, a manipulation of predictability still produced no significant facilitation for processing of highly predictable words (compared to neutrally predictable words) at this slower rate. This finding is particularly important in consideration of the usual robustness of the predictability effect: found for example across proof-reading tasks (Schotter, Bicknell, et al., 2014), older readers (Rayner, Reichle, et al., 2006), and deaf readers (Belanger & Rayner, 2015). Notably, one of the only examples of situations in which the predictability effect is eradicated is with readers with mild Alzheimer’s disease (Fernández et al., 2016; although there is an apparent lack of studies investigating the predictability effect in potentially challenging reading situations).

Together, the findings of the global and local oculomotor analyses suggest that the use of this predictability information may be supported by long-range regressions (which were increased to some degree in the slower format but not able to be restored to the levels seen in static text). This would seem to reflect increased difficulty in developing a coherent discourse of the text with the scrolling format, regardless of speed; this is investigated further in Chapter 5. It may also be the case that the increased attentional load due to a directional conflict in spatial deployment of attention and increased complexity from processing a moving text stimulus reduces available cognitive resources for integrating new and existing ideas and for generating predictions of likely candidates for upcoming words. The effect of the scrolling text format on deployment of attention during reading is investigated subsequently in Chapter 4.

Chapter 4: The Allocation Of Attention During Reading Of Scrolling Text

Introduction

The findings from Chapters 2 and 3 regarding changes to the oculomotor strategy taken and the extent of linguistic processing possible demonstrate a clear impact of the scrolling format on some of the processes involved in reading, with a particular decrement in processes involved in integrating information across sentences. As discussed previously, one factor that may explain these findings is a reduction in the available cognitive resources to be allocated to text processing, arising from the more challenging reading situation involved with scrolling text. Specifically, the movement of the text may cause a directional conflict in the allocation of attention around the point of fixation (as noted incidentally with the RSVP-with-flankers paradigm by Kornrumpf et al., 2016), disrupting processing.

As introduced in Chapter 1, although one particular fixated word will fall on the highest-acuity foveal part of the retina, ensuring sufficient detail for accurate identification and interpretation, the gradated nature of the decrease in acuity with increasing retinal eccentricity allows some useful information to be detected from the text falling in the parafoveal area (Drieghe, 2011). However, measuring acuity alone cannot adequately capture how much information is taken from this parafoveal area, as this is constrained by the allocation of attentional resources around the point of fixation to allow this information to be used. The perceptual span is a useful way to conceptualise this deployment of attention during reading, describing the extent of the effective field of view from which useful information is processed around the point of fixation (Rayner, 1975). In particular, information about the basic visual characteristics of the upcoming text can be accrued from this spatial window, including word spacing and word length information (Rayner, Well, Pollatsek, & Bertera, 1982). This information can be used for example to inform saccadic planning (O’Regan, Lévy-Schoen, & Jacobs, 1983; Paterson & Jordan, 2010; Rayner, Fischer, & Pollatsek, 1998; Schotter, Angele, & Rayner, 2012), and to begin early linguistic processing of the subsequent words (Schotter et al., 2012). In normal reading of static text, the perceptual span is typically characterised as covering an area from around 5 characters to the left to around 12 - 15 characters to the right of the point of fixation on a word. This finding has been established using the gaze-contingent *moving window* paradigm first developed by McConkie and Rayner (1975, 1976), wherein only a certain number of characters to the left and right of fixation are available to the reader; with the text outside of this window being replaced by other letters (e.g. ’X’s or visually similar or dissimilar letters) or masked in some other way (e.g. with a spatial filter; Rayner, 2014).

Whilst accurate reading is possible under this paradigm, even with a very small window extent, manipulating the amount of available information from the text in this way produces a characteristic profile of changes in a number of oculomotor measures, as the information which would usually help to begin processing of parafoveal words and in the planning of subsequent saccades is removed (McConkie & Rayner, 1973, 1975, 1976; Rayner, Slattery, & Bélanger, 2011; Rayner, 1986). At the point at which the amount of text made available is less than the area covered by the perceptual span, the rate of reading is reduced and readers typically start to employ an altered oculomotor pattern including shorter and more frequent fixations, interspersed with shorter saccades and increased regressions (e.g. Belanger, Slattery, Mayberry, & Rayner, 2012; Choi, Lowder, Ferreira, & Henderson, 2015; Jordan et al., 2013; McConkie & Rayner, 1975; Paterson et al., 2014; Rayner, Castelhano, & Yang, 2009; Rayner, 1986, 2014). The exact extent of this area may be modulated by a number of different factors including text difficulty (Rayner, 1986), the reader’s age (Rayner et al., 2009; Rayner, 1986), the reader’s language ability (Choi et al., 2015), whether reading is silent or oral (Ashby, Yang, Evans, & Rayner, 2012), reading speed (Rayner, Slattery, & Bélanger, 2011), and foveal and parafoveal load (i.e. the difficulty of processing the currently fixated or parafoveal word, as increased for example by low lexical frequency or high syntactic complexity; Henderson & Ferreira, 1990; White, Rayner, & Liversedge, 2005; Yan, Kliegl, & Shu, 2010).

Although the acuity limits of the retina necessarily determine the amount of information that can be perceived to contribute to processing, these findings regarding the influence of such factors on the extent of the perceptual span demonstrate that the main constraint on its extent must be the limits of the attentional system. This is demonstrated in particular by the asymmetry of the span, with more information taken from the side of fixation towards which saccades will be made; i.e. to the right of fixation in writing systems written horizontally left to right across a page (such as in English; McConkie & Rayner, 1976), to the left of fixation in systems written from the right to left of a page (e.g. Hebrew; Pollatsek, Bolozky, Well, & Rayner, 1981), and below fixation in systems written vertically from top to bottom of a page (e.g. Japanese; Osaka & Oda, 1991). Furthermore, one study replicated the same asymmetric span finding even after implementing compensatory magnification of letters in the parafoveal preview area to eradicate the acuity consideration (Miellet, O'Donnell, & Sereno, 2009), demonstrating conclusively that the amount of information processed is limited by factors other than the perceptual limitations of the visual field. Changes in the perceptual span are therefore particularly relevant in the context of scrolling text as they may help elucidate how movement of the text affects the attentional system. The movement of the text is hypothesised to introduce a conflict in the attentional and oculomotor systems, with leftward tracking of the text required in addition to the normal rightward shifts of gaze and attention required for reading (see Figure 12), as shown in the analysis of global oculomotor behaviour during reading presented in Chapter 2. This conflict may therefore be expected to be reflected in a change in the (attention-reliant) perceptual span, possibly showing as a reduction in the rightward extent of the span (as seen when attentional load is increased i.e. by increased difficulty of the text; Henderson & Ferreira, 1990), or a leftward shift in the span (as seen during regressions in normal reading; Apel, Henderson, & Ferreira, 2012).

The allocation of spatial attention is thought to be closely linked to motor planning, with allocation of attention to a target a necessary precursor to a saccade to the target (Sheliga et al., 1995, 1994). Attention is therefore proposed to be allocated serially from one word to the next along a line of text until such a time when sufficient information cannot be gained from the parafoveal preview to allow lexical processing of the attended word to take place, and a saccade is completed to move this word into the foveal region (Reichle et al., 2003). The amount of attention allocated to the left of fixation covers the region from a typical landing position on a word back to the beginning of the word, potentially including the interword spacing to delineate the fixated word *n* and the previous word *n - 1* (Rayner, Well, & Pollatsek, 1980).

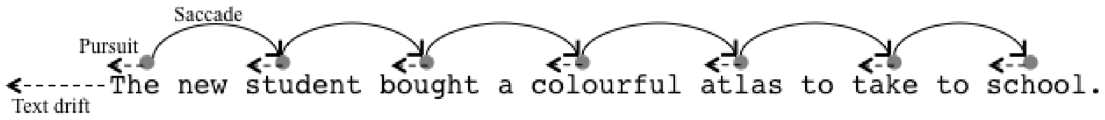

Figure 12. Schematic demonstrating the source of a directional conflict in the deployment of attention during reading of scrolling text, with leftward pursuit periods to track each 'fixated' word interspersed with rightward saccades to make progress through text. Hypothetical eye positions are indicated by the grey dots.

In studies investigating the allocation of spatial attention during pursuit tracking of non-text stimuli, results indicate that attention is allocated around the pursuit target, with a symmetrical window of around 1° either side outside of which performance for example on discrimination tasks falls to chance level (Lovejoy et al., 2009). There is some evidence that this may be modulated to some extent to voluntarily allocate additional resources in the direction of pursuit, up to around 2° ahead of the target (but not equivalently behind the target; Lovejoy et al., 2009; Van Donkelaar & Drew, 2002). If this was the case when pursuing words for identification during reading of scrolling text, it may be expected that the rightward extent of the perceptual span would be considerably reduced, and perhaps the leftward extent of the span slightly increased. However, in contrast to in reading tasks, there is little motivation in such pursuit tasks to allocate attention in any significant way to the area behind the target, and some investigations have indeed found that there is little difference in the way attention is deployed around a given target regardless of whether the eye is fixated on or in pursuit of the target (with no difference in the accuracy of peripheral probe identification when fixating a static target or pursuing a dynamic target, with a similar decline in accuracy with increasing probe eccentricity suggesting similar allocation of attention in both conditions; Watamaniuk & Heinen, 2015). Furthermore, constraint of a reader's view on a sentence such that there is a leftward asymmetry with little information available to the right results in considerably worse reading performance, with large increases in reading duration, many short fixations, and many regressive saccades (McConkie & Rayner, 1976). These findings would then suggest that a change in the direction of asymmetry of the perceptual span for scrolling text would be unlikely, as the pursuit situation itself does not appear to necessitate disproportionate allocation of attention ahead of the pursuit stimulus.

An alternative prediction is that the perceptual span might be increased with scrolling text: longer fixation durations (as are seen when reading this format; Buettner, Krischer, & Meissen, 1985; Valsecchi, Gegenfurtner, & Schütz, 2013) may allow more time for parafoveal processing, resulting in a greater preview. This effect has been noted in static text for example in the case of increased visual complexity of word *n* (Yan, 2015); contrasting with increased linguistic complexity, where the perceptual span is found to be reduced (Henderson & Ferreira, 1990; White et al., 2005). Therefore if the increased fixation durations were as a result of increased difficulty in perceiving the words, this may be expected to result in a similar pattern, with an increased perceptual span. This would also help to explain the higher rates of word skipping seen with this format (cf. Schotter et al., 2012). However, this would seem to be an unlikely outcome, as there is no particular evidence that a moving word is more visually complex to process than a static one (at least at the relatively slow speeds of movement used to display scrolling text, with very little difference in visual acuity for static and moving targets in foveal vision up to around 20^{o}/s; Ludvigh & Miller, 1958). Rather, analysis of the global oculomotor pattern used to read scrolling text (Chapter 2) suggests that this shift to longer fixation durations reflects a change in oculomotor strategy, with some degree of movement through a word during each fixation period and fewer saccades during which potential processing time (already limited by the movement of the text through and off of the screen) is reduced. Furthermore, although at a global level of analysis differences in the way the text is processed accumulate to produce a significant increase in average duration with scrolling text, the results of the local analysis in Experiment 1 with regards to the length and lexical frequency manipulation suggests that there is very little difference in processing difficulty at this single word level.

Few studies have investigated reading of scrolling text, and fewer still the allocation of attention during this task. Valsecchi et al. (2013) suggested that the parafoveal preview was comparable for scrolling as for static text, as they observed a similar relationship between preceding saccade amplitude and fixation duration for static and scrolling text. However, taking in consideration the significant difference in their reported intercepts, this relationship would actually seem to suggest that fixation periods of equivalent durations were associated with longer preceding saccades for static than scrolling text. This would in fact seem to support the idea of a smaller perceptual span with this format: if the preview was equivalent, the shorter saccade in scrolling text would presumably fall on text for which more processing had already taken place. Correspondingly shorter fixation durations would be expected if this was the case. Furthermore, their conclusion does not take into account the movement of the text during saccades on scrolling text, or the substitution of fixations for oculomotor pursuit (meaning that the position of the word on the retina may change across the fixation period to a degree that it would not during reading of static text), both of which may alter what the relationship between fixation duration and saccade amplitude means in practical terms.

A prediction of a reduced parafoveal preview with scrolling text is also supported by an incidental finding using the ‘passive reading’ paradigm in an EEG study of reading, where text was moved one word at a time from right to left whilst participants held a central fixation position (Kornrumpf et al., 2016). This study found that restricting the availability of parafoveal information increased the event-related N1 component (reflecting lexical processing, with increased amplitude indicating increased difficulty with processing; Kornrumpf & Sommer, 2015) to a greater degree when reading static text as normal compared to under the passive reading paradigm. This is suggestive of a reduced perceptual span with this paradigm, as a similar amount of processing is required on an encountered word regardless of whether it has been available prior to its direct fixation. Whilst it should be noted that the passive reading paradigm constitutes a rather different reading situation to the horizontally scrolling format, and the parafoveal preview may be affected by factors specific to this presentation method (such as the sudden onset of each word at fixation), this paradigm nevertheless does create an apparent leftward motion of the text as each word is shifted to the left, which may lead to a similar deployment of attention in this direction as proposed for scrolling text.

Finally, Fine and Peli (1996) investigated the perceptual span in reading of scrolling text directly (using fixed occluders on either side of the screen to vary the available window width), and found that this was reduced compared to the normal rightward 12 - 15 characters established for static text (Rayner, 1998), covering only about 4 - 5 characters extent to the right (the effect of the movement of text on the asymmetry of the span was not investigated). This also supports the hypothesis of a reduced perceptual span resulting from the directional conflict in scrolling text, although the use of an ageing sample in this study (median age 71 years; Fine & Peli, 1996) introduces a possible confound of reduced contrast sensitivity which may have impacted on the span independently of the presentation format (contrast sensitivity, which is known to deteriorate with age [Owsley, 2011], was not reported on, and older adults are known to have a reduced perceptual span; Rayner et al., 2009; Risse & Kliegl, 2011). Additionally, 14% of participants had some degree of central vision loss, although all had normal visual acuity, and a later study with participants with no visual problems only also found similar results (7 character window asymptote; although this study again was looking at older adults; mean age 68 years). Finally, as this study used fixed occluders rather than the gaze-contingent moving window paradigm (cf. McConkie & Rayner, 1975, 1976) and did not monitor gaze position, participants were not necessarily maintaining the assumed preview extent that the symmetric application of these occluders assumed (i.e. with a symmetrical 7 character window this could actually have allowed up to 14 characters to the right of fixation if readers adopted a position at the left of the available window). These studies would nevertheless appear to support the conclusion of a reduced perceptual span with scrolling text. However, as characterisation of the normal perceptual span was not the goal of this study, there was no investigation of the asymmetry of the span, and no direct comparison with static text on similar sentences.

Experiment 4: The Perceptual Span With Scrolling And Static Text

Introduction

To investigate the perceptual span during reading of scrolling text, Experiment 4 adopted the gaze-contingent moving window paradigm (McConkie & Rayner, 1975, 1976), to compare the effect of a series of ‘window’ sizes on reading speed and oculomotor measures (average fixation duration, fixation count, average saccade amplitude, and regression count) with scrolling and static text. This method allows the determination of the critical window size, i.e. the point at which restricting the information available in the periphery alters reading behaviour compared to reading with no restrictions on the availability of text. Two leftward asymmetry conditions were included to investigate whether the pursuit of the text stimulus to the left would encourage greater allocation of resources in the direction of pursuit (i.e. to the left, instead of the direction of upcoming text to the right; cf. Lovejoy et al., 2009; Van Donkelaar & Drew, 2002): however, as discussed, no change in the asymmetry of the span was expected, as the overriding cognitive goal of understanding the text was expected to take precedence in determining the broad allocation strategy. Instead, it was hypothesised that the rightward extent of the perceptual span would be reduced with leftward scrolling text, as a result of the increased foveal load resulting from a directional conflict in allocation of attention: to the left to pursue individual words for identification, and to the right to make progress through the sentence.

Method

Participants

Participants were 37 undergraduate students from Royal Holloway, University of London. All participants reported normal or corrected-to-normal vision, no reading or language impairments, and spoke British English as their first language. The experiment was approved by internal ethical review in the Department of Psychology at RHUL, and participants gave informed consent accordingly. The data of one participant was removed from the analysis due to equipment failure. This left 36 participants, with an average age of 21.2 years and of whom 35 were female.

Stimuli And Apparatus

Stimuli were 240 sentences composed of an average of 59 characters and 11 words each: for example, *The new student bought a colourful atlas to take to school* (see Appendix 1). These were created for this study. These were displayed in 12 pt Courier font as black text on a white background, with each character having a horizontal extent of around 11 pixels. The display monitor was a 1024 x 768 pixel CRT monitor running at a 100 Hz refresh rate as in previous experiments. Eye movements were recorded using an SR Research EyeLink 1000 eye tracker (remote desktop mount), taking one sample of pupil and corneal reflection position every millisecond. This information was used online to draw the gaze-contingent window, displayed using SR Research Experiment Builder with custom Python code. Scrolling text was moved at a rate of 3 pixels per screen refresh (about 235 wpm or 42.8 characters per second for the sentences used).

Procedure

The procedure was based on the gaze-contingent moving window paradigm developed by (McConkie & Rayner, 1975, 1976). Participants read sentences either with full view of the sentence (as in normal reading) or with only a fixed portion of the sentence available to them at any one time (with the position of this window moving around the sentence contingent on their gaze position, determined by the eye tracker and updated online). Outside of this window, a box blur filter (5 x 5 kernel, low pass filter gain 0.025 Hz cut-off; Chityala & Pudipeddi, 2014) was applied to the sentence, preserving word spacing information but degrading character form information (see Figure 13).

Five window sizes were displayed to all participants in addition to the full view of the sentence: a symmetrical window, with 4 characters available either side of fixation; two rightward asymmetry windows, with 4 characters displayed to the left of fixation and either 8 or 12 characters displayed to the right of fixation; and two leftward asymmetry windows, with 4 characters displayed to the right of fixation and 8 or 12 characters to the left of fixation (see Figure 13 for examples of each window condition as viewed by participants). All of these were displayed to the participants with both static and scrolling text displays. All participants also completed a practice block of 24 sentences with two sentences presented under each condition. Twelve files were prepared using a Latin Square design such that there were a different set of sentences for each of the 12 conditions (2 display types x 6 window types) in each file, and these were distributed such that three participants saw each combination of sentences. The text display format were blocked such that participants either completed all window conditions for static text and then for scrolling text or vice versa, the order of which were counterbalanced across participants (i.e. with 18 participants completing each order). Each window condition was completed in blocks, the order of which was randomised for each participant. Trials within each block were also randomised, and a simple 2AFC (yes/no) comprehension question completed by participants following each trial (e.g. for the sentence *The new student bought a* *colourful atlas to take to school.* participants were asked *Did the student buy an atlas?*). These questions resulted in a mean comprehension score of 93.6% (SD 4.5%), with no significant difference between static and scrolling sentences (*t*(35) = 0.04, *p* = 0.96).

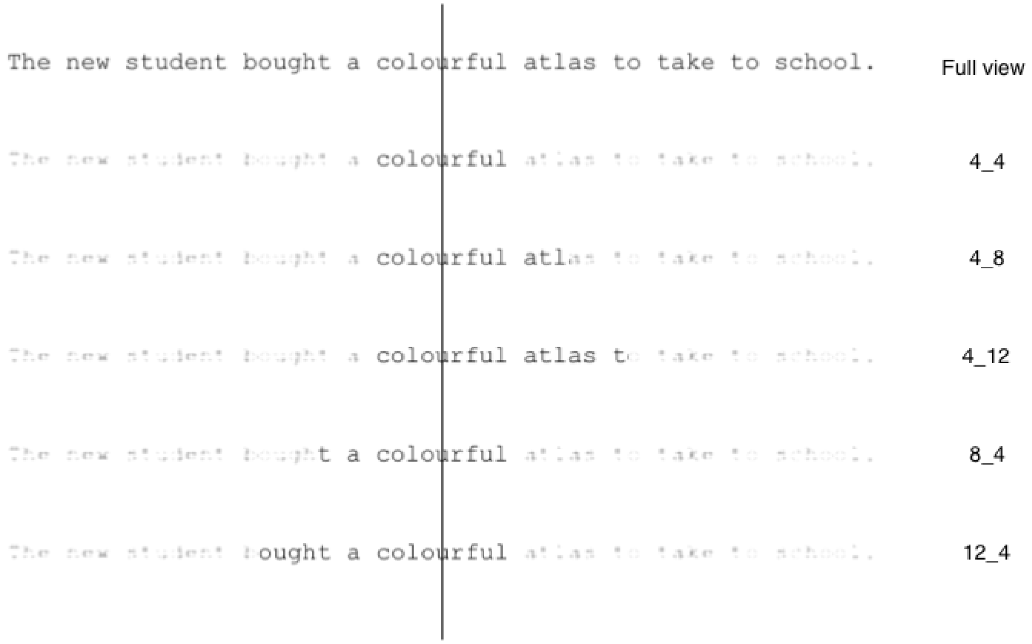

Figure 13. Examples of each window size (with the vertical line representing a hypothetical fixation on letter 'u' in the word 'colourful', from top to bottom of pane displaying: full unrestricted view of sentence; 4 characters available symmetrically either side of fixation; rightward asymmetry with 4 characters to the left and 8 characters to the right of fixation; rightward asymmetry with 4 characters to the left and 12 to the right of fixation; leftward asymmetry window with 8 characters to the left and 4 to the right of fixation; and leftward asymmetry window with 12 characters to the left and 4 to the right of fixation.

As for previous experiments, a 9- point calibration of the eye tracker was carried out before each block and as required. The presentation of each sentence was preceded by a drift correction and a black gaze-contingent square of 2 characters (0.8^{o}) width displayed at the location in which the text was to be subsequently displayed. The beginning of the trial was triggered when participants made a stable fixation within this square. This was implemented in order to ensure accuracy in the application of the gaze-contingent window. If the participant could not trigger trial onset by fixating the square, the following trial was marked to be excluded from analysis and recalibration of the eye tracker was carried out before progression to the next trial.

Statistical analyses were carried out using R 3.0.3 (R Core Team, 2014) with RStudio 0.98.1103. Data processing was as in previous experiments: pursuit periods spanning two words were split or pooled as appropriate (80 ms minimum duration criterion to split) in the scrolling text condition, fixations of less than 80 ms and more than 1200 ms were removed, and data were cleaned for 2.5 standard deviations for each participant and condition. Trials were also removed if the gaze contingent square was not triggered by the participant's fixation. This resulted in a loss of 1% of trials. Multiple comparisons were corrected for using the Bonferroni criterion throughout.

Results

To establish the critical extent of the available 'window' on the text, 2 (Display Format: scrolling vs. static text) x 6 (Window Extent) within-subject ANOVAs were carried out for the following measures: reading rate (words per minute), total sentence reading duration, average fixation duration, the number of fixations employed to read a sentence (fixation count), average saccade amplitude, and the number of regressive saccades made during reading (regression count). Average landing position (character position within targeted word) following a saccade was also computed in order to verify the results of this analysis in Experiments 1 - 3 and to ensure that a shift in this parameter was not able to account for any change in the determined perceptual span.

Reading Rate

The average reading rate (words per minute) was calculated for each window width and display type combination read by each participant (see Figure 14). An ANOVA indicated that there was a main effect of window extent only on reading rate $F(5, 175) = 34.21$, $p < 0.001$, $\eta_G^2 = 0.15$ (with no significant effect of display type, $p = 0.73$, $\eta_G^2 < 0.001$). Pairwise comparisons indicated that all but the 12 character rightward asymmetry window produced a slower reading rate than the full view on the sentence (all $p < 0.05$; 4_12 vs. full view $p = 1.00$). However, there was also an interaction of window extent and display type $F(5, 175) = 2.42$, $p = 0.04$, $\eta_G^2 = 0.01$, suggesting that the effect of window extent was modulated by the text display format. Pairwise comparisons were carried out to investigate this interaction further. These indicated that there was a similar increase in reading rate for both display types between the symmetrical 4 character window and the 8 character rightward asymmetry window. However, all windows except the 12 character rightward asymmetry window resulted in significantly slower reading than the full view on the sentence for static text ($p = 1.00$, all others $p < 0.05$), whereas for scrolling text the 8 character rightward asymmetry window was also not significantly different from either the 12 character rightward asymmetry or the full view condition ($p = 0.81$; 4_12 window $p = 1.00$, all others $p < 0.001$). This supports the prediction of a reduction in the perceptual span for scrolling text.

There was no significant difference between the 4 character symmetric window and the two leftward asymmetry windows for either display type, confirming the prediction that there would be no reversal of the span with the scrolling format.

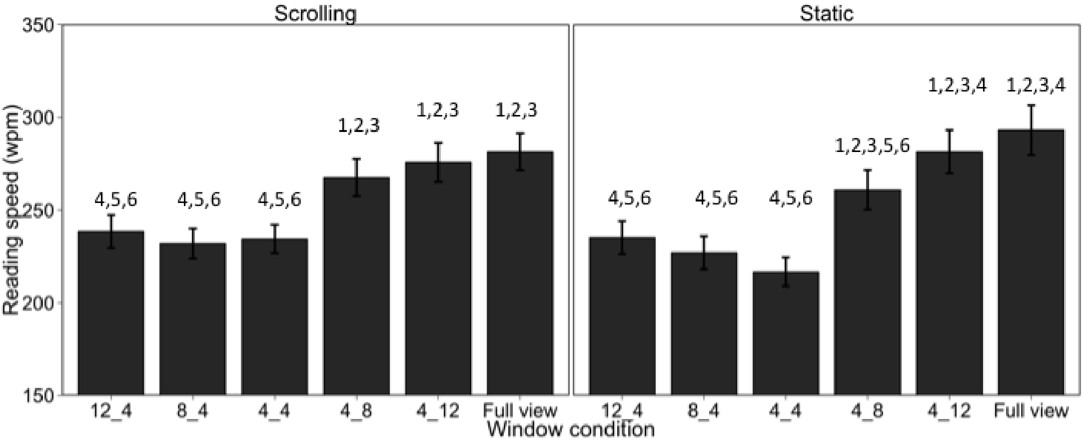

Figure 14. Average reading speed (words per minute) for sentences displayed as scrolling (L) or static (R) text under each viewing window condition. The numbers above the bars here and in all following comparable plots in this chapter denote significant differences (pairwise comparisons) from the other window conditions (within display type), with the numbers 1 - 6 representing the conditions as presented on the graph from left to right (i.e. 12_4 is 1, 8_4 is 2, etc.).

Total Reading Duration

The total sentence reading duration (see Figure 15) was significantly shorter with scrolling than static text $F(1, 35) = 4.29$, $p = 0.04$, $\eta_G^2 = 0.16$; replicating the findings of the global oculomotor analysis reported in Chapter 1. There was also a significant effect of window extent on this measure $F(5, 175) = 36.00$, $p < 0.001$, $\eta_G^2 = 0.02$. Pairwise comparisons indicated, as for reading rate, that all but the 12 character rightward asymmetry window resulted in a longer total reading duration than the full view on the sentence (all $p < 0.001$; 4_12 vs. full view $p = 1.00$). This effect was again mediated by display type $F(5, 175) = 4.20$, $p = 0.001$, $\eta_G^2 = 0.01$. Pairwise t-tests demonstrated the same pattern of effects as for reading speed, with increases in duration between the 4 character symmetrical window and the 8 character rightward asymmetry window, and between the 8 and 12 character rightward asymmetry windows for both display types, but a divergent pattern in the rightward asymmetry conditions. There was no difference between either rightward asymmetry window (8 or 12 characters) and the full view condition with scrolling text (4_8 vs. full view: $p = 0.1$; 4_12 v. full view: $p = 1.0$), but reading times were significantly longer for the 8 character rightward asymmetry window than the full view condition with static text (4_8 vs. full view: $p = 0.004$; 4_12 vs. full view: $p = 1.0$).

There was again no difference between either leftward asymmetry window and the 4 character symmetric window for either display type ($p > 0.3$ for all).

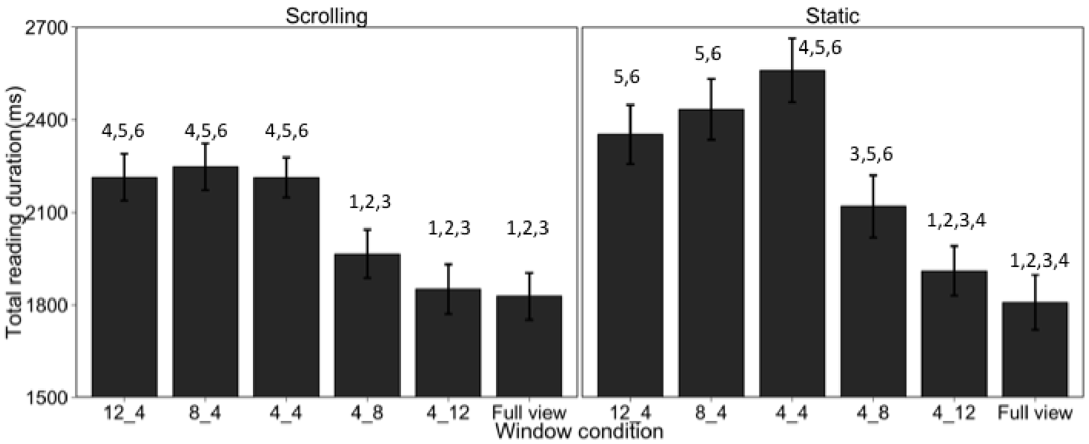

Figure 15. Average total reading duration taken to read sentence for scrolling (L) and static (R) text with each window display condition.

Average Fixation Duration

There was a significant effect of both window extent $F(5, 175) = 12.40$, $p < 0.001$, $\eta_G^2 = 0.06$ and display type $F(1, 35) = 15.32$, $p < 0.001$, $\eta_G^2 = 0.04$ on the average fixation duration made during reading, with longer fixation durations made for reading scrolling text (215 ms vs. 206 ms for static text; again replicating the pattern reported for this measure in Chapter 2). Pairwise comparisons for window extents across both display types indicated that all but the 12 character rightward asymmetry window produced longer average fixation durations than the full view on the sentence (all comparisons $p < 0.01$; 4_12 vs. full view $p = 0.07$). There was also an interaction of these two factors $F(5, 175) = 2.43$, $p = 0.04$, $\eta_G^2 = 0.01$ (see Figure 16). Pairwise comparisons indicated that the full view on the sentence was significantly different from the 4 character symmetric and leftward asymmetry windows for both display types (all $p < 0.01$). However, for static text only, there was a significant difference between the 4 character symmetric window and the both of the rightward asymmetry windows (8 characters $p = 0.03$, 12 characters $p = 0.02$), suggesting that these larger preview conditions provided a benefit for word identification for static but not scrolling text.

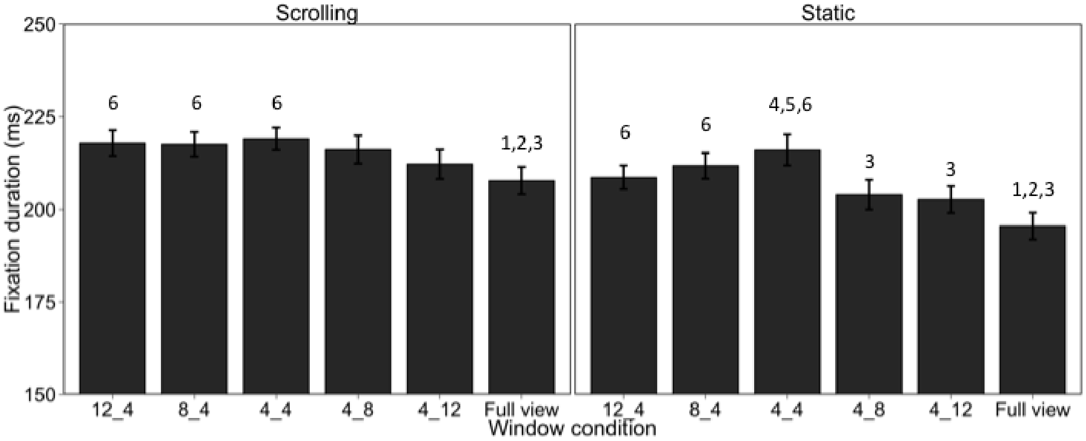

Figure 16. Average fixation duration for sentences displayed as scrolling (L) or static (R) text under each viewing window condition.

Fixation Count

The number of fixations made to read a sentence (see Figure 17) was affected by window condition $F(5, 175) = 39.24$, $p < 0.001$, $\eta_G^2 = 0.15$. Significantly more fixations were made with static text $F(1, 35) = 19.49$, $p < 0.001$, $\eta_G^2 = 0.06$ (1.0 extra fixation; again replicating the results reported in Chapter 2). Averaged across both display types, pairwise comparisons again demonstrated significant differences between all window conditions and the full sentence view except for the 12 character rightward asymmetry window (all comparisons $p < 0.001$; 4_12 vs. total view $p = 1.00$). The effect of window type was also again moderated by display type $F(5, 175) = 3.94$, $p = 0.002$, $\eta_G^2 = 0.01$, with the same pattern as seen in the reading speed measure: for both display types, significantly more fixations were made with the 4 character symmetrical window than with the full view or either rightward asymmetry window (all $p < 0.01$); however, again the pattern of results diverged when comparing the rightward asymmetry windows and the full view condition, with the 8 character rightward asymmetry window eliciting significantly more fixations than the 12 character rightward asymmetry window or the full view condition for static text (both comparisons $p = 0.005$), but there was no significant difference found between the rightward asymmetry conditions (4_8 vs. 4_12: $p = 0.21$) or between either of these conditions and the full view condition for scrolling text (4_8 vs. full view: $p = 0.96$; 4_12 vs. full view $p = 1.00$).

There was again no difference for either display type between either leftward asymmetry window condition and the symmetric 4 character window condition (all $p > 0.6$).

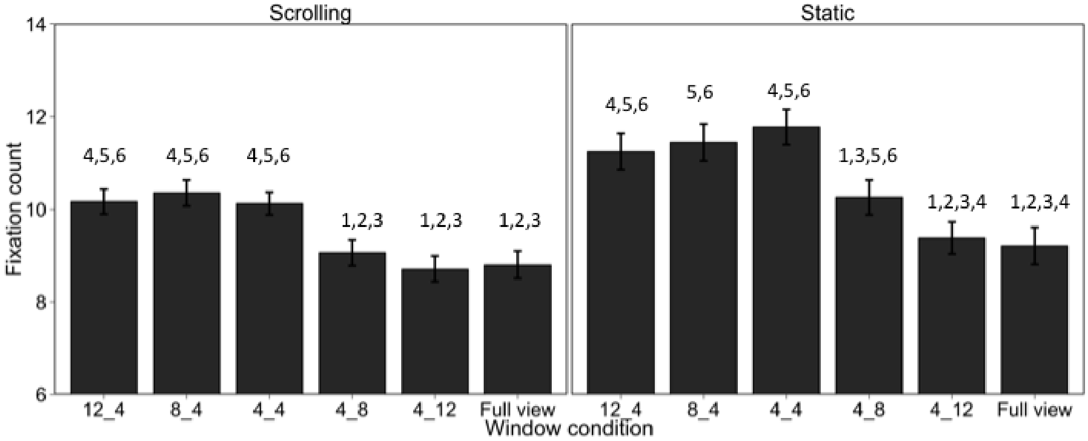

Figure 17. Average number of fixations made to read a sentence displayed as scrolling (L) or static (R) text under each viewing window condition.

Average Saccade Amplitude

Window extent had a significant effect of average saccade amplitude $F(5, 175) = 107.44$, $p < 0.001$, $\eta_G^2 = 0.24$, as did display type $F(1, 35) = 357.05$, $p < 0.001$, $\eta_G^2 = 0.69$ (with significantly shorter saccades made with scrolling text, here as in Chapter 2). Pairwise comparisons indicated that all restricted windows resulted in shorter saccade amplitudes than the full view on the sentence (all $p < 0.05$). There was again an interaction of these factors $F(5, 175) = 4.79$, $p < 0.001$, $\eta_G^2 = 0.01$ (see Figure 18). However, pairwise t-tests did not show a difference in the pattern of effects across display windows for static and scrolling text. Average saccade amplitude increased between the 4 character symmetrical window and each of the rightward asymmetry windows and the full view on sentence. Similarly saccade amplitude was significantly shorter with the 8 character rightward asymmetry window compared to the 12 character rightward asymmetry window and the full view on the sentence for both static and scrolling text, but there was no difference between the 12 character rightward asymmetry window and the full view for either display type (although the comparison was approaching significance in static text: p = 0.08 for static, p = 1.00 for scrolling).

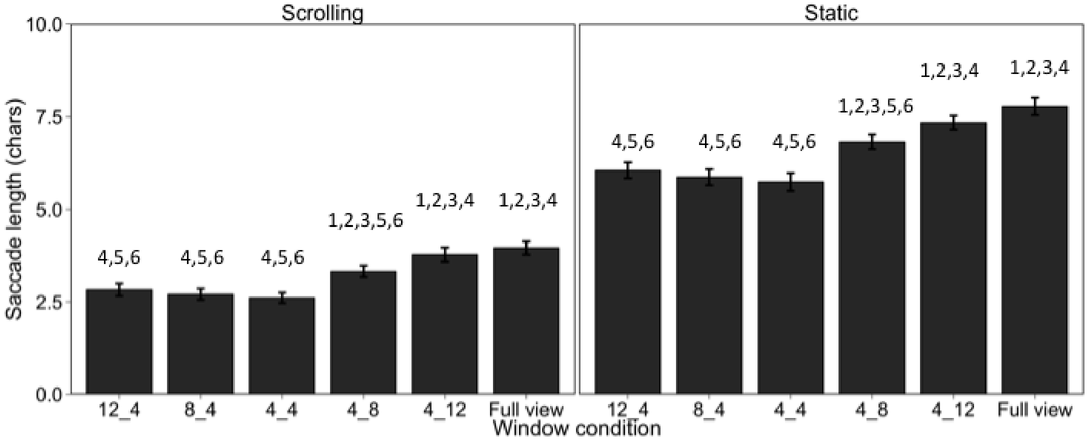

Figure 18. Average saccade length (in characters) made with scrolling (L) and static (R) text for each display window condition.

Regression Count

The number of regressive saccades made during reading (see Figure 19) was affected by window extent $F(5, 175) = 34.35$, $p < 0.001$, $\eta_G^2 = 0.14$ and display type $F(1, 35) = 39.27$, $p < 0.001$, $\eta_G^2 = 0.23$ (with significantly more regressions made with scrolling text, as reported in Chapter 2). Pairwise comparisons indicated significantly increased regressions for the symmetric 4 character window and both leftward asymmetry windows than for the full view on the sentence ($p < 0.001$ for all), but no significant difference between the 8 character (p = 0.15) or 12 character (p = 1.00) windows and the full view condition. There was also a significant interaction of these factors, $F(5, 175) = 6.91$, $p < 0.001$, $\eta_G^2 = 0.02$, with pairwise comparisons indicating that significantly more regressions were made with the 8 character rightward asymmetry window than with a full view on the sentence with static (p = 0.02) but not with scrolling text (p = 0.96). There were significantly more regressions made in the symmetric window and leftward asymmetry windows than the full view with both text display formats, and no significant difference between the number of regressions made with the 12 character rightward asymmetry window than with an unrestricted view with either format (p = 0.10 for static text, p = 1.00 for scrolling text). As with all other measures, there was again no significant difference between the leftward asymmetry conditions and the 4 character symmetric window for either display type (p = 1.0 for all).

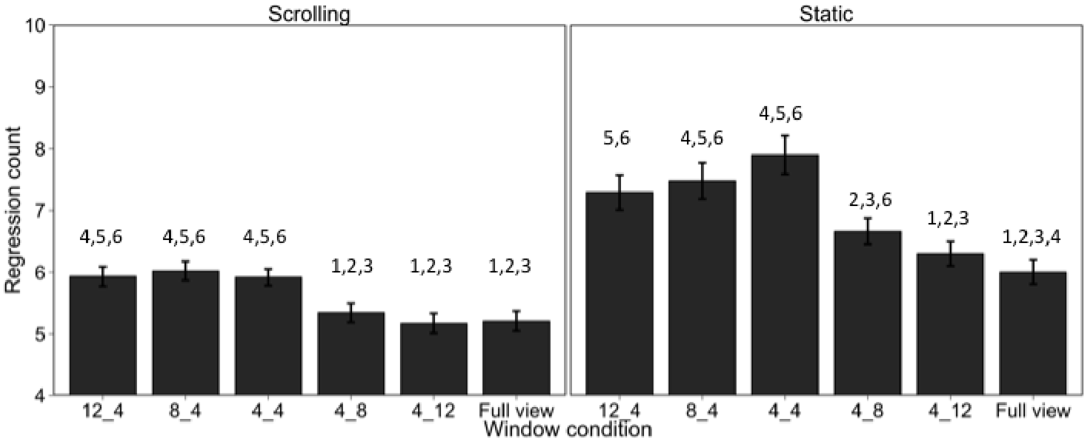

Figure 19. Average number of regressive saccades made when reading a sentence under each of the window display conditions for scrolling (L) and static (R) text.

Landing Position

There was no significant effect of window condition on landing position $F(5, 175) = 1.21$, $p = 0.31$, $\eta_G^2 = 0.01$. There was a main effect of display type $F(1, 35) = 14.47$, $p = 0.001$, $\eta_G^2 = 0.06$ (see Figure 20). However this was of just 0.07 characters on average, and therefore unable to account for the difference seen in critical window extent for the other measures; with an average landing position of 2.84 characters (SE 0.05) into the targeted word for static text and 2.91 characters (SE 0.05) into the word for scrolling text. There was also an interaction of window condition and display type $F(5, 175) = 2.51$, $p = 0.03$, $\eta_G^2 = 0.02$. Pairwise t-tests showed significant difference between the display types for only one window condition, with participants landing significantly further through a scrolling than static word for the symmetrical 4_4 window (3.03 characters with scrolling text vs. 2.55 characters with static text).

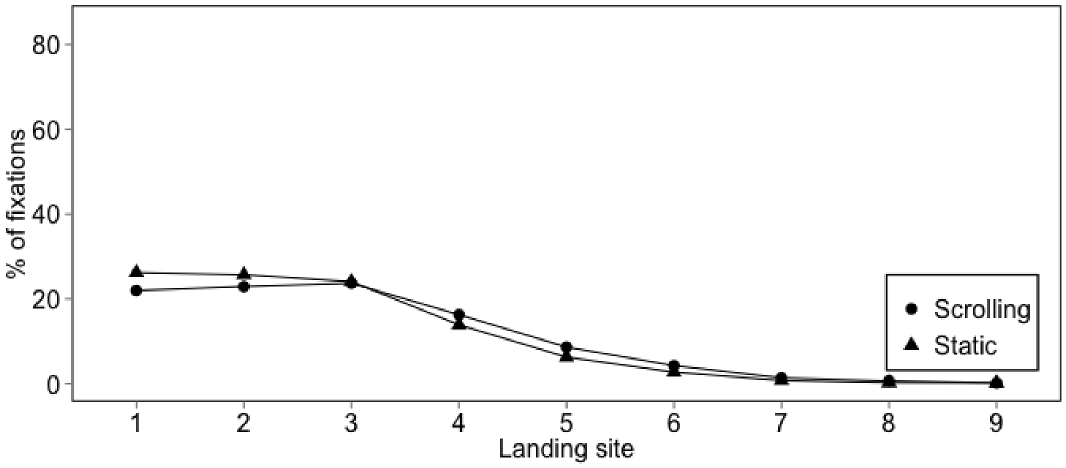

Figure 20. Landing position distributions under static and scrolling text conditions.

Discussion

The perceptual span describes an area around the point of any given fixation when reading a sentence from which useful information can be taken (Rayner, 1975). This area is assumed to represent the distribution of allocated attention, allowing readers to begin processing of upcoming text, for instance using information about word spacing and word length information to inform saccadic planning while progressing through the text (O'Regan et al., 1983; Paterson & Jordan, 2010; Rayner et al., 1998; Schotter et al., 2012). In reading of static text, this region is thought to extend to around 12 - 15 characters to the right of fixation and around 4 to the left (McConkie & Rayner, 1975, 1976), with this asymmetric distribution reflecting its attentional nature (i.e. with more resources allocated to the upcoming text rather than that which has already been read, supported by findings of a reversed asymmetry when the direction of text is reversed; Paterson et al., 2014; Pollatsek et al., 1981).

For scrolling text, however, this distribution was expected to be altered due to a directional conflict introduced into the allocation of attentional resources by the movement of text (cf. Kornrumpf et al., 2016): in addition to the normal requirement of making rightward shifts to progress through the sentence from left to right, the reader also needs to track each moving word leftwards for identification and place-keeping. The coupling of eye movements and covert attention is implicit in the premotor model of eye movement control (Deubel & Schneider, 1996; Rizzolatti et al., 1987, 1994; Sheliga et al., 1994), with volitional guidance of eye movements necessarily being based on prior allocation of attention to the target location. For scrolling text, then, this process of deploying attention to parafoveal words to the right of fixation (in order to plan saccades to progress) is complicated by the requirement to track a word leftward in order to fixate it. During tasks of dynamic following, it has been shown that allocation of attention for effective tracking is biased towards the direction of movement (Lovejoy et al., 2009; Van Donkelaar & Drew, 2002): i.e. for scrolling text, to the left. Thus, when scrolling text is processed, a directional conflict exists 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. This may increase the foveal load (Henderson & Ferreira, 1990; Schroyens et al., 1999; White et al., 2005), which would be expected to contribute to reduced attentional resources for allocation to the parafoveal area.

The established pattern of effects for each of the measures investigated indicated that, for static text only, the largest rightward asymmetry condition (12 characters to the right of fixation) appeared to be a good representation of the average size of the perceptual span for the participants and stimuli used in this study, with significant differences between the 8 character but not the 12 character rightward asymmetry window and the unrestricted view of the sentence for reading rate, total reading duration, number of fixations, and number of regressions, as well as a marginal effect for saccade amplitude. By contrast, as expected, the rightward extent of the perceptual span appeared to be reduced to around 8 characters with the scrolling text format (compared to 12 characters with static text), with no difference between the 8- or 12- character rightward asymmetry windows and the full view on the sentence for this format on reading speed, total sentence reading time, fixation count, and regression count measures (contrasting with a significant difference between the 8 character window and full view for static text).

There was no difference between the 4 character symmetric window and the leftward asymmetry windows for any measure, indicating that tracking the word to the left did not seem to encourage additional resources to be allocated in the direction of pursuit. This was also expected, as the text speed was constant and the most important information for the reading task still to the right of fixation, and therefore there is no advantage to be achieved from allocating additional resources to the left of fixation. The estimated perceptual span for scrolling text in this study (8 characters) is slightly larger than reported in previous investigations of the parafoveal preview with scrolling text (between 4 - 7 characters; Fine & Peli, 1996; Fine, Woods, & Peli, 2001), however the participants in these studies were older (with average ages of 68 and 71 years respectively in these reports) and it is known that older adults show a slight decrease in perceptual span even with static text (Rayner et al., 2009; Risse & Kliegl, 2011). These studies were also carried out slightly differently with regards to their implementation of the window technique, with fixed occluding panels of various widths placed on either edge of the monitor screen restricting the amount of text available to participants, rather than the gaze-contingent movement of the windows as implemented here (following McConkie & Rayner, 1975, 1976); this means that, given their estimation of 4 - 7 characters was based on a symmetric availability of this extent, this actually could have provided up to 8 - 14 characters to the right of fixation if participants positioned their gaze at the left edge of the available window.

During reading of static text, attention is thought to be allocated serially to each upcoming word in the sentence for lexical processing (i.e. therefore largely to the right of the point of fixation in English text), with attention shifting away from fixation to each subsequent word having the potential to result in a saccade to fixate it when sufficient processing cannot be completed in the absence of direct fixation (Clifton et al., 2016; Reichle & Drieghe, 2013; Reichle et al., 1998, 2003). A combination of reader (e.g. Belanger et al., 2012; Choi et al., 2015; Rayner et al., 2009, 2011; Yu, Cheung, Legge, & Chung, 2010; including acuity limits) and text characteristics (e.g. Henderson & Ferreira, 1990; Rayner, 1986; Schroyens et al., 1999; White et al., 2005; Yan et al., 2010; including text processing difficulty) together determine the extent of this effective preview to the right of fixation. The reduction of this extent with scrolling text suggests that the movement of the stimuli in this case does increase the foveal load, resulting in fewer available attentional resources for allocation to the parafoveal area. Allocation of a small amount of attention to the left of fixation is proposed in normal reading to serve only to allow the beginning of a word to be attended (McConkie & Rayner, 1976; Rayner et al., 1980; given the typical landing position of 3+ letters into a word; McConkie, Kerr, Reddix, & Zola, 1988; Rayner, Sereno, & Raney, 1996; Vitu, O'Regan, Inhoff, & Topolski, 1995; White & Liversedge, 2006), and reversal of the asymmetry of the available window on the text (i.e. to provide more information to the left of fixation) results in considerable disruption to the reading process, with significant increases in reading duration, significantly reduced fixation durations, and significantly more fixations and regressive saccades (McConkie & Rayner, 1976). Therefore, as expected, the reading goal takes precedence over the pursuit task, meaning that the attention is allocated predominantly to the right of the point of fixation, with no evidence for a reversal of the span, despite the attentional conflict and in contrast to findings from pursuit tasks where a small symmetrical (or possibly slightly asymmetrical in the direction of pursuit) window of attention is deployed (Lovejoy et al., 2009; Van Donkelaar & Drew, 2002). Finally, analysis of landing position in this study showed very little difference in average landing position between scrolling and static text (of less than one character, and constrained to the smallest window restriction), suggesting that leftward preview provides a similar function in scrolling text, and also ruling out any role of a shift in the landing position to explain the apparent reduction in perceptual span with this format. In sum, these findings demonstrate a reduction in the rightward extent of the perceptual span when text is horizontally scrolled during reading.

Experiment 5: Asymmetry Of The Perceptual Span With Scrolling And Static Text

Experiment 4 demonstrated that fewer resources were allocated to the right of fixation when reading scrolling text, and ruled out an explanation of a shift in landing position. However, one possibility that was not entirely discounted with this study was of a reallocation of some resources to the left of fixation, rather than a straightforward reduction in available resources to be allocated. A second experiment was therefore carried out to further investigate the effect of scrolling text on the perceptual span. In particular, this study planned to address the outstanding question of whether the movement of the text to the left leads to a shift of any attentional resources to this side. In Experiment 4, the leftward asymmetry conditions (12_4 and 8_4) ruled out a complete reversal of the asymmetry of the span, but not a reallocation of resources such that the apparent compression of the perceptual span seen in this experiment (from around 12 to around 8 characters to the right of fixation) was actually a shift of the window to extend less far to the right but further to the left (i.e.

with a preservation of the rightward asymmetry as in normal reading but an increase in attention to the left; see Figure 21).

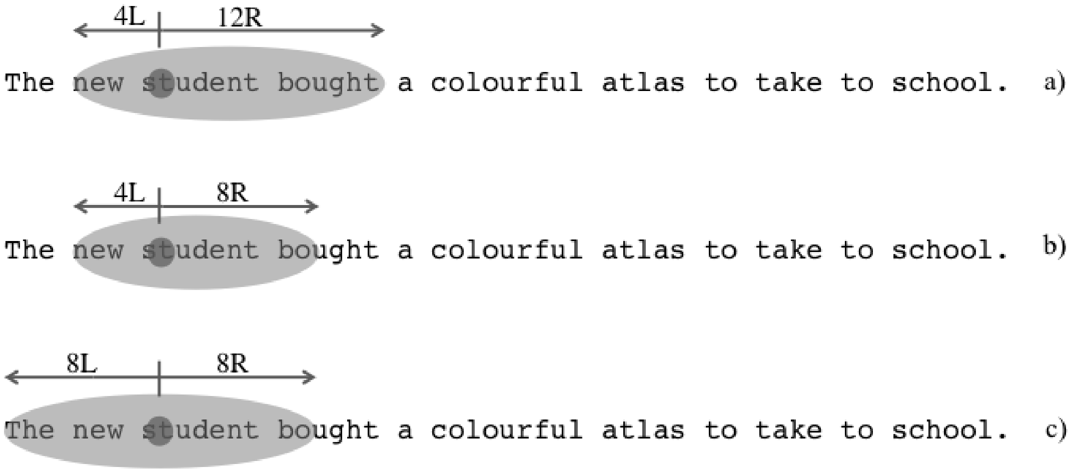

Figure 21. Schematics demonstrating possible changes to the typical perceptual span area (shaded light grey oval spanning text, around hypothetical point of fixation shown as darker grey circle) seen with static text (a): a straightforward reduction in the rightward extent of the span, with no change to the leftward extent (b); or a leftward shift of the span, with reallocation of the resources lost from the rightward extent of the span to the left (in direction of pursuit of scrolling text).

Experiment 4 also used a less common implementation of the moving window paradigm, with letters outside of the moving window being spatially degraded rather than replaced with meaningless characters. This method has precedence in the literature (Paterson et al., 2014), and similar results have been demonstrated for static text with either implementation (Rayner, 2014). However, Fine and Peli (2001) reported slightly different results when using opaque or diffuse occluders in their study of window sizes with scrolling text (although this experiment used fixed occluders, as opposed to the gaze-contingent moving window paradigm employed here, with a sample of older adults). The window restriction method was therefore altered in this second experiment (from spatial filtering to a more traditional implementation, of replacement of characters with upper-case ‘X’s; see e.g. McConkie & Rayner, 1976; Rayner, 2014) in order to ensure that similar results were obtained across both methods.

Method

Participants

Participants were 35 undergraduate students from RHUL. All participants reported normal or corrected-to-normal vision, no reading or language impairments, and spoke British English as their first language. The experiment was approved by internal ethical review in the Department of Psychology at RHUL, and participants gave informed consent accordingly. Data from 3 participants were excluded from analysis due to poor data quality, leaving 32 participants in the final analysis (29 female, mean age 20.2 years).

Stimuli And Procedure

Stimuli were 120 sentences with an average of 85.6 characters and 15.1 words per sentence. These were adapted from short items in the popular science magazine *New Scientist* (‘In Brief’ section). The window conditions compared were as follows: two symmetric windows, with either 4 or 8 characters symmetrically available to the left and to the right of fixation (4_4 and 8_8 windows respectively); three rightwardly asymmetric windows, with 4 characters to the left and 8 or 12 to right of fixation (4_8 and 4_12), and 8 characters to the left and 12 to the right of fixation (8_12); and finally a full view condition, with no restriction on the availability of text (as in Experiment 4). All participants viewed all conditions, as before, as both static and scrolling text (presented in counterbalanced blocks with 10 cells per condition, with sentences rotated in a Latin Square design as previously). The window restrictions were created by replacing all letters outside of these defined windows by upper case Xs, with word-spacing information retained (see Figure 22). Procedure and data analysis were otherwise as for Experiment 4. As before, there was no significant difference between 2AFC comprehension scores for static (mean 84.9%; SD 4.44%) and scrolling (mean 84.7%; SD 4.85%) text ($t(31) = -0.15$, $p = 0.88$l). Data were cleaned similarly to in Experiment 4, with all fixations of less than 80 ms and more than 1200 ms removed, and data cleaned for 2.5 standard deviations for each participant and window condition. These procedures resulted in a loss of 2.5% of trials. Multiple comparisons were again corrected for using the Bonferroni criterion throughout.

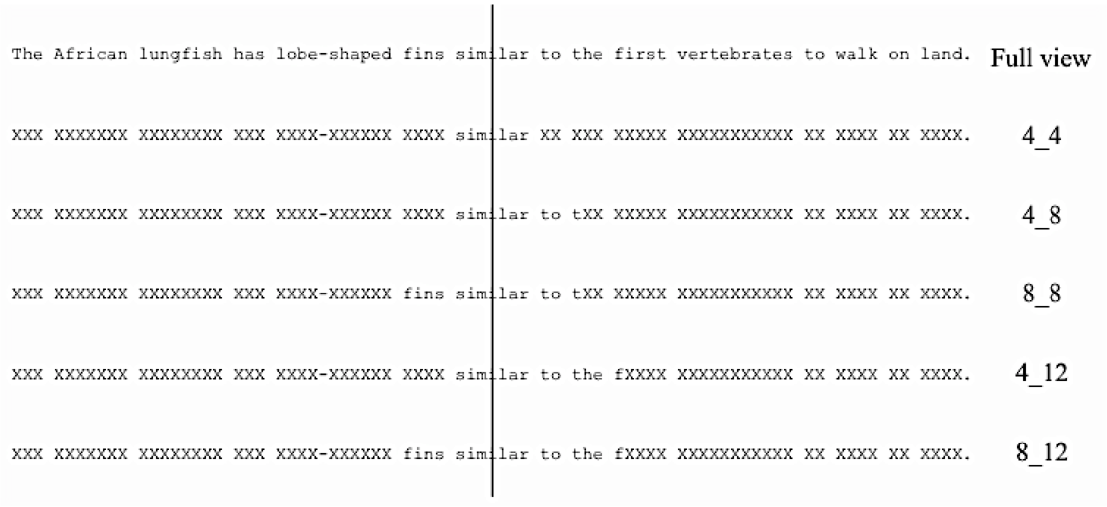

Figure 22. Examples of each window size (with the vertical line indicating a hypothetical fixation on letter 'i' in the word 'similar', from top to bottom of pane displaying: full unrestricted view of sentence; 4 characters available symmetrically either side of fixation; rightward asymmetry with 4 characters to the left and 8 characters to the right of fixation; 8 characters available symmetrically either side of fixation; rightward asymmetry with 4 characters to the left and 12 to the right of fixation; and rightward asymmetry with 8 characters to the left and 12 to the right of fixation.

Results

Analyses were carried out as for Experiment 4, with 2 (Display Format: scrolling vs. static) x 6 (Window extent) within-subjects ANOVAs computed for reading rate, total sentence reading duration, average fixation duration, fixation count, average saccade amplitude, and regression count. As before, landing position was also compared across display formats.

Reading Rate

Participants' average reading speeds were calculated for each condition (6 window sizes x 2 display types; see Figure 23). An ANOVA indicated that, as for Experiment 4, there was a significant effect of window size $F(5, 155) = 55.31$, $p < 0.001$, $\eta_G^2 = 0.19$, and an interaction of window extent and display type $F(5, 155) = 6.91$, $p < 0.001$, $\eta_G^2 = 0.02$ (with no effect of display type $p = 0.48$, $\eta_G^2 = 0.003$). Pairwise t-tests indicated a replication of the pattern seen in Experiment 4, with significantly longer reading times for the rightward 8-character windows than the full view for static but not scrolling text (4_8 vs. full view and 8_8 vs. full view: static p <0.001 for both; scrolling $p = 0.09$ and $p = 0.14$ respectively), and no difference between the rightward 12-character windows and full view for either display type (all $p > 0.25$). There was no significant difference found between the 4 characters and 8 characters to left of fixation windows for either rightward extent (4_8 vs. 8_8 and 4_12 vs. 8_12; $p = 1.00$ for both display types).

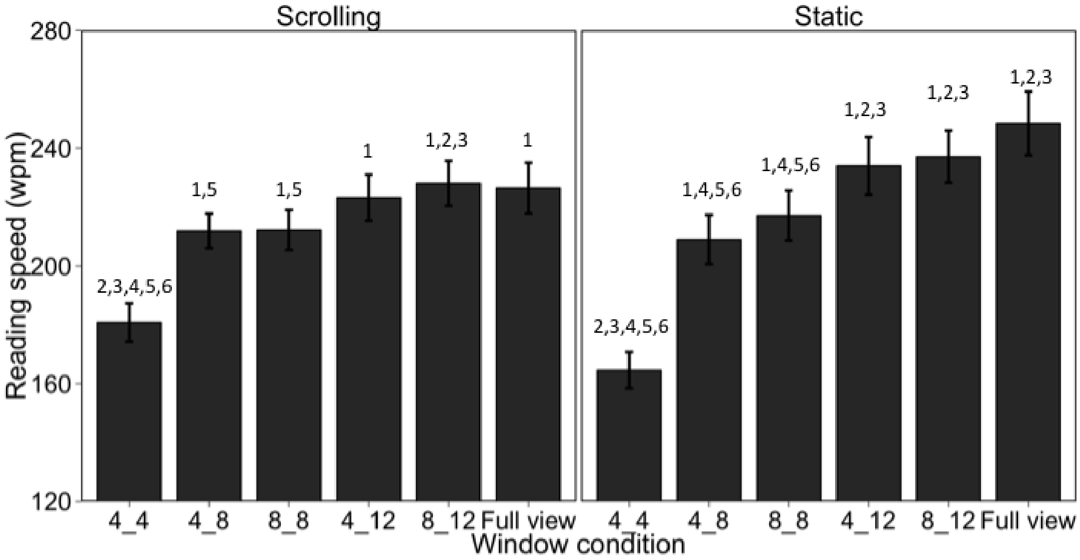

Figure 23. Average reading speed (words per minute) for sentences displayed as scrolling (L) or static (R) text under each viewing window condition.

Total Reading Duration

As for reading speed, there was a significant effect of window extent on total reading duration $F(5, 155) = 66.44$, $p < 0.001$, $\eta_G^2 = 0.24$, and this effect was mediated by an interaction of window extent and display type $F(5, 155) = 4.98$, $p < 0.001$, $\eta_G^2 = 0.02$ (effect of display type approaching significance; $F(1, 31) = 3.56$, $p = 0.07$, $\eta_G^2 = 0.01$, with marginally shorter average reading durations for scrolling than static text as previously). Pairwise comparisons indicated that reading durations (see Figure 24) were significantly longer for the symmetric 4_4 window and the 4_8 window with scrolling text ($p < 0.001$ and $p = 0.002$ respectively; all others $p > 0.70$), and for the 4_4, 4_8, and 8_8 windows with static text ($p < 0.001$, $p = 0.007$, and $p = 0.04$; others $p > 0.50$). Reading durations were significantly longer for the 8 characters rightwards extent windows (4_8 and 8_8) than 12 character rightward windows (4_12 and 8_12) for static text ($p < 0.05$ for all) but not scrolling text ($p > 0.70$ for all).

There was again no difference between the 4_8 and 8_8 windows or the 4_12 and 8_12 windows for either display type.

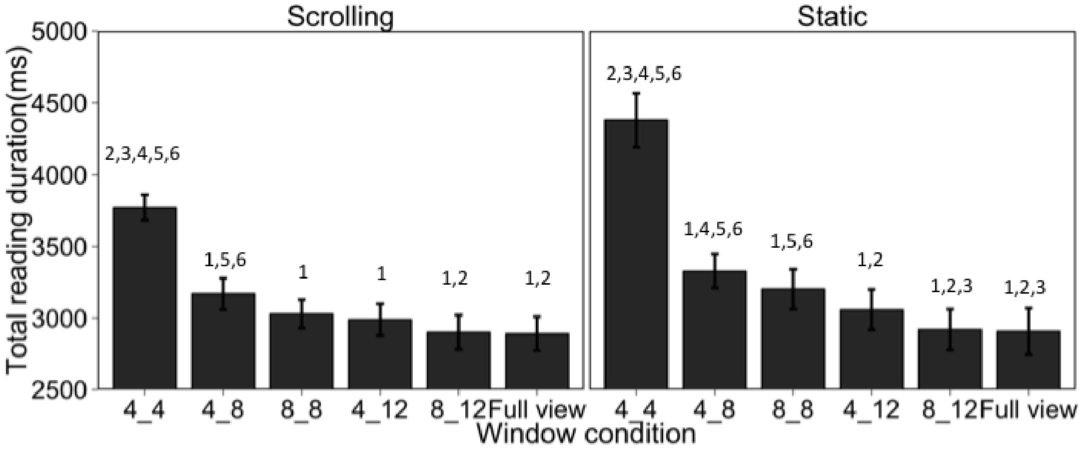

Figure 24. Total average duration taken to read whole sentences for scrolling (L) and static (R) text under each window display condition.

Average Fixation Duration

For the average fixation duration made on a sentence (see Figure 25), there were main effects of window size $F(5, 155) = 44.32$, $p < 0.001$, $\eta_G^2 = 0.18$ and of display type $F(1, 31) = 19.14$, $p < 0.001$, $\eta_G^2 = 0.04$ (with longer average durations with scrolling text as before). There was no significant interaction found between these factors ($p = 0.13$, $\eta_G^2 = 0.01$). There was again no significant difference between the 8 or 12 character windows with 4 character or 8 characters to left of fixation (4_8 vs. 8_8 and 4_12 vs. 8_12 for either display type; $p > 0.1$ for all).

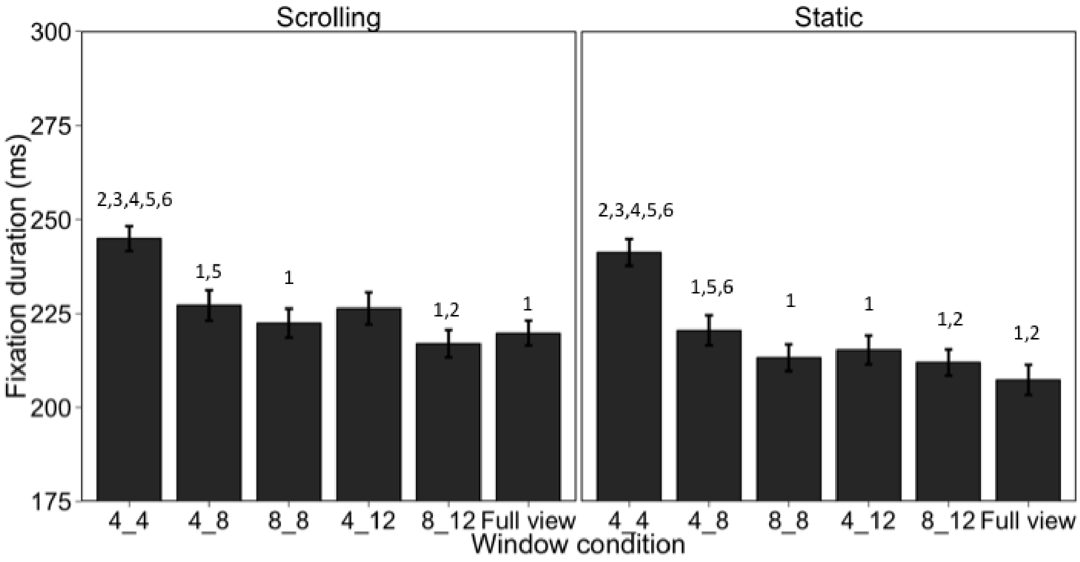

Figure 25. Average fixation duration during reading of scrolling (L) and static (R) sentences under each window display condition.

Fixation Count

Analysis of the average number of fixations made to read a sentence (see Figure 26) indicated an effect of window extent $F(5, 155) = 38.07$, $p < 0.001$, $\eta_G^2 = 0.13$ and of display type $F(1, 31) = 9.67$, $p = 0.004$, $\eta_G^2 = 0.04$ (with significantly fewer fixations made on average with scrolling text as before), as well as a significant interaction of these two factors $F(5, 155) = 3.74$, $p = 0.003$, $\eta_G^2 = 0.01$. Pairwise t-tests indicated that only the 4- character symmetrical window elicited significantly more fixations than the full view with either display format. However, for static text only there was also a significant difference between the rightwards asymmetry 12-character windows and 8-character windows ($p < 0.05$; scrolling text $p > 0.20$), indicating that the extended window afforded some benefit for static but not for scrolling text.

As for all previous measures, there was no difference between the 4_8 and 8_8 windows or between the 4_12 and 8_12 windows for either display type (all $p = 1.00$).

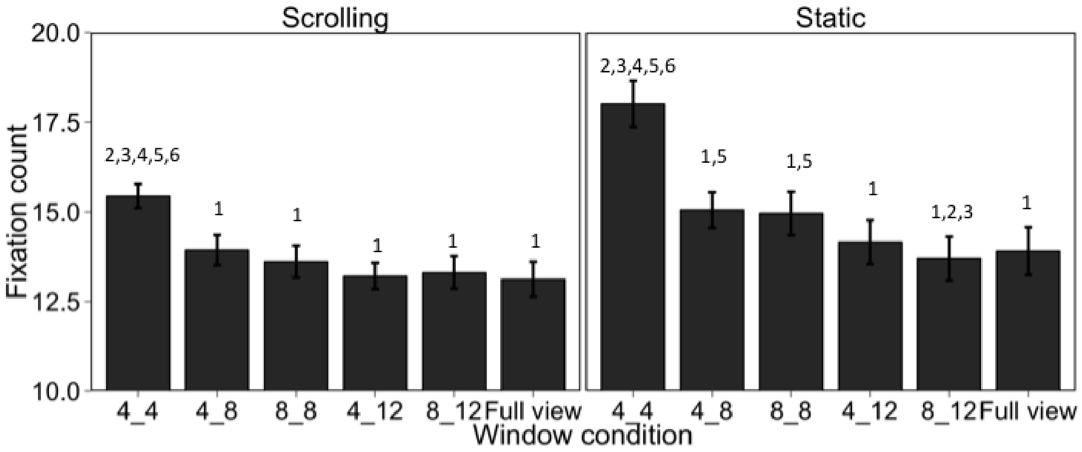

Figure 26. Average number of fixations made to read a sentence displayed as scrolling (L) or static (R) text under each window viewing condition.

Average Saccade Amplitude

Analysis of the average saccade amplitude (see Figure 27) made during reading indicated a significant effect of window extent $F(5, 155) = 95.72$, $p < 0.001$, $\eta_G^2 = 0.32$ and of display type $F(1, 31) = 330.48$, $p < 0.001$, $\eta_G^2 = 0.59$ (with significantly shorter saccades made with scrolling text as previously), and a significant interaction of these two factors $F(5, 155) = 3.12$, $p = 0.01$, $\eta_G^2 = 0.01$. All restricted window conditions resulted in significantly shorter saccades than the full view condition for both display conditions. Pairwise comparisons indicated no differences in the pattern of differences between window extents for scrolling and static text, but visual inspection of the data suggests a more pronounced difference between the 4- character symmetric window and all other window conditions (including full view) for static text than for scrolling text.

There was again no difference between the 4_12 and 8_12 conditions and 4_8 and 8_8 conditions with either display type (all $p > 0.15$).

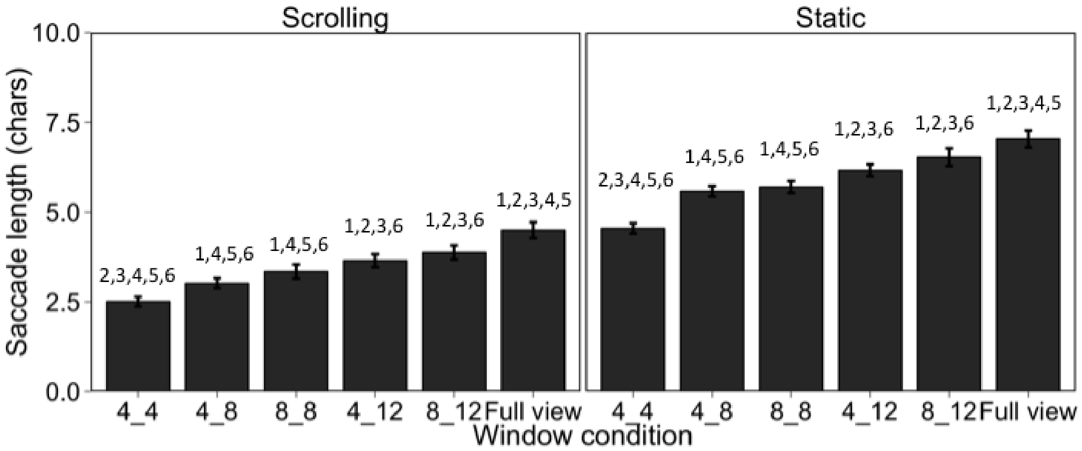

Figure 27. Average saccade length (in characters) with scrolling (L) and static (R) text for each window display condition.

Regression Count

There was a significant effect of window extent $F(5, 155) = 19.64$, $p < 0.001$, $\eta_G^2 = 0.11$, and of display type $F(1, 31) = 11.41$, $p = 0.002$, $\eta_G^2 = 0.05$ on the number of regressive saccades made during reading (with significantly more regressions made with scrolling text as before; see Figure 28). These effects were mediated by an interaction $F(5, 155) = 3.46$, $p = 0.005$, $\eta_G^2 = 0.02$. Pairwise t-tests indicated no significant difference between any restricted window extent and the full view condition when reading scrolling text, but significantly more regressions made with the 4_4 window ($p < 0.001$) and 8_8 window ($p = 0.04$; and marginally more with the 4_8 window; $p = 0.06$) than with the full view condition when reading static text.

As for all other measures, there was no significant difference for either display format between the 4_12 and 8_12 windows or the 4_8 and 8_8 windows (all $p = 1.00$).

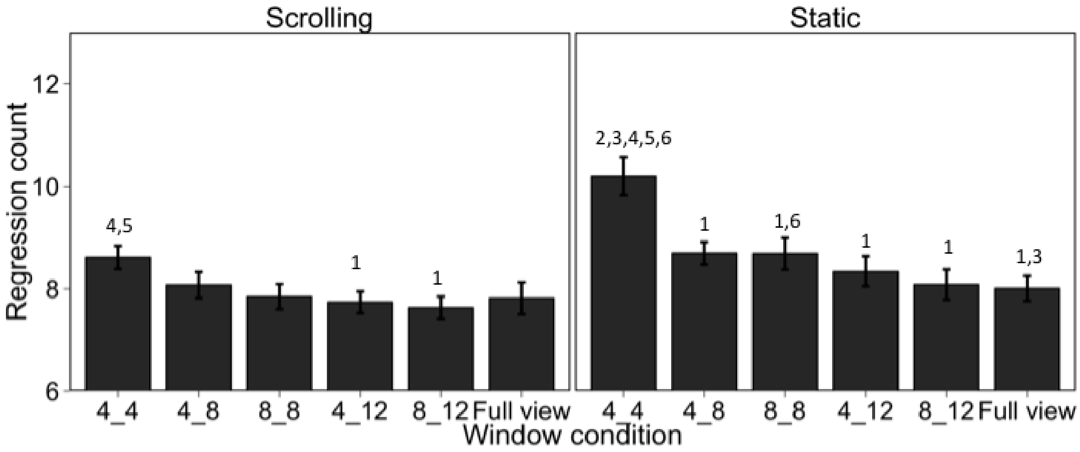

Figure 28. Average number of regressive saccades made when reading a sentence under each of the window display conditions for scrolling (L) and static (R) text.

Landing Position

There was no significant effect of either window condition ($F(5, 155) = 0.55$, $p = 0.74$, $\eta_G^2 = 0.01$) or display type ($F(1, 31) = 1.49$, $p = 0.23$, $\eta_G^2 = 0.01$) on landing position, and no interaction of these factors ($F(5, 155) = 0.87$, $p = 0.50$, $\eta_G^2 = 0.01$). The average landing position for each display type was 2.30 characters (SE 0.05) into the targeted word for static text and 2.30 characters (SE 0.04) into the word for scrolling text (see Figure 29).

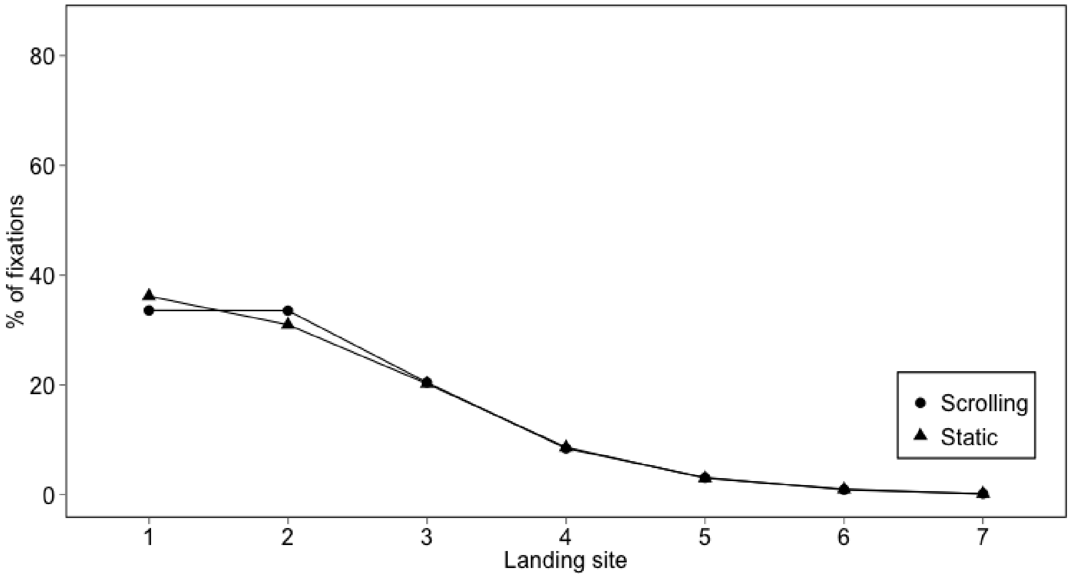

Figure 29. Landing position distributions under static and scrolling text conditions.

Discussion

Experiment 5 further investigated the changes to the perceptual span with scrolling text (compared to static text), confirming the finding of a reduced rightward extent of the span as found in Experiment 4, and extending the findings to verify that this pattern of results reflected a reduction in resources, rather than a leftward shift in their allocation (i.e. with a reduced rightward span but an extended leftward span). This was confirmed in this experiment, with no difference on any measure between windows with matched rightward extents (8 or 12 characters available to the right of fixation) and 4 characters or 8 characters available to the left of fixation.

A similar pattern of findings was found in this experiment as to in Experiment 4, and, importantly, the reading speed measure demonstrated the critical window size for scrolling text to be smaller than for static text (around 8 characters cf. around 12 characters). For total reading duration, fixation count, and regression count (all of which showed the same pattern as reading speed in Experiment 4), there was some deviation from this pattern: for instance for regression count the 4_8 vs. full view comparison was non-significant with static text (p = 0.06; significant p = 0.02 in Experiment 4). However, this pattern of results is still clearly suggestive of a similar reduction in perceptual span with scrolling text. The finding of no difference in average landing position between the two text display formats confirmed that this factor has no explanatory power for the finding of a reduced perceptual span with scrolling text.

The critical manipulation of interest in this experiment was the comparison of windows with 4 or 8 characters available to the left of fixation (i.e. 4_8 vs. 8_8 and 4_12 vs. 8_12 windows), in order to investigate the possibility of a leftward shift of the centre of the attentional window (i.e. hypothetically producing a shift in the perceptual span from 4 characters to the left and 12 to the right of fixation with static text to 8 characters to the left and 8 to the right with scrolling text). However, none of these comparisons were approaching significance for any measure, whereas the comparisons indicating a straightforward reduction in the rightward extent of the span (4_8 vs. full view and 4_12 vs. full view comparisons) all produced a similar pattern as seen in Experiment 5 (despite the use of different stimuli and a slightly different paradigm, with X-masking rather than spatial filtering). This would again seem to confirm the interpretation of the results from Experiment 4 as indicating a reduction in attentional resources to be allocated ahead of the point of fixation (i.e. to upcoming text to the right), and thus a shrunken rightward extent of the perceptual span with the scrolling format.

Chapter Conclusion

The experiments in this chapter demonstrate that the deployment of attention to upcoming text is altered when reading with scrolling text. This was as predicted, due to the conflict between deployment of attention to upcoming text to the right of fixation and to track the currently fixated word as it moves to the left (cf. Kornrumpf et al., 2016).

Ideally, a comparison of the slower scrolling rate would also have been carried out in order to verify whether the perceptual span is affected by the movement of text regardless of the speed, or whether reducing the display speed would allow sufficient extra time for processing to compensate for the directional conflict. However, a pilot study revealed a tendency of readers to fixate close to the rightward edge of the screen to wait for text to appear at very slow speeds made this infeasible, as the longer windows in particular were truncated by the eye position (e.g. 4_12 character window would not able to provide a full 12 character preview for a substantial proportion of the reading period (a pilot study with n=10 participants found that the window was truncated on around a third of fixations made by participants when reading at this speed). However, given the clear effect of imposing a restriction on the available preview on reading (as shown by the gaze-contingent window paradigm here and in many other studies; Belanger et al., 2012; Choi et al., 2015; Jordan et al., 2013; McConkie & Rayner, 1975, 1976; Paterson et al., 2014; Rayner et al., 2009; Rayner, 1986, 2014), this in itself may be an important factor for the effectiveness and efficiency of reading the scrolling text format at such slower speeds. Relevantly in particular for the decrements in performance seen with text moving at either of the scrolling speeds investigated in Chapter 3, a restricted perceptual span has been suggested to increase cognitive load as the text must be processed in smaller (and therefore more numerous) sections (e.g. Smith, 1971). The restriction to the available parafoveal preview with slower scrolling text, and the demonstrated reduction in the perceptual span with faster scrolling text, may therefore increase the difficulty in integrating information across these propositions (reflected in reduced use of sentence-based predictability information as seen in Experiment 3). Text-level integration of information during reading of scrolling text is explored further in Chapter 5, including the functional consequences for this in terms of text comprehension, and other factors that may contribute to this difficulty.

Chapter 5: Reading Comprehension With Scrolling Text Of Different Rates

Introduction

The results of the oculomotor investigations reported up to this point demonstrate a number of factors that reflect the more challenging nature of the reading task with scrolling text. This chapter therefore moves away from eye movement measures to characterise the functional impact of these challenges on reading performance. The findings of Experiments 2 and 3 indicated that the early facilitation of processing for highly predictable target words, as established by context from a previous sentence constraining possible candidate words, was diminished by the movement of scrolling text (i.e. in comparison to the effect seen with static text). This suggests that the ability of readers to establish and use context information across sentences is reduced with this text display format. It has also been found that regressions are important in supporting good understanding of text when reading normally (Schotter, Tran, et al., 2014), whilst the opportunity for and ease of making long-range regressions is reduced in reading of scrolling text (as confirmed by analysis of the global oculomotor pattern employed for this format seen in Chapter 2). This may reflect the reduced availability of the text as it constantly moves out of range of the screen, as well as increased difficulty in mapping the spatial location of each word in the sentence to plan future long-range regressions (cf. Kennedy, 1982); a factor which may be further complicated by a potential reduction in available working memory capacity to support it (Kerzel & Ziegler, 2005). Finally, a smaller perceptual span extent, as demonstrated with scrolling text in the previous chapter, has been associated with difficulty in understanding text; both in the context of the maximum span of poor or developing comprehenders, and in the context of competent comprehenders when reading difficult material (e.g. Henderson & Ferreira, 1990; Patberg & Yonas, 1978; Rayner, 1986; Smith, 1971; White et al., 2005; although also see Patberg & Yonas, 1978 for evidence that text difficulty does not impact on perceptual span, and McConkie & Rayner, 1973 for evidence that artificially reducing the perceptual span does not compromise understanding).

Given all of these factors, it may therefore be expected that text comprehension would also be reduced with the scrolling text format (compared to typical static text). Reading comprehension was measured in Experiments 1 and 2 using periodical two-answer forced choice (2AFC; yes/no) questions and this showed no significant differences between comprehension levels when reading with scrolling or static text in either study. However, this simple comprehension measurement could rely on recognition memory for the presence or absence of certain key words (e.g. in Experiment 1 following the sentence *Opening night was held at a red theatre in the centre of London*, participants were asked *Was the opening night held in central London?*), or may be answerable solely on the basis of the reader's existing knowledge (Rayner & Pollatsek, 1989) resulting in a ceiling effect (demonstrated e.g. by an average comprehension score of 90.3% in Experiment 1) which may therefore obscure any true differences in understanding of the text. Furthermore, the task of text comprehension necessarily becomes more difficult as the length of the text increases, as it contains more ideas that must be decoded and integrated into the overall discourse representation.

Some previous studies have investigated reading comprehension with scrolling text, variably reporting better, equal, or worse comprehension for this format than other display formats (Dyson & Haselgrove, 2000, 2001; Kang & Muter, 1989; Öquist & Lundin, 2007; So & Chan, 2013); however these have largely been interested in the use of dynamic formats for reading from digital displays, and as such have not included a comparison with normal static text or much detail about their assessment of comprehension. One study of RSVP text compared this format with traditional static text presentation, and indicated poorer comprehension for the dynamic format in a sustained reading comprehension task (Benedetto et al., 2015). However, although scrolling text shares some similarities with RSVP (such as an inability to spatially map text or make regressions), there are also some key differences: crucially, the lack of any parafoveal preview information with RSVP, contrasting with a preserved (although reduced; Chapter 4) preview available with scrolling text.

Successful text comprehension involves a series of processes, which may provide numerous opportunities for interference. Many models of comprehension have been developed, which largely rest on the principles set out by Kintsch and Van Dijk in their Construction-Integration model (Kintsch & Rawson, 2007; Kintsch & van Dijk, 1978; Kintsch, 1988, 1998; van Dijk & Kintsch, 1983). This model makes a useful distinction between different levels of understanding of text, with each building on the former leading to a coherent discourse representation. These are: a surface level, involving processing of the perceptual characteristics of the text; a semantic level, involving analysis of the *microstructure* of the text, combining words in to meaningful clause units known as propositions, and the *macrostructure* of the text, building an interrelated network from the microstructures for gist formation; and a situational level, constructing the *textbase*, a model of micro- and macro- structures in the text fully integrated along with the reader's relevant existing knowledge. This model may help explain why a decrement in reading comprehension is not detected on a relatively straightforward 2AFC measure, tapping lower levels of understanding only, and provides a guide for how this may be overcome with a more detailed assessment (i.e. focusing on the macrostructure and textbase). The interaction of the reading situation or strategy with this hierarchy of processing and its impact on text comprehension is demonstrated for example by findings of skim reading, where readers swiftly scan a text performing only a macrostructural level of analysis (Coke, 1976; Huckin, 1983), and are consequently unable to achieve a high level of text comprehension (Rayner et al., 2016).

The progression through the levels in this model to form a coherent text discourse provide numerous opportunities for comprehension failure. For instance, at the microstructure level it is proposed that each new proposition triggers a new cycle of processing to decode and parse the text (Kintsch & van Dijk, 1978; McNamara & Magliano, 2009; Rapp & van den Broek, 2005; van den Broek, Beker, & Oudega, 2015; van den Broek, 1990, 1994). Interference at this stage of processing may lead to information from previous propositions being lost, and therefore unavailable for integration with subsequent propositions and relevant background knowledge at a later stage. Furthermore, encoding of individual words within each proposition may lead to increased difficulty when building these microstructures if these are underspecified in orthographic, phonologic, syntactic, and/or semantic domains (i.e.

the *lexical quality* of the encoded words is insufficient to restrict likely candidates appropriately; Perfetti & Hart, 2001, 2002; Perfetti, 2007; Verhoeven & Perfetti, 2008).

This model has been extended to further explain the processes whereby the textbase is produced: for instance, the Landscape Model (van den Broek & Young, 1998) suggests that units of information from text activate relevant parts of existing background knowledge and that these are maintained in working memory at different levels (i.e. constructing a 'landscape' of interconnected nodes that are activated according to their saliency to the discourse construction. Good readers are proposed to be able to more efficiently identify the most important and structurally central concepts and thus afford these more activation, and also to have sufficient working memory capacity to simultaneously maintain multiple candidate representations to resolve any arising lexical ambiguity (to interpret words with multiple possible meanings e.g. *bear* as in *there was a bear in the woods* or as in *he could not bear it*) or syntactic ambiguity (e.g. of a sentence beginning *The man searched* with the man either as the subject *The man searched his office for the important paper* or as the object *The man searched by the police for the stolen ring was found to be innocent;* Mcvay & Kane, 2012). The relationship that this implies between working memory capacity and reading comprehension was supported by the development of a complex reading span task by Daneman & Carpenter (1980), wherein participants have to recall the last word of each in a series of sentences they recall and then report these words after all sentences have been read.

Working memory is a capacity-limited storage facility, allowing information to be stored for a short period whilst information manipulations, such as the processes involved in text comprehension, are carried out (Baddeley & Hitch, 1974; Baddeley, 1992). The working memory span is defined using this task as the number of these final target words a participant is able to remember, and this measure has been reliably found to correlate with reading comprehension scores across a number of different measures (Daneman & Carpenter, 1980; with higher working memory scores associated with better text comprehension). Lower working memory capacity clearly would be expected to result in fewer pieces of information from the text being able to be maintained at any one time to be integrated with each new piece of information that the reader encounters, as well as fewer candidates to be maintained for resolution of syntactic or lexical ambiguity. However, this relationship has also been specified as being mediated by increased executive control, including better goal maintenance ability (i.e. being more able to stay focussed on the task of comprehending the text) and better competition resolution (i.e. ability to overcome specific distractors from this goal mid-task; Mcvay & Kane, 2012). This may be particularly important for the higher levels of processing involved in text comprehension, aligned with macrostructures and ultimately textbase formation in Kintsch's model. The construction of both of these levels requires integration of information, between spatially separate microstructures and/or between the text and relevant existing background knowledge. This allows the reader to understand both what is concretely stated within the text and also what can be inferred from these associations, and it has been suggested that text cannot be properly comprehended if its constituents cannot be stored in working memory for long enough for this integration to take place (e.g. Cowan et al., 2005).

The scrolling text format clearly does not impair text comprehension entirely, and there is evidence from previous reports that even with sustained reading tasks, a good level of comprehension is achievable (e.g. Laarni, 2002; with comparable or better comprehension achieved with scrolled text compared to static paragraphs, although little information about the comprehension assessment is provided). However, given the results of Experiments 2 and 3 in regards to predictability effects and regression behaviour as discussed, and the clear increase in potential for interference or distraction combined with the likely decrease in cognitive resources to be deployed to the task resulting from this more challenging reading situation, it would seem likely that higher-level (in particular inference-based) comprehension would be reduced compared to that achievable with static text.

Experiment 6: Assessment Of Reading Comprehension With Scrolling And Static Text

Experiment 6 therefore investigates reading comprehension in scrolling and static text using a sustained reading comprehension task adapted from a test battery specifically designed to investigate reading comprehension ability: the *York Assessment of Reading for Comprehension: Passage Reading Secondary* (Stothard, Hulme, Clarke, Barmby, & Snowling, 2010). The resources deployed for storing key concepts from the text is measured using a complex reading span task (following Daneman & Carpenter, 1980), and a reduction in span is expected to underlie a decrement in performance. In order to understand whether reading comprehension performance is constrained by display speed, the two scrolling speeds investigated in Experiment 3 are compared to performance when reading static text. In view of the lack of difference in predictability effect between these two scrolling speeds seen in Experiment 3, it is expected that whilst literal comprehension may be better with a slower rate due to the reduced time pressure and associated increased opportunity for regressive saccades, both scrolling formats are likely to be equally impacted for higher levels of comprehension.

Method

Participants

Participants were 30 native English speakers from Royal Holloway University of London with self-reported normal or corrected-to-normal vision, no language or reading difficulties, and who spoke British English as their first language. The mean age of participants was 19.1 years and 24 were female.

Stimuli And Apparatus

Stimuli were displayed on a 1024 x 768 pixel CRT monitor running at a 100 Hz refresh rate as black text on a white background in 12 pt Courier New typeface. Static text was displayed in paragraph format, and scrolling text in a single line moving across the page, with the faster condition moving at 3 pixels per screen refresh (around 240 wpm) and the slower condition at 3 pixels per 2 screen refreshes (around 120 wpm; producing a comparable display rate for scrolling text formats as in previous experiments).

For the text comprehension assessment, three passages were used from the *York Assessment of Reading for Comprehension: Passage Reading Secondary* (Stothard et al., 2010); *Honey for you, honey for me*, *The Schoolboy,* and *Food in medieval times*. This is a comprehension battery designed for use with children aged 12 - 16 years to assess their reading comprehension ability. The passages were selected for their question type composition (more than two of each of literal and inference-based questions) and reasonable passage length (average of 464 words each; *Honey for you, honey for me* 463 words, *The Schoolboy* 472 words, *Food in medieval times* 457 words).

For the working memory task, 192 single sentences (e.g. *Mel always rushed home after school to make sure she didn't miss her favourite soap*) were constructed with an average of 15.2 words and 86.0 characters per sentence (see Appendix 2). These were randomly allocated to three groups of 64 sentences with the following characteristics: group 1 containing on average 15.3 words and 86.2 characters; group 2 containing on average 15.0 and 85.6 characters; group 3 containing on average 15.5 words and 86.3 characters. There was no significant difference in the number of words or characters contained in the sentences allocated to each group ($p > 0.1$ for all comparisons). These sentences were displayed in the same way as for the comprehension paragraphs, with a group of 64 sentences allocated to each of the three display type conditions (static, faster scrolling, and slower scrolling). Static sentences were displayed at the same vertical location as the single-line scrolling text presentation ($y = 384$), inset from the left edge of the screen by 80 pixels.

Design And Procedure

The passages were displayed to participants in three ways: as static text in standard paragraph form, as scrolling text displayed at around 240 wpm, or as scrolling text displayed at around 120 wpm. A pilot study ($n = 10$) produced comparable results for comprehension and reading speed for static text when displayed for a fixed amount of time (matched to the time taken for the same passage to be displayed in its entirety in the fast scrolling format) or when displayed until the participant terminated the trial; therefore, to produce a better understanding of any intervening role of reading duration on the comprehension results, the reading duration for static text was under participant control (i.e. was displayed until the participant made a button press response to terminate the trial). Participants did not report perceiving any blurring or unevenness in the text motion for either speed.

A reduced list of comprehension questions was given to participants directly following complete reading of the relevant passage. Questions from the original battery were omitted if they asked for the meaning of a word in a particular context (e.g. for *The Schoolboy: "*In the second paragraph, what does 'propel' mean?"), as the participants did not have access to the passage whilst answering the questions. The composition of the set of questions for each passage is shown in Table 8.

Table 7. Composition of different question types for comprehension passages (Stothard et al., 2010) used in Experiment 6.

Passage title	**Literal questions**	**Inference questions**	**Summary question (points available)**	**Total possible score**
Honey for you, honey for me	7	4	8	19
The Schoolboy	5	6	9	20
Food in medieval times	7	3	7	17

The working memory task was carried out following Daneman and Carpenter's (1980) procedure, with participants asked to read firstly two sentences consecutively and then report the final word of each, proceeding to blocks of increasing numbers of sentences to be read (adding an extra sentence each time, with three trials in each block; i.e. 2-2-2, 3-3-3, 4-4-4, etc.) until they were unable to correctly report all of the words required (plus one sentence longer to ensure that no further correct answers would be produced). Two practice trials (of two sentences each) were completed at the start of the task for each display condition. Participants' scores were recorded as the number of words they could recall correctly on two out of three trials. In the fast scrolling condition, a third of participants were unable to reach this level even for two sentences, in which case their score was recorded as 1.

All participants completed all three display conditions for the comprehension and working memory tasks. The allocation of the passages to display format (static, fast scrolling, or slow scrolling) was counterbalanced across participants, and no significant difference was found in comprehension scores between the three passages $F(2, 58) = 0.74$, $p = 0.48$ (passage A 58.67%; passage B 62.28%, passage C 57.84%), or in working memory scores between the three blocks of sentences $F(2, 58) = 0.02$, $p = 0.98$ (mean working memory score 2.6 SE 0.2 for all three blocks).

Analysis

Analyses were carried out in RStudio 0.9.1091 running R 3.0.3 (R Core Team, 2014). To standardise results by paragraph length, reading durations were analysed as reading speed, calculated as number of words divided by reading duration (in minutes). For static text in particular this duration may include more than one complete reading of the text. Multiple comparisons were corrected for using the Bonferroni criterion throughout.

Results

Average reading speed (words per minute; see Figure 30) was significantly different for each of the three display types $F(2, 58) = 77.60$, $p < 0.001$, $\eta_G^2 = 0.60$, with fast scrolling text (mean 200.4 wpm, SE 3.5) read significantly faster than static text (mean 173.7 wpm, SE 9.1), which was read significantly faster than slow scrolling text (mean 111.5 wpm, SE 1.4; all comparisons $p \leq 0.01$). This is in line with the findings reported in Chapter 2 for shorter stimuli (of one or two sentences). There was no significant association found between reading speed and overall comprehension score ($r = -0.15$, $p = 0.16$).

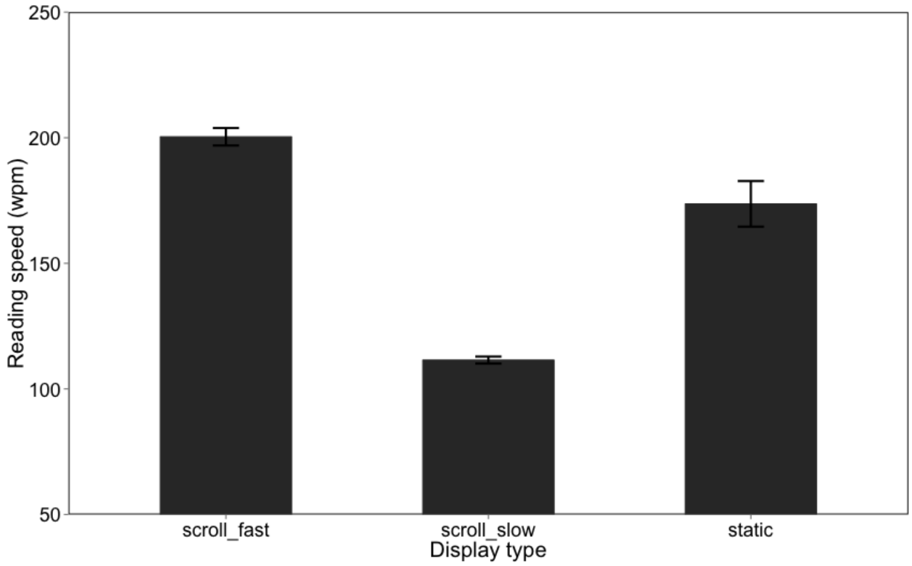

Figure 30. Average number of words read per minute for each text display format (text scrolling at the faster speed of ~240 wpm, scrolling at the slower speed of ~120 wpm, or presented as static paragraphs).

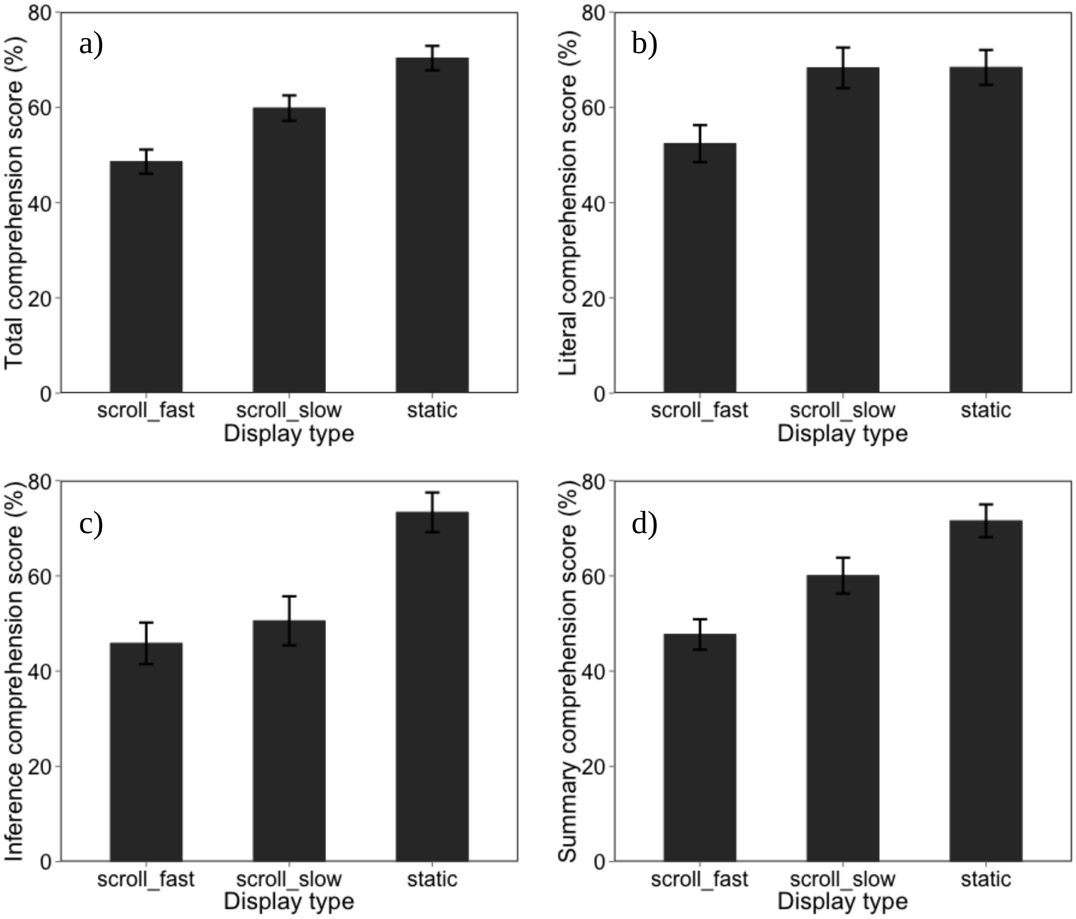

Figure 31. Average comprehension scores by text display type: a) overall comprehension scores, b) literal questions only, c) inference-based questions only, d) summary only.

To compare reading comprehension, the total comprehension score was calculated, summing across all three types of questions in the battery (literal information, inference-based, and summary points). There was a significant difference in this overall comprehension score (see Figure 31a) across the three display types $F(2, 58) = 32.33$, $p < 0.001$, $\eta_G^2 = 0.29$, with pairwise comparisons indicating that static text allowed significantly better comprehension than both slow ($p = 0.001$) and fast ($p < 0.001$) scrolling text, and slow scrolling text better than fast scrolling text ($p = 0.003$).

Comprehension scores were then also analysed for each question type separately, to understand how different parts of the comprehension process may be affected differentially by the text display format:

For questions based on literal information only (see Figure 31b), there was again an effect of display type $F(2, 58) = 6.63$, $p = 0.003$, $\eta_G^2 = 0.11$, with static text and slower scrolling text producing significantly better comprehension than faster scrolling text ($p < 0.001$ and $p = 0.03$ respectively). There was no significant difference between slower scrolling and static text ($p = 0.99$).

For inference-based questions only (see Figure 31c) there was again an effect of display type on comprehension scores $F(2, 58) = 12.37$, $p < 0.001$, $\eta_G^2 = 0.19$. Static text resulted in a higher level of comprehension than fast or slow scrolling text (both $p < 0.001$), with no difference between the scrolling speeds ($p = 0.47$).

The number of points recalled in the summaries produced (see Figure 31d) was also affected by display type $F(2, 58) = 15.39$, $p < 0.001$, $\eta_G^2 = 0.21$. Participants included more points with static text than with faster scrolling ($p < 0.001$) and slower scrolling ($p = 0.045$) text. There was also a difference between scrolling speeds, with better performance with the slower scrolling rate ($p = 0.027$).

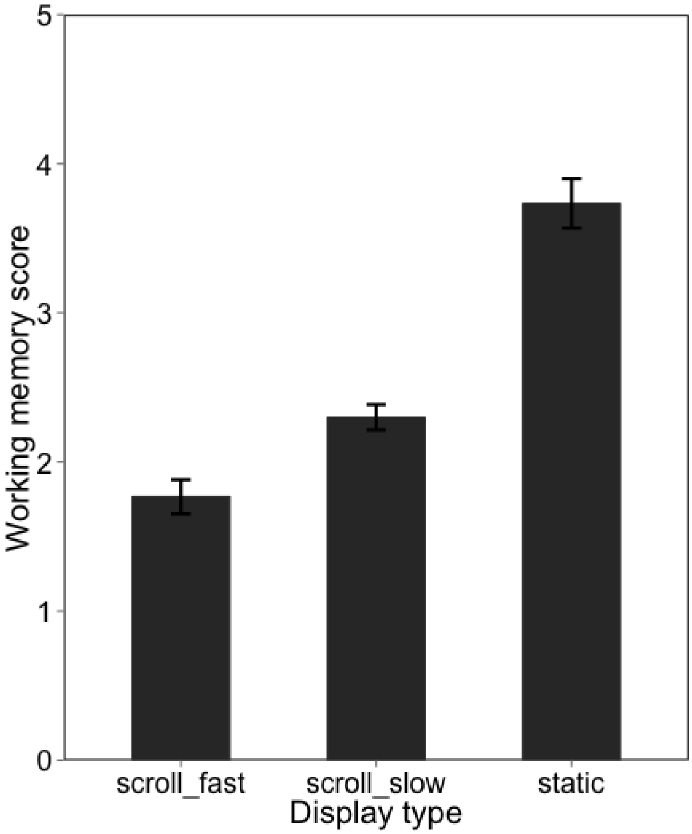

Figure 32. Average working memory capacity scores across the three types of text display formats.

Display type also had a significant effect on working memory scores $F(2, 58) = 73.17$, $p < 0.001$, $\eta_G^2 = 0.60$, with significant differences between all conditions ($p < 0.001$; see Figure 32). As seen for the overall comprehension scores, performance on the complex working memory task was significantly better for static text than for either scrolling format, and for the slower than the faster scrolling format. The average number of items held in working memory for the faster scrolling text was in fact slightly less than the lowest set size of 2 items, whereas the average for the slower speed was slightly above this level, and for static text the average number of items able to be recalled was almost 4 items.

Correlations between working memory score and overall comprehension score indicated that there was a significant association between these for static text only (static $r = 0.77$, $p < 0.001$; slow scroll $r = 0.27$, $p = 0.15$; fast scroll $r = 0.29$, $p = 0.12$). However, the correlations between working memory score for static text and the overall comprehension score for slower and faster scrolling text were both approaching significance (slow $r = 0.34$, fast $r = 0.35$, both $p = 0.06$). Furthermore, there were significant associations between working memory score and inference-only scores for both static and slower scrolling text (static $r = 0.56$, $p = 0.001$; slow scroll $r = 0.49$, $p = 0.006$).

Discussion

Experiment 6 investigated text comprehension ability with scrolling text in a sustained reading task, and the relationship between this and working memory capacity. The results indicate that comprehension is reduced when reading scrolling text (compared to reading normal paragraph-form static text). This decrement was especially pronounced with a faster scrolling speed overall, although inference-based comprehension was equally poor at both scrolling speeds investigated. Working memory scores were significantly lower with scrolling text than static text, which may help to explain this performance decrement in part (cf. Daneman & Carpenter, 1980).

The overall comprehension score (combined over three different question types: those relying on memory for information literally stated in the text; those relying on an inference being made from the text, potentially in combination with existing background knowledge; and a summary question) was significantly reduced for scrolling text (cf. static text), and furthermore was significantly worse for faster scrolling text than slower scrolling text. Breaking this down further to inspect the three question types separately indicated that the difference between the two display speeds seen for scrolling text can be attributed to better recall of literal information and more comprehensive summaries produced with the slower scrolling speed. In particular, the slower scrolling speed allowed participants to achieve the same level of performance on questions requiring information literally stated in the text as with normal static text. Summaries contained fewer of the pre-defined key points with scrolling than with static text, particularly with the faster scrolling speed. There was however no difference between these two speeds for questions requiring an inference to be made, with participants scoring significantly worse on these questions at both speeds (compared to with static text).

Working memory capacity was also significantly lower for scrolling text, with the faster scrolling speed again showing a particular decrement: performance in the working memory task with this display format was in fact surprisingly low, with a third of participants (n=10) failing to complete three trials correctly for the smallest set number (2 items; no participant failed to reach this level in either of the other text display conditions). These low levels of working memory capacity may in part be explained by entrainment of attention from right to left in order to track each word (which may reasonably expected to become stronger at faster text speeds), producing a conflict (in competition with the normal deployment of attention along text from left to right as previously discussed) which may constitute an effective reduction in attentional control (identified as an important mediator of complex working memory capacity and its relationship with reading comprehension; Engle & Kane, 2004; Mcvay & Kane, 2012).

Research into text comprehension ability with static text has shown an association with working memory capacity, with higher capacity supporting better levels of comprehension (Daneman & Carpenter, 1980). This association is replicated here in static text, and may help explain the decline in comprehension scores with the dynamic formats at least to some extent (with reduced working memory capacity and reduced comprehension compared to static text). Although there is no association between the working memory scores and comprehension scores within display type for either of the scrolling speeds, there is a moderate association between working memory capacity as determined with static text and the overall comprehension scores for both scrolling presentations (r = 0.34 and 0.35 for slow and fast scrolling respectively, both approaching significance p = 0.06). The lack of association within the display types is likely due to the reduced dispersion of working memory scores for both display speeds (fast scrolling SD 0.6 and slow scrolling SD 0.5, compared to SD 0.9 for static text). The reduction in working memory capacity with scrolling text may be particularly problematic given the reduction in sustained availability of the text, as evidence from static text suggests that readers with lower working memory capacity may try to compensate for this by making increased selective returns to previously read parts of the text, in order to reinstate this information for integration (Burton & Daneman, 2007).

Reading speed was calculated as the number of words in the passage divided by total reading duration for the passage: this was done to standardise for the differences in passage lengths, but clearly may produce lower reading speeds than would typically be expected (i.e. average 174 wpm here compared to a usual figure of around 250 wpm for static text; Rayner, 1998) as, given the nature of the comprehension task, this duration will likely include more than one complete reading of the text. However, given that static text was read significantly faster than the slower scrolling speed but significantly slower than the faster scrolling speed, and given the lack of correlation between reading speed and comprehension score, it seems clear that reading speed was not an important factor in levels of text comprehension. This was expected, given that none of the text presentation formats gave rise to unusually fast reading speeds (i.e. speed reading, which is associated with poorer reading performance; Rayner, Schotter, Masson, Potter, & Treiman, 2016), and slow reading is not reliably associated with a comprehension decrement (Legge, Ross, Maxwell, et al., 1989).

Perhaps the most striking finding from this study was that the inference-based comprehension score was the only measure studied which did not show some improvement with a slower display speed (compared to the faster display speed). Inference-making is a crucial part of building a coherent discourse of a body of text (van den Broek et al., 2015). That performance on this measure was similarly poor at both speeds is perhaps unsurprising given the similarity of the results regarding the predictability effect in Experiment 3; with the predictability effect similarly resting on the ability to integrate information across sentences and perhaps with existing background knowledge (compared to the simpler literal questions which may rely more on individual word identification and recall). This lack of forward inferencing (i.e. making predictions about upcoming text) implied by the results of Experiments 2 and 3 may also be a factor in this later decrement in inference-based text comprehension, as these predictions may help readers to prioritise storage of certain parts of the text for later use (Fletcher & Bloom, 1988; Fletcher, Chrysler, van den Broek, Deaton, & Bloom, 1995).

Another factor which may help to explain the apparent difficulty with making inferences is working memory capacity (Kintsch, 1988; van den Broek, Rapp, &

Kendeou, 2005). Studies have suggested that there are three key factors which may lead to poor inference generation ability: a deficit in levels of pre-existing knowledge, retrieval error (due to overloaded memory structures), and inadequate vocabulary skills (e.g. Ntim, 2015). Of these three, it is clear that only the second of these (retrieval failure due to storage difficulty) could be invoked to explain the deficit in inference-making found with scrolling text here, and this is supported by the finding that performance on a complex working memory span task (following Daneman & Carpenter, 1980) was significantly worse with either scrolling format than with static text. However, the presence of a difference in working memory scores between the two display speeds would suggest that any reduction in available processing resources that may be reflected in this measure (compared to static text) is insufficient to explain the decrement in performance seen for inference-making with scrolling text. Furthermore, the results of the global oculomotor analysis in Chapter 2 indicated that, although there remained a reduction in long-range regressive saccades for scrolling compared to static text even at the slower display speed, this effect was again reduced in comparison to the faster display speed, and thus could not account for the similar performance for inference generation.

The most likely unifying factor underlying the uniform reduction in inference reduction across both scrolling text conditions would seem to be restricted text availability for both scrolling formats, compared to the sustained availability of the whole passage for static text. Given the increased availability of the text for re-reading in both the static and slower scrolling conditions (although still to a lesser extent with the scrolling format, and with the additional difficulty with spatial representation of text as discussed previously), this clearly allows more time to establish and remember the key concepts from the text as they are encountered: especially important in the way the comprehension battery was administered here, as the questions were all presented after the passage had been read and was no longer available, increasing the importance of memory for the facts stated in the text. The lack of association between reading speed and comprehension measures here likely arises due to the forced extended exposure to restricted portions of the text with the slower scrolling rate, resulting in a slower reading rate for this than for the static text despite less access to re-read earlier parts of the text for instance on reaching the end of the passage. Participants could read any part of the static text as many times as they chose before terminating the trial, whereas this was not the case for either scrolling condition (although opportunity for re-reading each part of the passage as it passed through the screen was increased at the slower rate). However, whilst it is clear to see how this may confer an advantage for recalling specific individual ideas in the text at the slower scrolling rate compared to the faster text, supporting better literal comprehension and increasing participants' ability to produce a summary including more of these key points from the text, the process of integrating the ideas across the text and with existing knowledge is less likely to gain an advantage from this. In both scrolling conditions, a common factor is the restriction on the amount of text displayed at any one time, as this is limited by the screen dimensions rather than the rate of display. Participants are therefore equally unable to revisit parts of the text for instance to verify a link with subsequent text. This may be particularly important with regards to the less automatic processes involved in inference-making, which have been shown to involve searching previously seen parts of the text for information relevant to any given current processing cycle (van den Broek et al., 2015). Furthermore, at the faster rate participants have less time to make inferences online, whilst at the slower rate participants must devote more resources to remembering the concepts across an artificially raised retention period imposed by the slow scrolling speed.

Both this lack of sustained availability and the reduced working memory span may also encourage readers to try and resolve ambiguities early on in the processing chain (i.e. very soon after they encounter a new chunk of information), rather than holding the information in working memory storage for longer and reaching a decision about the most coherent way to integrate this information into their overall representation of the text at a later stage. Karimi and Ferreira (2015) propose an *online cognitive equilibrium* model of discourse formation, where readers search for a 'good-enough' linguistic representation of discourse coherence: the standards for which are influenced by factors such as individual working memory capacity, with those readers with lower capacity accepting an earlier resolution in order to achieve an equilibrium state and relieve demands on their working memory storage. Readers of scrolling text, doubly constrained by working memory capacity and text availability, are therefore also likely to make these inferences soon after encountering new information and without always being able to look back in the text: resulting in a reduced ability to identify links between spatially separated parts of the text, and an increased likelihood of making underspecified inferences.

The movement of the text, entraining a nystagmus-like oculomotor strategy as demonstrated in the global oculomotor analyses reported in Chapter 2, may also itself alter the comprehension process: increased perceptual complexity (arising from the movement of the words) may lead to poorer specification of text characteristics (and therefore lower lexical quality, known to be a contributing factor to poor reading comprehension; Perfetti & Hart, 2001, 2002; Perfetti, 2007; Verhoeven & Perfetti, 2008); furthermore, frequent switching between oculomotor pursuit and saccadic eye movements (as occurs to read this format; Chapter 2; Buettner et al., 1985; Valsecchi et al., 2013) may introduce interference, disturbing the integration of individual propositions (at the microstructure level; Kintsch & van Dijk, 1978; Rapp & van den Broek, 2005). Finally, although there appears to be no literature that has directly addressed the question of whether spatial text organization would have any particular role in aiding inference generation, an additional factor worth consideration is that the scrolling format necessarily strips the text of informative navigational ‘landmarks’ such as paragraph breaks. These cues may help readers to organize the information they are receiving from the text, aiding in the identification of structurally central concepts (Tinker, 1965); a key process in successful text comprehension (van den Broek, Mouw, & Kraal, 2016). The importance of this information in reading text can be supported by findings that readers are able to use this information to recall the position of information on a page for when asked to revisit it (Christie & Just, 1976; Rothkopf, 1971; Zechmeister & McKillip, 1972), and, furthermore, that removal of such information has been found to reduce reading speed (Paterson & Tinker, 1940).

Chapter Conclusion

Experiment 6 showed that, in contrast to findings from the simple 2AFC assessments used for example in Experiments 1 - 3, sustained reading comprehension is reduced with scrolling text (compared to normal paragraph-format presentation of static text). A slower scrolling speed enabled a better understanding to some extent, but only for information stated literally in the text: a finding of equally reduced inference-making ability at faster or slower scrolling speeds further supports a conclusion of increased difficulty in integrating information across spatially separated parts of the text and with existing reader knowledge. The limitations placed on sustained text availability would seem to be an important factor in causing this, as well as the likely increase in perceptual load and directional conflict in deployment of spatial attention resulting in a compressed perceptual span. Readers are therefore receiving more ‘chunks’ of information (due to the reduced perceptual span), are more susceptible to interference when storing each of these propositions, and have reduced storage capacity to store them. They are further less able to identify the key parts of the text in order to prioritise storage of this information for later use, and revisiting previously read text is more complicated or impossible (due to increased difficulty in storing spatial position information and a limited temporal window of availability besides). In response to these challenges, it is unsurprising that a ‘good-enough’ (Karimi & Ferreira, 2015) interpretation of the text would be less good than with static text.

However, it should be noted that the results show that a reasonable level of text comprehension is achievable even with faster scrolling text, with participants able to answer questions on the basis of literal information and (to a lesser extent) inferences made, and to complete some level of gist formation (producing summaries with at least slightly less than half of the key points on average from the passages read) with all three text display formats. Furthermore, for the majority of applications of the scrolling format in digital media (such as on LED announcement boards and in mobile apps) the level of comprehension capability seen in this study would be sufficient. Nonetheless, particularly as digital media becomes increasingly more widely used, including for educational purposes (Al-Fahad, 2009; Dahlstrom, 2012; Gikas & Grant, 2013; Pegrum, Oakley, & Faulkner, 2013; Wallace, Clark, & White, 2012), such limitations should be taken into consideration.

Chapter 6: Application Of The Scrolling Text Format As A Reading Aid For Central Vision Loss

Introduction

The experiments presented thus far have focussed on reading horizontally scrolling text with unimpaired vision, demonstrating a number of observable changes arising with this format compared to normal reading of static text. It may therefore seem paradoxical that dynamic horizontally scrolling text has been suggested to be a possibly useful format for displaying text to reduce difficulty and discomfort in reading with central vision loss: with some support for the application of this format in this way from both simulation and real patient studies (Bowers et al., 2004; Harvey & Walker, 2014; Walker et al., 2016; Walker, 2013). However, it must be recognised that the baseline of reading performance is dramatically shifted for this population. Crucially, whereas most people affected by a degenerative macular condition (especially in age-related forms; e.g. age-related macular degeneration) will have spent many years reading static text on a daily basis, establishing the stereotypical oculomotor pattern required for this task as a highly over-practised skill, dynamic scrolling text is much less widely encountered and therefore less practiced. It may therefore be easier to adapt to a new oculomotor strategy for reading to accommodate a loss of central vision (CVL) with the scrolling format, helping to overcome the problem of fixation instability that is implicated in exacerbating difficulty with reading of static text with a CVL (Crossland et al., 2004). This may be further enhanced by the fact that the scrolling format can allow readers to aim for suppression of eye movements altogether, holding fixation at a specific designated point away from the fovea (a *preferred retinal locus*), to allow text to move through the best remaining part of the vision. This technique is known as steady eye strategy (Watson & Berg, 1983), and its usefulness may be supported to some extent by the widespread use of manual aids with static text which can allow this technique to be adopted by those with a CVL (e.g. CCTV devices and stand-mounted magnifiers; Ahn & Legge, 1995). Finally, the scrolling format necessarily presents the text as a single line, removing the difficulty associated with navigation of a multiline text stimulus with a central scotoma (Deruaz, Whatham, Mermoud, & Safran, 2002).

The use of scrolling text as an aid has been experimentally supported by a number of studies that have found that this format is preferred over formats including normal static text presentation and rapid serial visual presentation (RSVP; another method of presenting text dynamically, with words or small sections of text displayed sequentially at a fixed point) (Bowers et al., 2004; Harland et al., 1998; Walker et al., 2016; Walker, 2013), and may also confer advantages in reading performance measures (Legge, Ross, Maxwell, et al., 1989; Walker et al., 2016). A study using the gaze-contingent simulated scotoma paradigm with normally-sighted observers also found that adherence to the facilitative eccentric viewing strategy (EV; wherein readers must try to fixate away from the text and read the text as it falls in their peripheral retina, as opposed to trying to foveate the text as would be the case in normal reading; Nilsson & Nilsson, 1986a, 1986b) was improved when reading scrolling compared to static text, with over 50% of total fixation duration in dynamic text trials spent fixating eccentrically. This appeared to confer an advantage for reading accuracy with this format (Harvey & Walker, 2014).

In the context of these initially positive findings, it is necessary to investigate how the scrolling text presentation would be best applied to provide the maximum improvement. Two broad classes of factors which must be considered in order to do this are patient characteristics (i.e. profiles of visual function, such as the scotoma extent), and text presentation characteristics. The latter of these in particular may be guided by those factors that have been identified as being important to improve performance when reading with other text formats (i.e. static and RSVP formats). One such factor which has been both shown to improve reading with static text (Blackmore-Wright et al., 2013) and suggested to partially underlie the improvements seen with the RSVP format (Falkenberg, Rubin, & Bex, 2007; Pelli et al., 2007), is the alteration of presentation to reduce visual crowding.

This chapter therefore presents two experiments that investigate the use of this application of the horizontally scrolling format further, using the gaze-contingent simulated scotoma paradigm to look at the patient characteristic of scotoma extent and the text presentation characteristic of text spacing to reduce visual crowding during reading of this format in the peripheral retina (and its interaction with scotoma extent; Experiment 7), and to establish whether the apparent benefits of this format result in an improvement in sustained reading comprehension (Experiment 8).

Experiment 7: Increased Word Spacing For Scrolling Text To Improve Reading With A Simulated Loss Of Central Vision

Introduction

One factor that is known to contribute to the difficulty in reading with a central vision loss is visual crowding, an effect that involves difficulty in identifying individual objects when they are surrounded by other spatially close objects due to misattributing features from the surrounding objects to target object (Pelli & Tillman, 2008; Whitney & Levi, 2011; Zahabi & Arguin, 2014). Even in normal reading with no visual impairment, sufficient word spacing is known to be important to allow efficient parsing of individual words by delineation of word boundaries (Paterson & Jordan, 2010) and to reduce crowding, with findings of increased overall reading times and increased difficulty with word identification when typical word spacing information is removed (Rayner et al., 1998). There is some indication that the typical spacing of one character width is optimal, with 50% reduced or increased word spacing resulting in a similar pattern to removing spacing altogether; although the only study that has investigated this altered spacing between words (inter-word spacing) in tandem to character spacing within words (intra-word spacing), so it is not clear how much of the effect can be uniquely attributed to the inter-word manipulation (Slattery & Rayner, 2013).

Nevertheless, the importance of minimising crowding in the text stimulus may be even greater for effective reading with a central vision loss, and the inter-word spacing required to do this is likely greater: it is known that the crowding effect worsens with increasing eccentricity (Bouma, 1970), with clear negative implications for trying to read with the peripheral retina (He, Legge, & Yu, 2013; Latham & Whitaker, 1996; Pelli et al., 2007). In order to combat this, it has been suggested that increased text spacing may be helpful for populations with central vision loss in order to reduce crowding and therefore ease identification of individual words. Increased line spacing and increased inter-word spacing have both been shown to be advantageous for reading of static text in a sample with age-related macular degeneration (AMD; Blackmore-Wright, Georgeson, & Anderson, 2013), with increased reading speed and fewer errors recorded during reading with double typical line and inter-word spacing. Clearly the presentation of scrolling text (in a single line across a display screen) reduces crowding in the vertical axis (between lines) already; however, it is not known whether a similar benefit would be conferred as in static text if inter-word spacing was increased (reducing crowding in the horizontal axis). Blackmore-Wright et al. (2013) found no additional benefit for three-times than twice regular spacing with static text. However, given previous findings of investigations of dynamic non-text stimuli suggesting that crowding may be increased for targets positioned in the opposite direction to the flow of motion (Harrison et al., 2014), as is the case for upcoming words that may be detected in the parafoveal preview whilst tracking word *n* (see Figure 33), it may even be the case that enhanced inter-word spacing to reduce crowding is more important for optimised reading of scrolling text than has been found for static text.

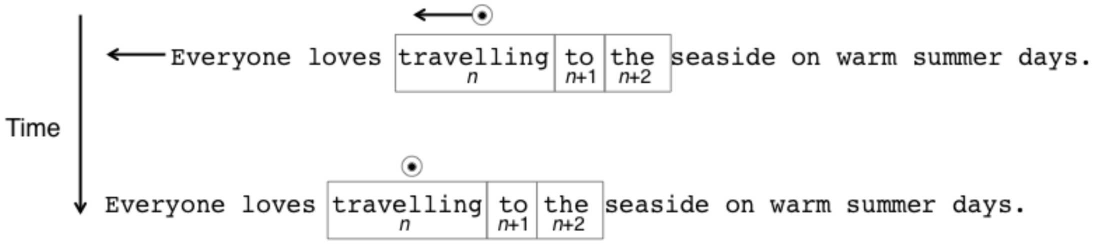

Figure 33. Processing of upcoming words in the parafoveal area (e.g. word n + 1 and word n + 2) may be disrupted by increased crowding of objects positioned behind the direction of movement (i.e. to the right whilst the eye tracks word n 'travelling' as it moves to the left).

This study therefore aimed to investigate whether increased word spacing improves scrolling text reading performance with (simulated) central vision loss, as has been found for reading of static text (Blackmore-Wright et al., 2013), and whether, in line with the findings regarding increased crowding for dynamic stimuli, triple word spacing provides additional benefit above double word spacing for this display format. Given the necessary increase of the forced eccentricity of the text stimulus to be read with increasing scotoma size (with this factor reflecting the degenerative nature of conditions involving central vision loss such as age-related macular degeneration), the study also aimed to address the question of whether any potential benefit for reading performance with increased interword spacing would be preserved over increasing scotoma extents. Furthermore, given that one of the advantages of dynamic text formats is removing any space limitations for the extent of the text stimuli, a secondary aim was to investigate if increasing scotoma diameter could be effectively countered by increased text size, without detrimental effect on any of the measures of reading performance quality (accuracy, comprehension, or memory).

Method

Participants

Participants were 12 Psychology undergraduate students from Royal Holloway, University of London (8 female, mean age 19.5). All reported having normal or corrected to normal vision, no reading or language impairments, and their first language as British English. All received course credit for their participation and gave informed consent as approved by departmental ethical review.

Stimulus And Apparatus

Stimuli were 90 sentences based on the MNRead corpus (Legge, Ross, Luebker, et al., 1989). The average number of words in each sentence was 11.3 (SD 1.3), with an average of 4.4 characters (SD 0.6) in each word: for example, *The play was so boring that everyone wanted to leave early* (see Appendix 3). These were randomly allocated to each of the 9 conditions prior to the experiment, and one-way ANOVAs showed no significant differences in the average word count or word length between the conditions ($p = .866$ and $p = .629$ respectively). A further 30 sentences with similar characteristics were produced to provide a practice block.

All stimuli were displayed as black text (Courier font, identified as an adequate font for reading with central vision loss; Chung, 2002; Tarita-Nistor, Lam, Brent, Steinbach, & González, 2013) on a white background, on a 1024 x 768 pixel CRT monitor running at a refresh rate of 100 Hz. Viewing distance was maintained at 70 cm with a table-mounted headrest. The size of the font was scaled for each scotoma size, with 16 pt, 32 pt, and 48 pt sized fonts used respectively across the increasing scotoma sizes (5^{o}, 8^{o}, or 12^{o} diameter; see Figure 34). The text size for each scotoma extent was determined using the eccentric minimum character size formula developed by Anstis (1974), with the text size chosen for each forced eccentricity calculated as 4 times the determined minimum.

The program was prepared and displayed using SR Research Experiment Builder software with custom Python code. Scrolling text was moved across the screen from right to left at a speed of 2 pixels per screen refresh (6.7 ^{o}/s; translating to 18.2, 9.1, and 6.3 characters/s for the 5^{o}, 8^{o}, and 12^{o} scotoma conditions respectively).

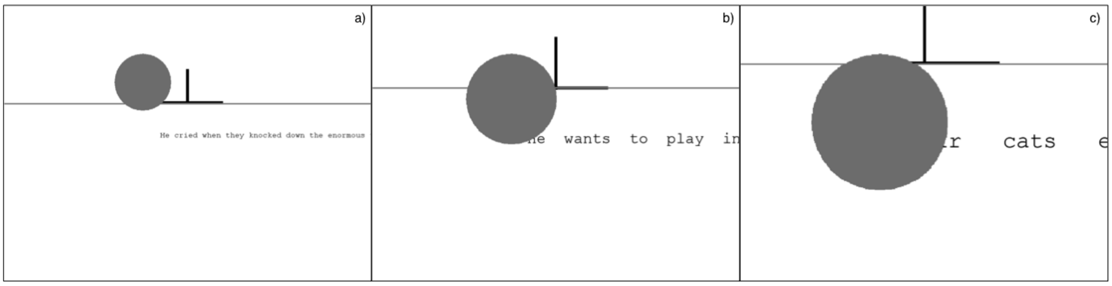

Figure 34. Schematics showing display for a) 5^{o} diameter scotoma (single spacing condition displayed), b) 8^{o} diameter scotoma (double spacing condition displayed), and c) 12^{o} diameter scotoma (triple spacing condition displayed). The horizontal grey line across the screen for each was positioned to guide an eccentric viewing technique, such that when the line was fixated the sentence was not obscured by the scotoma (i.e. was positioned a radius length above the text; 2.5^{o}, 4^{o}, 6^{o} respectively from left to right). The black cross was positioned centrally on this EV line to provide a guide location for where a steady position could be held (i.e. to guide use of the Steady Eye strategy).

Gaze-Contingent Scotoma

Monocular (right-eye, left eye patched) recording of eye movements by an EyeLink 1000 video-based eye tracker at a sample rate of 1000 Hz (i.e. 1 sample of gaze position recorded every 1 ms, using pupil and corneal reflection to determine position; see Appendix 4) was carried out during reading of each sentence. The scotoma extent was either of 5^{o}, 8^{o}, or 12^{o} diameter (with 30 trials for each scotoma size in the main experimental block), and was displayed as a homogenously filled grey circle. The program used to display the scotoma was developed (in SR Research Experiment Builder with advice from Marcus Johnson; SR Research) in consideration of the recommendations made by Aguilar and Castet (2011) with regards to the issue of pupil size changes (e.g. due to blinks) for the validity of gaze-contingent scotoma paradigms. The eye position was used to draw a scotoma based on the last sample location every 10 ms, with the exception of when a blink was detected, when the scotoma was redrawn continuously in the same position until the blink was over. Blinks were identified as beginning when the size of the pupil dropped below 90% of the size of the three-sample moving average of pupil size, at which point each subsequent pupil sample was compared against the last average computed before a blink was detected until it no longer violated this criterion (after which point the scotoma was redrawn at the newest sample location, and a new three-sample moving average was computed).

Procedure

All participants completed 30 practice sentences prior to the main experimental session in order to familiarise themselves with the paradigm. The main experimental block consisted of 90 sentences, with 30 sentences displayed with each scotoma size (5^o, 8^o, or 12^o diameter), with 10 sentences for each spacing condition (single, double, or triple spacing) within each of these. The order of conditions was randomised.

Participants were asked to adhere to the eccentric viewing strategy in conjunction with steady eye strategy as much as possible. Both of these techniques were explained to the participants prior to their completing the experiment. To encourage adherence, a grey line was placed above the text such that, if participants fixated along this line, full view of the text in the inferior peripheral visual field was available (i.e. the text was not obscured by the scotoma at all; see Figure 34). A black cross was positioned in the middle of this line, with the size of the cross scaled with scotoma diameter to allow 20 pixels visible horizontally either side of the scotoma if participants fixated centrally at the intersection of the cross.

Prior to each trial a drift correction was performed, and a gaze contingent square presented in order to ensure accuracy of recorded gaze position (participants required to make a stable fixation within a 0.8^o square, in the absence of the gaze-contingent scotoma, prior to the presentation of each sentence). Recalibration was performed after any trial where participants experienced any difficulty triggering the gaze-contingent square as well as after any breaks taken as necessary (including a rest break imposed after every 30 trials).

Participants were asked to read the sentences presented to them aloud, and a transcript recorded for later inspection to determine accuracy rates. They were also required to answer two-answer forced choice (yes or no) comprehension questions (e.g. for the sentence *The play was so boring that everyone wanted to leave early.* participants were asked *Did everyone like the play?*), and asked to repeat sentences aloud after reading them on two-thirds of all trials. This allowed measures of reading speed, accuracy, comprehension, and memory to be analysed.

Analyses were carried out using RStudio 0.98.953 running R 3.0.3 (R Core Team, 2014). Data were cleaned to exclude trials where participants failed to read any of the sentence, trials were terminated prematurely, or calibration failed during the trial. This resulted in removal of 3% of trials. Multiple comparisons were corrected for using the Bonferroni criterion throughout.

Results

Reading Speed

Reading speed was analysed in two ways to take into account the impact of the increased spacing, with measures of mean reading duration standardised by a) the number of characters in the sentence and b) the horizontal extent of the text stimulus (in degrees of a visual angle) calculated; i.e. giving a measure of milliseconds spent fixating a) per character or b) per degree. For reading speed standardised by the character extent of sentences, there were significant effects of scotoma size $F(2, 22) = 761.4$, $p < 0.001$, $\eta_G^2 = 0.95$ and of spacing condition $F(2, 22) = 40.5$, $p < 0.001$, $\eta_G^2 = 0.22$, qualified by an interaction of these factors $F(4, 44) = 12.3$, $p < 0.001$, $\eta_G^2 = 0.18$ (see Figure 35a). Reading duration was significantly quicker per character in the 5^o scotoma condition than in both others, and in the 8^o scotoma condition than in the 12^o scotoma condition. Reading durations were significantly quicker per character in triple spacing than single or double spacing conditions for the 5^o scotoma condition ($p < 0.001$ for both; $d = 2.14$ and $d = 1.41$ respectively), and for the 8^o scotoma condition (with triple spacing significantly less time spent per character than double spacing $p = 0.01$, $d = 0.88$ and less than single spacing $p = 0.001$, $d = 1.30$), There were no significant differences between spacing conditions with the 12^o scotoma for this measure.

For reading speed standardised by the degree extent of sentences, there were again significant effects of both scotoma condition $F(2, 22) = 52.7$, $p < 0.001$, $\eta_G^2 = 0.66$ (8° scotoma less time spent per degree than both of 5° and 12° conditions, 12° scotoma less time spent per degree than 5° scotoma) and spacing condition $F(2, 22) = 37.0$, $p < 0.001$, $\eta_G^2 = 0.16$ (triple spacing less than single and double spacing, $p < 0.001$ for both), as well as an interaction between these two factors $F(4, 44) = 39.7$, $p < 0.001$, $\eta_G^2 = 0.32$, showing that triple spacing was quicker per degree than either single or double spacing for 5° scotoma, and slower per degree than either single or double spacing for the 12° scotoma, with no differences in spacing conditions for the 8° scotoma (see Figure 35b).

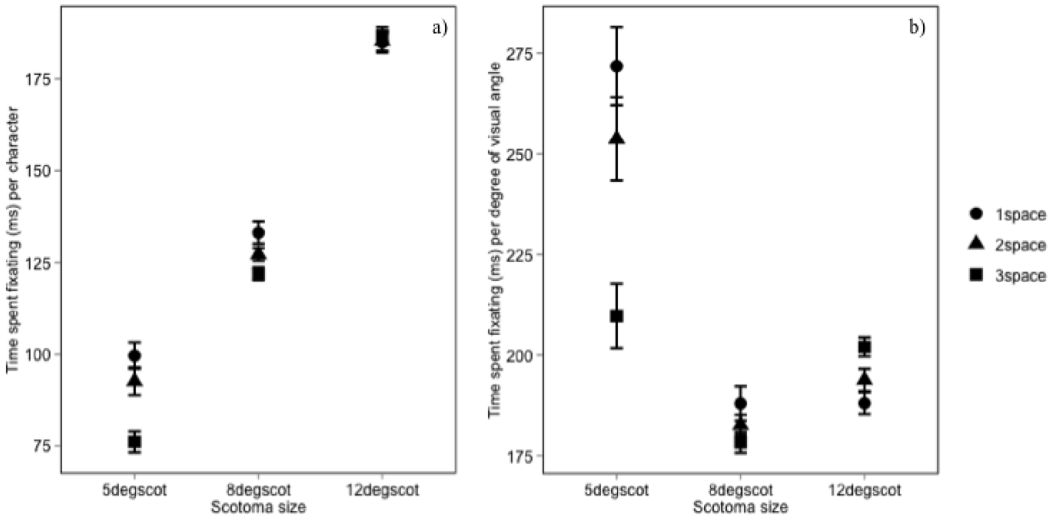

Figure 35. Reading duration standardised by a) character extent of stimuli (ms per character) and b) degree extent of stimuli (ms per degree). Error bars show standard error above and below the mean (here and in all following).

Accuracy

Reading accuracy was measured as number of errors (omissions, substitutions, insertions, or incorrect word order) made in each sentence. There was an effect of spacing condition on accuracy ($F(2, 22) = 9.8$, $p < 0.001$, $\eta_G^2 = 0.14$). T-tests showed that this was a result of significantly fewer errors made in triple-spaced than double-spaced sentences ($t(11) = -4.64$, $p = 0.001$, d =55) and than single-spaced sentences ($t(11) = -4.00$, $p = 0.002$, $d = 0.96$). This word spacing effect was qualified by an interaction of spacing condition and scotoma extent ($F(4, 44) = 2.9$, $p = 0.03$, $\eta_G^2 = 0.01$). As illustrated in Figure 36, t-tests indicated that triple spacing was significantly more accurate with a 5^{o} scotoma than double (*t*(11) = -5.11, *p* < 0.001, *d* = 0.48) or single (*t*(11) = -4.09, *p* = 0.001, *d* = 0.83) spacing, and similarly with a 12^{o} scotoma reading with triple word spacing was again more accurate than with double-spaced (*t*(11) = -3.00, *p* = 0.01, *d* = 0.45) and single-spaced (*t*(11) = -3..49, *p* = 0.005, *d* = 1.03) text). These differences were only marginally significant (when corrected for multiple comparisons) in the 8^{o} scotoma conditions (*p* = 0.03 for both; triple vs. double spacing *d* = 0.51, triple vs. single spacing *d* = 0.86).

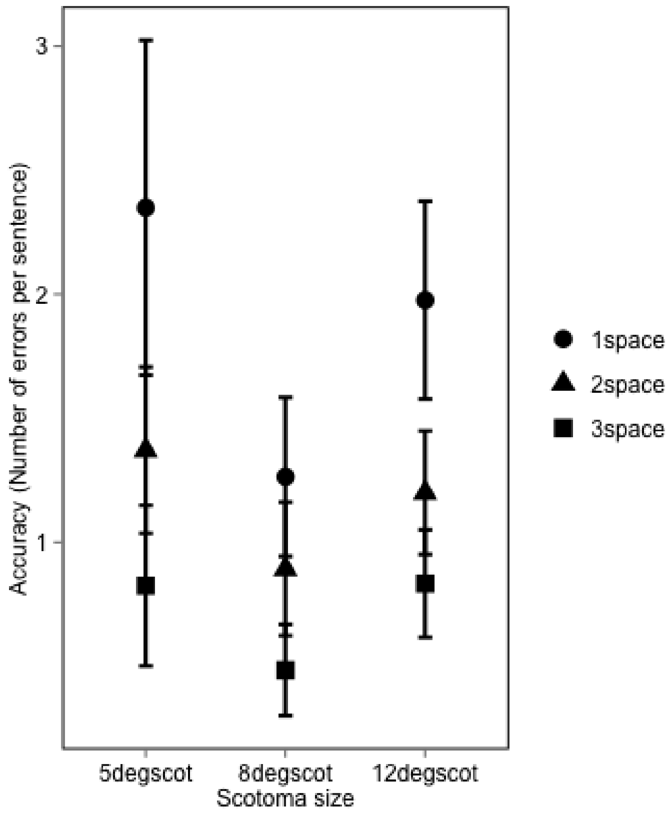

Figure 36. Average number of reading errors made per sentence read for each scotoma size condition, by spacing condition.

Comprehension

There were no effects of scotoma size or spacing condition for comprehension. Average comprehension score was 68.5% (SE 2.3). Numerical trends in the 8^{o} and 12^{o} scotoma extent conditions showed increasing comprehension scores across spacing conditions (decreasing scores across spacing conditions were seen in the 5^{o} scotoma condition), but none of these comparisons reached significance. Average comprehension scores across scotoma extent conditions were 68.3%, 68.0%, and 69.7% for 5^{o}, 8^{o}, and 12^{o} extent respectively.

Memory

There was an effect only of spacing condition on memory performance $F(2, 22) = 14.3$, $p < 0.001$, $\eta_G^2 = 0.16$, with triple spacing producing better memory scores than either other spacing condition ($p = 0.002$, $d = 1.28$ for double spacing and $p = 0.001$, $d = 1.74$ for single spacing; see Figure 37).

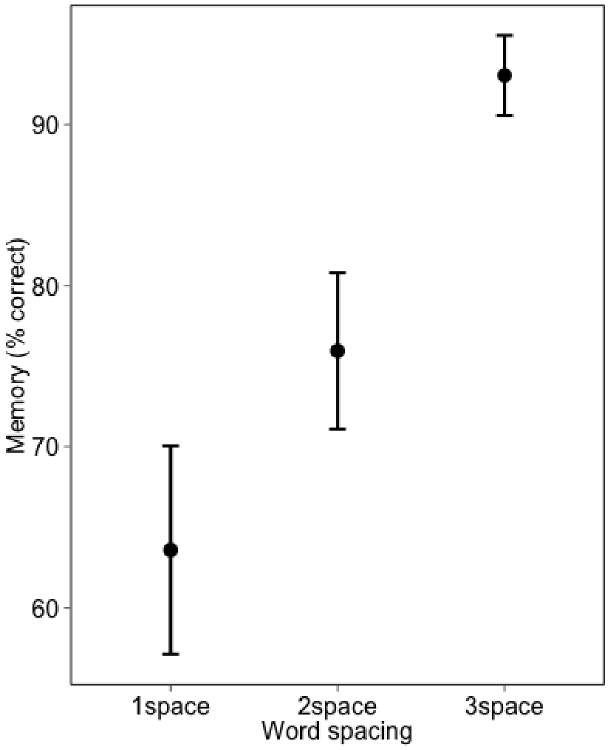

Figure 37. Average percentage of sentences correctly recalled for single-, double-, and triple-spaced sentences.

Eccentric Viewing Adherence

Adherence to the eccentric viewing strategy was investigated by examining the positions of fixation made on the screen during reading (see Figure 38), and categorising according to whether they were made in a superior eccentric position (i.e. above the line of the text) or not. Adherence to this strategy was negatively correlated with reading speed, with increased adherence to EV being associated with decreased time spent fixating per degree of a visual angle ($r = -0.25$, $p = 0.009$; i.e. an improvement in reading speed with improved adherence to this strategy). No relationship was found between EV adherence and any of memory, comprehension, or accuracy scores.

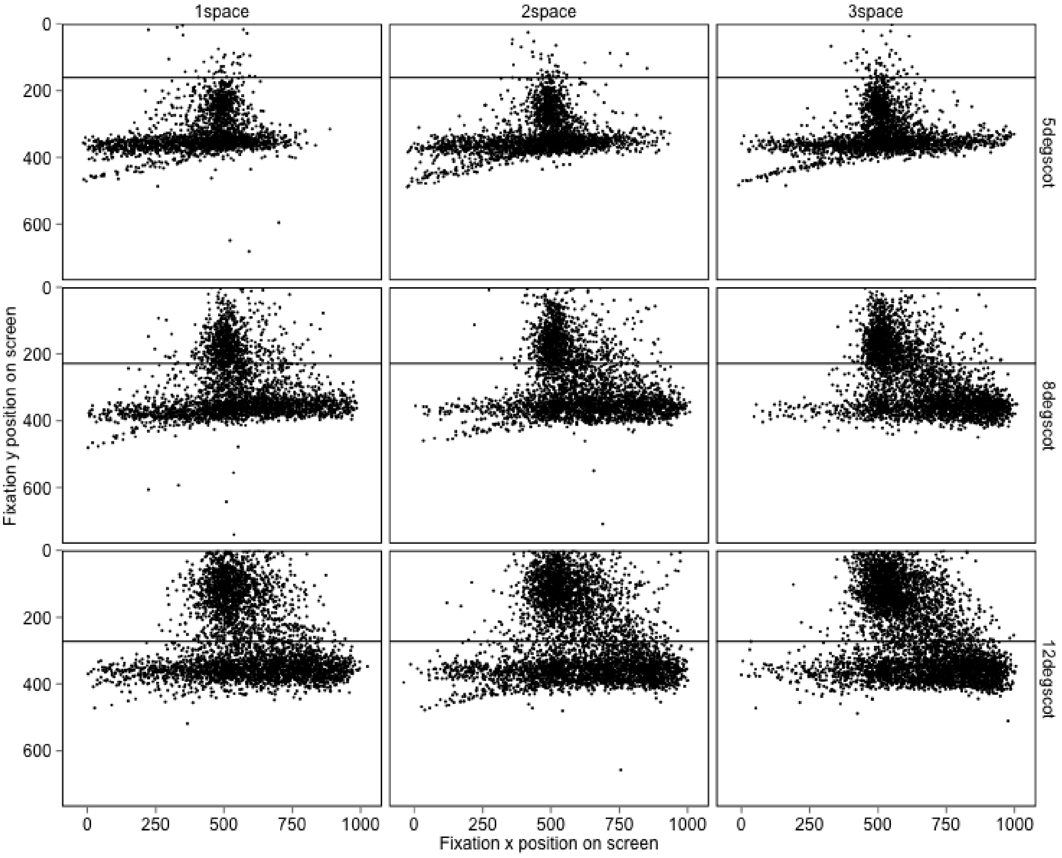

Figure 38. Fixation positions of all participants when reading under each viewing condition (vertically from top to bottom: 5º, 8º, and 12º scotoma diameter; horizontally from left to right: single, double, and triple word spacing). The line indicates the position of the EV guide line as displayed during reading to participants.

There was a significant effect of scotoma extent on EV adherence $F(2, 22) = 7.52$, $p = 0.003$, $\eta_G^2 = 0.07$, with significantly worse adherence to the EV strategy with a 5º scotoma than an 8º scotoma; $t(11) = -3.58$, $p = 0.004$, $d = 0.62$ (worse than 12º scotoma comparison non-significant when corrected for multiple comparisons, p = 0.03, $d = 0.03$), and also of spacing condition $F(2, 22) = 9.74$, $p = 0.001$, $\eta_G^2 = 0.01$ (triple spacing better adherence than single or double spacing; $t(11) = 3.52$, $p = 0.005$, $d = 0.24$; $t(11) = 4.08$, $p = 0.002$, $d = 0.15$ respectively). This was qualified by an interaction of these two factors $F(4, 44) = 6.98$, $p < 0.001$, $\eta_G^2 = 0.01$, with no difference between spacing conditions with a 5º extent scotoma, significant increases in adherence between single, double, and triple spacing conditions with an 8º scotoma, and a significant difference only between single and triple spacing conditions with a 12º extent scotoma (see Figure 39).

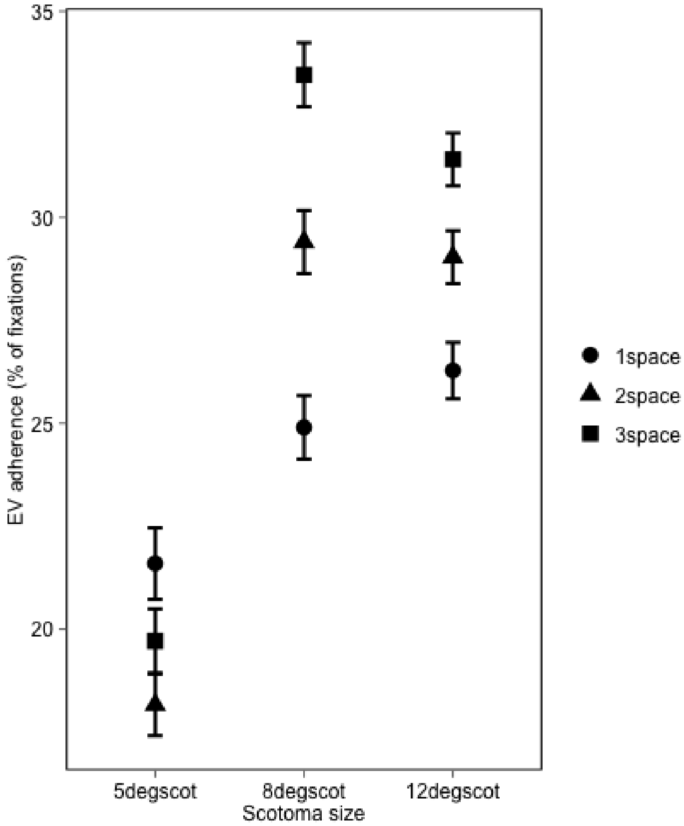

Figure 39. Average percentage of reading time spent fixating eccentrically (on EV guide line or above) from the sentence for single, double, and triple spacing across the 5^o, 8^o, and 12^o scotoma extents.

Discussion

This study investigated the impact of increased word spacing on reading performance with a dynamic horizontally scrolling text format across three different sizes of artificial central scotoma. The findings suggest that increasing word spacing to triple standard spacing improves reading performance when reading with a simulated loss of central vision, with accuracy, memory, and comprehension increased, and average fixation duration (per degree extent of text stimulus) decreased with this increase in word spacing. The findings also provide additional support for the use of the eccentric viewing strategy for reading dynamic text with central vision loss, with decreased reading times associated with increased adherence to this viewing strategy, and suggest that increased word spacing may help improve adherence.

An improvement in reading performance with increased word spacing has previously been shown in a patient sample with reading of static text, with double word spacing being shown to confer an advantage over regular single spacing and, in some cases, over triple word spacing as well (with triple spacing never conferring additional advantage over double spacing; Blackmore-Wright et al., 2013). However it was expected here that triple word spacing might be more beneficial than double spacing given the moving format increasing the crowding effect (Bex, Dakin, & Simmers, 2003; Harrison et al., 2014). This was found to be the case, with triple spacing producing better accuracy in reading and improved memory for sentences, as well as reduced duration spent fixating per character, than either double- or single-spaced text.

There is an obvious confound for the reading speed measure insofar as that the scrolling text presentation forces a certain maximum reading speed: this is unavoidable, as any attempt to control for this introduces a new set of confounds. For instance, one way to standardise the maximum reading speed would be to adjust the scrolling speed (pixels moved per screen refresh). However, this would adjust the retinal speed of individual words, possibly leading to blurring or aliasing (known to negatively impact on the ease of processing text; Slattery & Rayner, 2010). The way in which the text was presented in the current study resulted in a maximum reading speed ranging between around 54-218 words per minute. However, there is little evidence that slow reading speed alone has a particular impact on comprehension (e.g. Legge, Ross, Maxwell, & Luebker, 1989; notwithstanding factors which may cause slow speed in free reading such as dyslexia or other reading or language problems; e.g. de Oliveira, da Silva, Dias, Seabra, & Macedo, 2014; Jackson & McClelland, 1979; Wolf, Bally, & Morris, 1986; Wolf, Bowers, & Biddle, 2000), and the indication across scotoma size conditions here would be that the rate of text presentation indeed does not have much of an impact on reading quality measures (comprehension, accuracy, and memory; none of which showed a significant effect of scotoma size). This is despite the maximum reading rate for the 5° scotoma conditions (around 218, 182 and 156 wpm for single, double, and triple spacing respectively) being higher than the 8° scotoma conditions (around 109, 91, and 78 wpm), which are higher than for the 12° scotoma conditions (around 75, 63, and 54 wpm). This would indicate that the differences seen in performance between word spacing conditions are attributable to the reduction in crowding achieved by increasing the intra-word spacing, rather than being a reflection of the associated rate of presentations. The lack of difference across scotoma conditions for the three measures of reading performance (comprehension, accuracy, and memory) would also indicate that scotoma extent may successfully be compensated for by increasing text size; although there may be additional difficulties in real central vision loss, such as increased metamorphopsia (distortion) as degeneration progresses (although increased reading difficulty here may also be mediated to some degree by text size; Wiecek, Dakin, & Bex, 2014).

Another interesting finding was that better eccentric viewing (EV) strategy adherence was related to lower average processing times, supporting previous findings which have indicated that this is a beneficial strategy (Gustafsson & Inde, 2004; Hong et al., 2014; Jeong & Moon, 2011; Nilsson & Nilsson, 1986a; Palmer et al., 2009; Palmer, 2009; Pijnacker, Verstraten, van Damme, Vandermeulen, & Steenbergen, 2011). In particular, results indicated that scotoma size might be influential, with better adherence to the strategy with the larger scotoma sizes (8^o and 12^o). This might indicate that participants were more able to compensate for the 5^o scotoma without using the eccentric strategy, whereas with the increased scotoma extent the increased difficulty encouraged them to use and maintain the suggested strategy. Furthermore, importantly, it seemed that triple word spacing improved adherence to EV for the larger scotoma extents, further supporting the use of increased spacing to help improve reading ease.

Experiment 8: Reading Comprehension With A Simulated Loss Of Central Vision

Introduction

Research investigating reading with visual impairments often focuses on the maximum achievable reading speed as the key measure of ability (e.g. Bowers et al., 2004; Chung, 2011; Crossland et al., 2004; Rubin, 2013). Although this is a useful measure of reading performance, it is clearly not the defining characteristic of successful reading, with no evidence for significant break-down of text comprehension even at very slow reading speeds (Legge, Ross, Maxwell, et al., 1989). As in Experiment 7 here, any direct attempts to quantify reading comprehension tend to take a 2AFC (yes/no) approach following reading of single sentences, with identical problems as to those discussed in Chapter 5 (i.e. they are able to be answered on the basis of very little actual understanding of the text, often requiring nothing more than key word recognition). Some studies have suggested a benefit for reading accuracy with the horizontally scrolling format (Harvey & Walker, 2014; Walker et al., 2016; Walker, 2013), as well as reports of subjective preference for this format over the static format and other dynamic formats (Bowers et al., 2004; Harland et al., 1998; Walker et al., 2016; Walker, 2013). Furthermore, the reduced load on the oculomotor system which from possibly increased use of facilitative viewing strategies (Harvey & Walker, 2014) may increase the cognitive resources available for allocation to text comprehension in this case. This is clearly in contrast to the findings from Chapter 5, of reduced text comprehension with scrolling text. However, the text presentation in this case is user-controlled, overcoming the restrictions on text availability seen with the fixed presentation rate investigated in the previous experiments. Furthermore the reading situation with a central loss of vision is considerably more effortful with any text format than in unimpaired reading, which likely has a significant impact on the cognitive processes involved.

Experiment 8 therefore used a reading comprehension battery (Hulme et al., 2009) completed for scrolling and static text under conditions of simulated central vision loss to assess whether scrolling text may be improved text understanding for populations with a central loss of vision.

Method

Participants

Participants were 22 undergraduate students from Royal Holloway, University of London (19 female, mean age 19.0 years). All reported having normal or corrected to normal vision, no reading or language impairments, and their first language as British English. All received course credit for their participation and gave informed consent as approved by departmental ethical review.

Stimulus And Apparatus

Passages used were from the York Assessment of Reading for Comprehension: Early Reading and Passage Reading Primary (Hulme et al., 2009). This battery is designed with use for children between the ages of 4 - 11 years, but was used in preference to the Secondary battery (Stothard et al., 2010) used in Experiment 4 because of the shorter passage length (passages used: *Goannas* 182 words and *Pirates* 228 words). This was deemed more suitable for the task of reading with a simulated CVL, as this is a much more demanding task than unimpaired reading, and takes much longer (therefore putting greater demand on memory). As in Experiment 6, the passages were read completely and then removed prior to the comprehension questions being presented, although in this case the scrolling text was under user control allowing participants to revisit parts of the text as they wished. One question was omitted (for the *Pirates* passages: '*In the context of this passage, what does 'bold' mean?')*, leaving 7 questions about the *Pirates* passage and 8 questions about the *Goannas* passage.

A further passage from the battery (*Bees*, 179 words) was read as a practice passage prior to the comprehension task in each text display format (static and scrolling), in order to allow the participants to familiarise themselves with the scotoma and text controls (for scrolling text only).

The passages of text were displayed as black text (24 pt, Courier New typeface; 18 pixels horizontal character extent) on a yellow background (thought to provide better contrast discrimination than black on white, and with some evidence that people with real age-related macular degeneration have a subjective preference for reading from this presentation style; Alizadeh-Ebadi, Markowitz, & Shima, 2013) on a 1024 x 768 pixel CRT display running at 100 Hz refresh rate. Static text was displayed in paragraph form with double line spacing and double word spacing (following Blackmore-Wright et al., 2013). Scrolling text was displayed in a single line with triple word spacing (following Experiment 7; see Figure 34). A visible horizontal ‘guide’ line to aid adherence to the EV strategy was provided above the text for the scrolling condition. This was positioned 4^o above the text, allowing a full view of the text in the inferior visual field when this line was centrally fixated. Analysis of the proportion of the total fixation time during the task spent fixating in accordance with the eccentric viewing strategy, where adherence to the strategy was defined as any fixation which fell in the region from 2^o above the text to the top of the screen (see marked area on the scrolling display schematic in Figure 40).

Gaze-Contingent Scotoma

Monocular recording of eye movements by an EyeLink 1000 video-based eye tracker at a sample rate of 1000 Hz (pupil and corneal reflection) was carried out during reading. The scotoma was displayed as a homogenously filled dark grey circle of 8^o diameter (see Figure 40). The eye position was used to draw a scotoma based on the last sample location every 10 ms, with the exception of when a blink was detected, when the scotoma was redrawn continuously in the same position until the blink was over. Blinks were identified as beginning when the size of the pupil dropped below 90% of the size of the three-sample moving average of pupil size, at which point each subsequent pupil sample was compared against the last average computed before a blink was detected until it no longer violated this criterion (after which point the scotoma was redrawn at the newest sample location, and a new three-sample moving average was computed).

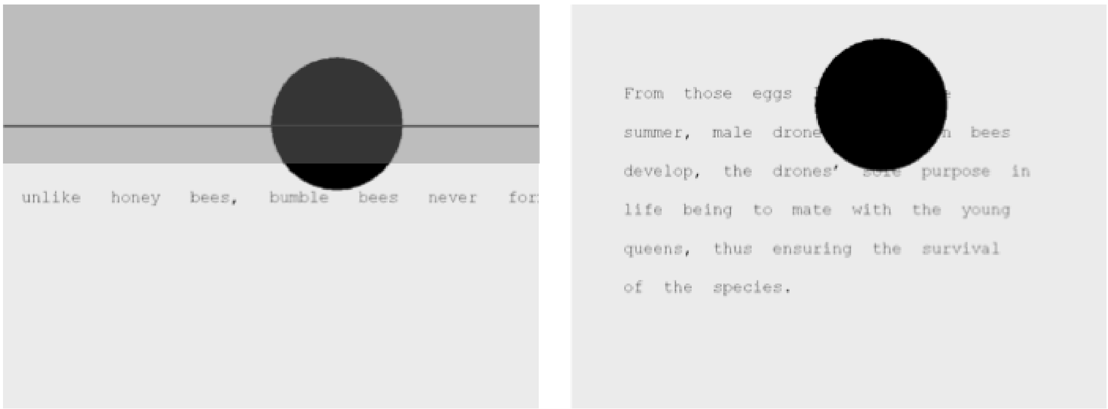

Figure 40. Example displays of scrolling (L) and static (R) text presentation for Experiment 7. The horizontal line on the scrolling schematic was displayed to the participants, in order to help them guide their use of the eccentric viewing strategy (positioned 4^o above the top of the text display area). The shaded box was not visible to participants, but demonstrates the interest area for fixations defined as being made in adherence to the eccentric viewing strategy, spanning from 2^o above the top of the text display area to the upper vertical extent of the screen.

Procedure

The consequences of central vision loss, the simulated scotoma paradigm, and the eccentric viewing strategy were explained to the participants prior to the experiment. The order and display type of the passages was counterbalanced. All participants read the practice passage (*Bees*) in the appropriate display format before reading the experimental passage in order to familiarise themselves with the simulation paradigm and the display format (especially relevant for the scrolling format, as they were able to use the right and left arrow keys to speed up, slow down, and reverse the movement of the text). The default scrolling speed at which the programme started was around 96 words per minute (same rate as in the previous experiment for the 8^o scotoma condition). An increase or decrease in speed (by arrow key press) altered the speed in steps of 1 pixel per screen refresh (100ms). The participants were given this control of the text speed to support text comprehension, as the longer passages (cf. single short sentences in the previous experiment) provided greater opportunity for them to miss part of the passage, leaving them unable to gain a complete reading of the text. Allowing them to slow down or move the text back into view therefore provided them with equal opportunity to revisit any parts of the text with the scrolling format as they had for the static format. Furthermore, unlike for unimpaired reading of dynamic text, user control of the speed of presentation has been demonstrated (with RSVP) to be advantageous for reading with central vision loss (Arditi, 2004).

Following the practice, each participant read the experimental passage (with no constraint on reading time), and, after termination of the reading period, was presented with the comprehension questions for the passage. After completion of the questions, they were also asked to produce a summary of the key points. A summary of the scores available for each passage is shown in Table 9 following.

Table 8. Composition of scores available for comprehension passages (Hulme et al., 2009) used for Experiment 8.

Passage title	**Comprehension questions**	**Summary points**	**Total score available**
Pirates	7	12	19
Goannas	8	12	20

Results

Comprehension

Two participants were excluded from the final analysis due to calibration failure at some point during at least one of the reading tasks. This left a final sample size of n = 20, with appropriate counterbalancing. Comprehension questions were compared separately to the number of summary points produced, and composite scores were then also calculated for each display type, combining the results of the comprehension questions and the number of key points included in the summaries produced (with a possible total score of 19 for the *Pirates* passage and 20 for the *Goannas* passage; see Table 9 for composition of scores). There were no significant differences on any of these measures (comprehension questions score, summary points produced, and composite score) across counterbalancing groups (all comparisons $p \geq 0.2$).

Scrolling text produced significantly better text comprehension than static text (questions only $t(19) = 2.91$, $p < 0.001$, $d = 0.63$; summary only $t(19) = 2.90$, $p < 0.01$, $d = 0.55$; composite score $t(19) = 3.94$, $p < 0.001$, $d = 0.73$; see Figure 41 a-c). Surprisingly, there was no difference (all comparisons $p > 0.1$; see Figure 42 a-e) between static and scrolling text for reading speed (scrolling text: mean 80.5 wpm, SE

6.9; static text: mean 82.2 wpm, SE 11.2), average fixation duration (scrolling text: mean 231.0 ms, SE 10.9; static text: mean 224.8 ms, SE 7.4), average number of fixations made per word (scrolling text: mean 4.1 fixations per word, SE 0.3; static text: mean 4.4 fixations SE 0.4), or regression probability (scrolling text: mean 51.9%, SE 0.8; static text: mean 50.7%, SE 1.0). Saccade amplitude however was modulated by display type, with significantly longer saccades for static text ($t(19) = -5.54$, $p < 0.001$, $d = 1.06$; scrolling text mean 8.1 characters, SE 0.5; static text mean 9.9 characters, SE 0.4; see Figure 42 b). There was also no significant relationship between any oculomotor measure and comprehension performance (all $p > 0.2$) except for saccade amplitude, with increasingly poorer comprehension scores associated with longer average saccade lengths ($r = -0.43$, $p = 0.006$).

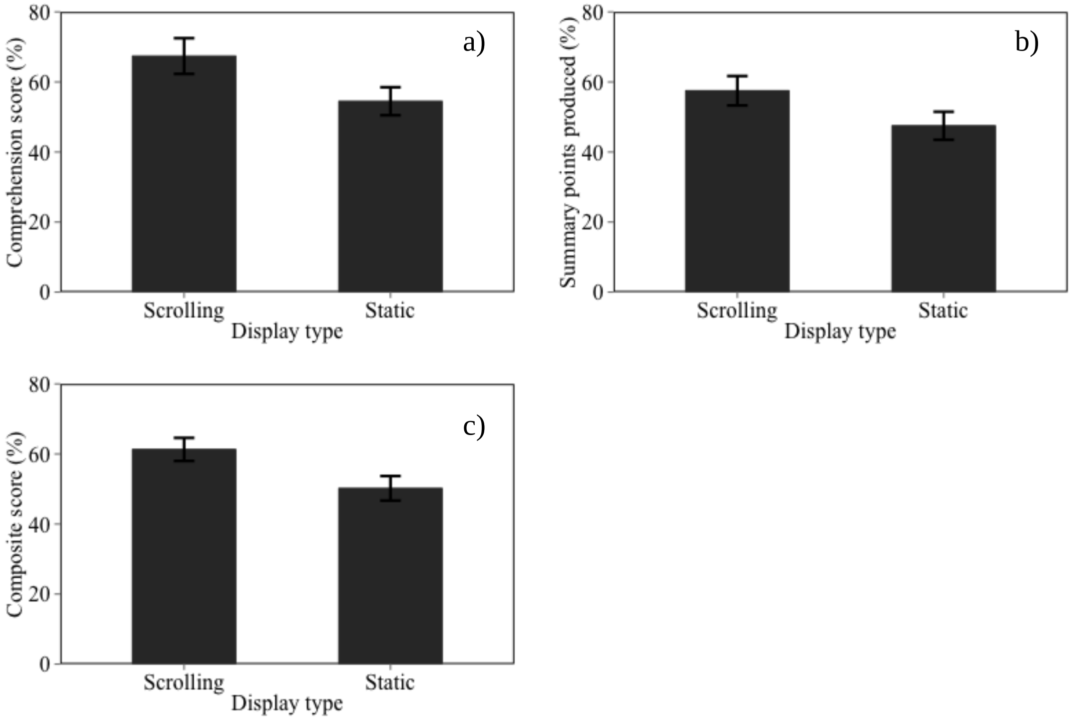

Figure 41. Average scores for reading under scrolling and static text conditions: a) comprehension questions, b) percentage of total possible key points recalled, and c) composite scores.

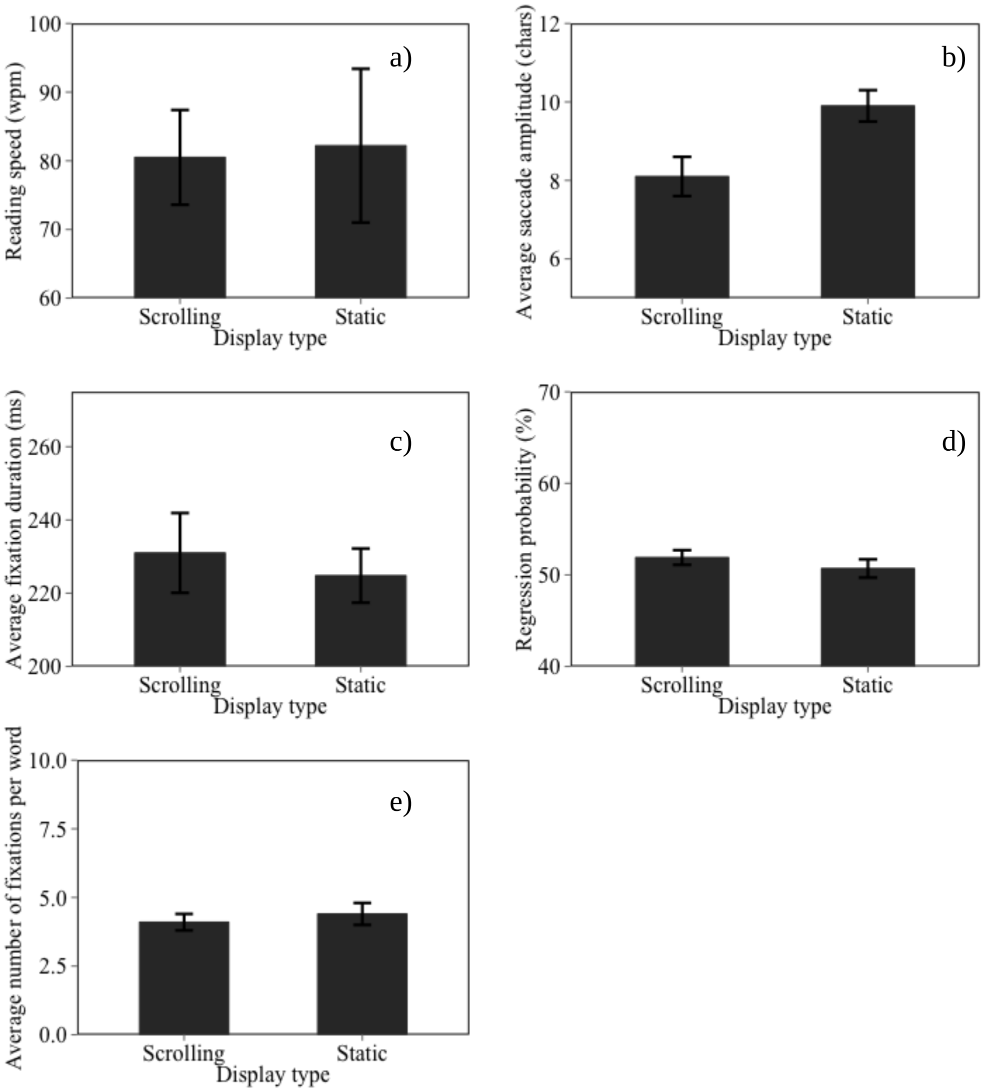

Figure 42. Comparison of reading speed (a) and oculomotor measures (b - average saccade amplitude; c – average fixation duration; d - regression probability; and e – average number of fixations made per word) between scrolling and static text conditions with an 8^o diameter simulated scotoma. Average saccade amplitude was significantly longer with static text, otherwise all other comparisons showed no significant difference.

Eccentric Viewing

Due to the presentation of the static text condition (i.e. standard multiline paragraph format), it was not possible to determine eccentric viewing strategy adherence for this format (although participants were informed about the strategy and encouraged to adopt its use). However, for scrolling text only, the percentage of total fixation time on the experimental passage made in an eccentric position (defined as any fixations falling within the region from 2^o above the top of the text to the top of the screen) was calculated. On average, participants spent 24.2% of their fixation time in this eccentric position when reading scrolling text (SE 6.8). There was a marginally positive relationship between EV adherence and comprehension question scores (r =

0.41, *p* = 0.07; see Figure 43). EV adherence was also significantly positively associated with average fixation duration (*r* = 0.50, *p* = 0.03), and significantly negatively associated with average saccade amplitude (*r* = -0.60, *p* = 0.005).

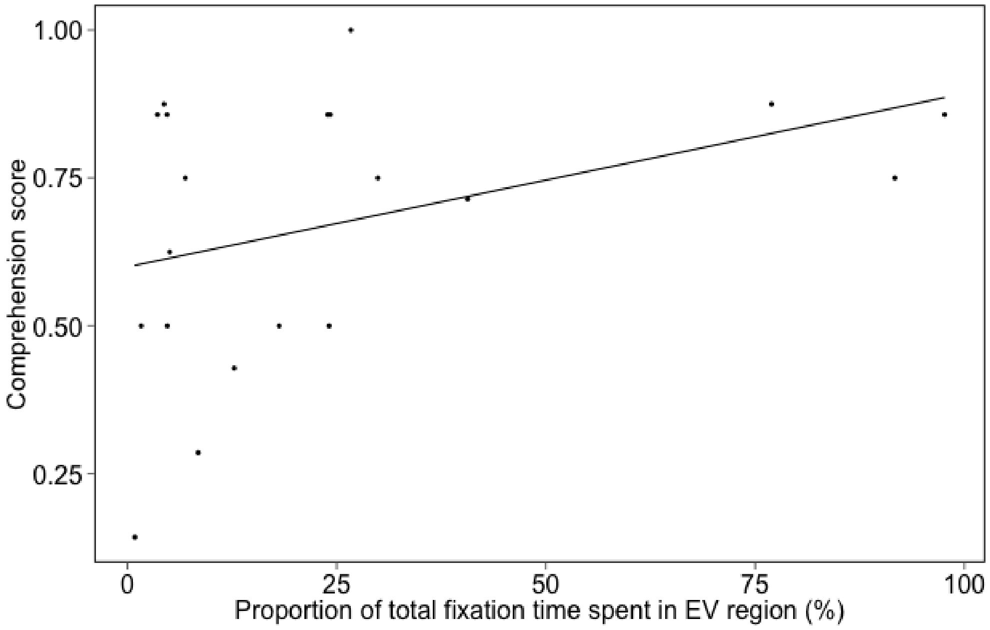

Figure 43. Relationship between adherence to eccentric viewing strategy and comprehension score (for scrolling text only).

Discussion

Experiment 8 used the gaze-contingent simulated scotoma paradigm for central vision loss to compare performance in a sustained reading comprehension task for reading with static and scrolling text. Previous studies have shown that people with central vision loss may have a subjective preference for reading with the scrolling format (compared to static and other dynamic text formats; Bowers et al., 2004; Harland et al., 1998; Walker et al., 2016; Walker, 2013), and that this format may improve reading accuracy (Walker et al., 2016). However, no improvement in reading speed has been found (Bowers et al., 2004; Walker et al., 2016; Walker, 2013), and, although 2AFC questions following single sentence reading has demonstrated no difference between the formats, no detailed assessment of reading comprehension undertaken. This study therefore constituted an initial investigation into this issue with a simulated central vision loss.

In accordance with previous reports suggesting that reading accuracy and adherence to the facilitative eccentric viewing strategy may be improved with scrolling text (Harvey & Walker, 2014; Walker et al., 2016; Walker, 2013), reading comprehension scores showed a small (and significant) improvement with scrolling text. This was the case across both measures of comprehension assessed: direct short-answer questions, and the number of key points identified and recalled from the experimental passage.

Oculomotor behaviour was also investigated to determine if any improvements in comprehension were associated for example with fewer fixations made (suggesting greater fixation stability). The only oculomotor measures investigated that appeared to have a relationship with comprehension was saccade amplitude, with shorter saccades associated with better comprehension. Given that average saccade length was increased for both static and scrolling text compared to the results from unimpaired reading reported in Chapter 2 (9.9 and 8.1 characters for static and scrolling text respectively, compared to 8.0 and 5.2 characters for unimpaired reading), this may suggest that readers were making a greater number of counterproductive longer saccades, with the primary purpose of trying to achieve a direct fixation (i.e. to 'evade' the gaze-contingent scotoma) rather than to read the text; it may therefore be conjectured that readers with a shorter average saccade amplitude were making fewer of this type of saccade. However, the presentation of each display format was optimised in terms of increased word spacing (and line spacing for static text only; following Blackmore-Wright et al., 2013), and use of the eccentric viewing technique was encouraged for both formats. This may have played some role in the similarity of oculomotor behaviour across formats, with no difference in fixation count, fixation duration, or regression probability. There was also no difference in average reading speed for the two formats. However, it may also be worth considering that this lack of difference is in stark contrast to the findings for normal (unimpaired) reading with these formats: compared to static text, average fixation duration, fixation count, and regression probability are all increased with scrolling text (see Chapter 2 comparison of slower scrolling rate and static text). Although it is clearly important to exercise caution in drawing any comparisons given the very different reading situation and the instruction to attempt a manipulation of the oculomotor viewing strategy besides, these results may therefore constitute a relative increase in fixation count and regression probability with static text (i.e. comparatively poorer oculomotor control when reading without a central visual impairment, relative to scrolling text).

Adherence to the facilitative viewing strategy EV could only be determined for scrolling text, due to the multiline nature of the presentation of static text. Reasonable adherence was seen to the strategy with the scrolling format (around a quarter of fixation time spent in the prescribed region for eccentric fixation; at least 2^o above the text), and there appeared to be some evidence for a positive relationship ($r = 0.41$) between adherence and comprehension (although this did not reach significance; $p = 0.07$). Adherence was also significantly positively associated with fixation duration and negatively associated with saccade amplitude (which is also negatively associated with comprehension score), both of which may indicate some degree of increased fixation stability: however, there was no relationship between the average number of fixations made per word and these or any other measure.

Chapter Conclusion

This chapter has investigated a possible area of application for the scrolling text format, as a reading aid for populations with a central loss of vision, using the gaze-contingent scotoma simulation paradigm. Both experiments have provided further support for the potential of this format to be used in this way. In particular, Experiment 8 provides valuable evidence that scrolling text may lead to better comprehension in a sustained reading task than normal paragraph-form static text. Furthermore, both experiments provide some support for the use of the eccentric viewing strategy in conjunction with the scrolling format, with a negative relationship between adherence and reading speed in Experiment 7, and a marginally significant ($p = 0.07$) relationship between adherence and comprehension scores in Experiment 8.

It will be important to verify these findings in real clinical groups with a genuine loss of central vision. However, the simulated CVL data provide initial insight into the value of investigating particular parameters with such a sample, whilst bypassing difficulties in recruitment and data collection. This simulation paradigm has been widely used to this end (Aguilar & Castet, 2011; Bernard, Scherlen, &

Castet, 2007; Bertera, 1988; Cornelissen, Bruin, & Kooijman, 2005; Fine & Rubin, 1998; Geringswald, Baumgartner, & Pollmann, 2013; MiYoung Kwon, Nandy, & Tjan, 2013; Miyoung Kwon et al., 2012; McIlreavy, Fiser, & Bex, 2012; Pidcoe & Wetzel, 2006; Rayner & Bertera, 1979; Scherlen, Bernard, Calabrèse, & Castet, 2008; Varsori, Perez-Fornos, Safran, & Whatham, 2004), and is generally accepted to provide a reasonable approximation of conditions involving CVL (such as age-related macular degeneration).

Other research groups (notably e.g. Chung, 2011; Rubin & Turano, 1992, 1994) have advocated the use of a different dynamic text presentation, the RSVP format, for reading with central vision loss. This format undoubtedly provides an advantage compared to scrolling text insofar as it is much easier for readers to achieve a stabilised gaze position (i.e. to suppress almost all saccadic eye movements) with this format than with the scrolled position (Rubin & Turano, 1992; it is clear from results of the oculomotor recordings here as well as previous reports (Harvey & Walker, 2014) that readers find it extremely difficult to hold a steady gaze position with the scrolling format, as the movement of the text entrains the eye into pursuit). The single word presentation with the RSVP format also necessitates the removal of inter-word visual crowding (Falkenberg et al., 2007; Pelli et al., 2007). However, given what is known about the importance of these factors for reading without visual impairment (e.g. Schotter et al., 2012; Schotter, Tran, et al., 2014), the removal of parafoveal preview information and the further reduction in sustained text availability (compared to the scrolling format) seems likely to have a negative impact on measures such as reading comprehension. A direct comparison of these two formats using a detailed comprehension assessment, such as the battery used in Experiment 8, will be necessary to determine whether this is the case. Further investigation would also be useful to determine whether these two formats may both be advantageous at different stages of rehabilitation; for instance, an initial training period with RSVP may be useful to improve fixation stability when reading, followed by training with the scrolling format to aid their transition back to reading typical static text more effectively.

Chapter 7: General Discussion

Dynamic text display formats are of increasing practical relevance in today's society, as use of personal media devices becomes more prevalent (Lee, 2015): such formats allow unlimited text to be displayed in limited presentation windows, and are showing promise for example as tablet-based reading aids for people with visual impairments including age-related macular degeneration (e.g. Walker et al., 2016; Walker, 2013). The horizontally scrolling format is of particular interest, being one of the few dynamic formats (see Figure 44) which allow word-form (cf. 'marquee'-style vertical scrolling text) and at least some parafoveal preview (cf. RSVP) information to be preserved (both of which factors are known to be important in effective reading; e.g. Byrne, 2002; Clifton et al., 2016; Ehri & Wilce, 1982; Gagl, Hawelka, Richlan, Schuster, & Hutzler, 2013; Mayall, Humphreys, & Olson, 1997; Rayner, 1998).

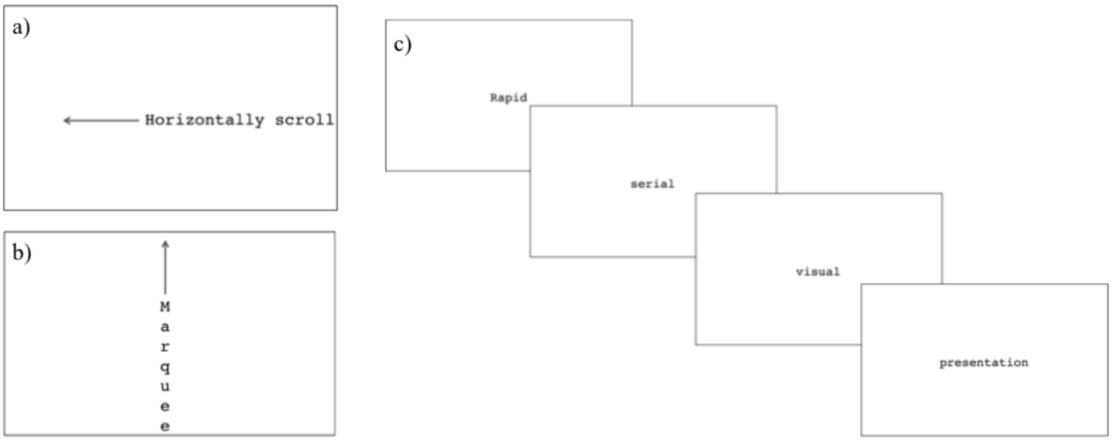

Figure 44. Dynamic text formats: a) horizontally scrolling text, where text drifts in a single line from left to right; b) marquee (vertically scrolling) text, where text drifts from bottom to top in a single line of one character's width; and c) rapid serial visual presentation (RSVP), where text is presented one word at a time in a central location.

This format is also of considerable theoretical interest, providing an unusual reading situation introducing a number of additional challenges to the already complex task of reading. For instance, this format both increases the difficulty of making and reduces the opportunity to make regressive saccades to reinspect the text once it has been viewed. It furthermore results in a more complicated situation for the deployment attention around the point of fixation, with a requirement to attend to the right in order to begin processing of upcoming information, concurrent with a need to attend to the left in order to track the foveated word as it moves across the screen (necessary to establish a clear retinal image of the word for processing and to maintain the current location in the text).

This thesis sought to examine the impact of the horizontally scrolling text display format on processes involved in successful reading, and to consider its applied potential. In relation to the hypotheses set out in Chapter 1, this investigation has found that:

- Word-level lexical processing is seemingly unaffected by the dynamic scrolling of text.
- Sentence-level integration of information is compromised when reading with this format, compared to with normal static text.
- The deployment of attention to upcoming text is altered by the conflict introduced by the leftward movement of text, reducing the available resources to be allocated to the right to begin processing of upcoming text.
- A reasonable level of text comprehension is still achievable with scrolling text, but understanding is reduced compared to with standard paragraph-form static text, with a particular deficit in inference-making.
- It is possible to improve reading performance when reading scrolling text with a simulated loss of central vision by optimising the presentation of scrolling text (i.e. by increasing interword spacing to reduce visual crowding)
- Despite the finding of reduced comprehension in unimpaired reading, the scrolling format improves comprehension with a simulated loss of central vision.

The main part of this investigation characterised some of the key processes involved in reading with scrolling text. Chapter 2 provided an overview of the changes to the oculomotor strategy employed to read with this format, with some consideration of the effect of text display speed on this pattern. Chapter 3 indicated that word-level processing was unchanged with the scrolling format, but that sentence-level processing was compromised, even at a slow display speed. Chapter 4 showed that the attentional conflict reduced the resources available for deployment around the point of fixation, resulting in a reduced perceptual span. Finally, Chapter 5 demonstrated that all of these factors had a detrimental effect on text comprehension, with a particular deficit in inference generation that, in accordance with the results regarding sentence-level processing in Chapter 3, is not recovered at a slow display speed.

A secondary aim was to investigate one of the potential applications of the horizontally scrolling display format: its use as a reading aid for people with conditions involving damage to the central visual field, such as age-related macular degeneration. Chapter 6 addressed this area, with two experiments using the gaze-contingent scotoma paradigm (Rayner & Bertera, 1979). These demonstrated that the presentation of scrolling text may be optimised differently for people at different stages of the disease progression (i.e. with different degrees of CVL), and that a better level of text comprehension may be achievable with scrolling than static text in this population. This latter finding in particular is especially positive for this population in consideration of the reduction in comprehension performance with scrolling text seen in Experiment 6 with unimpaired vision.

Detailed Overview Of Findings

Characterisation Of Normal Reading With Scrolling Text

The processes involved in reading normal static text have been studied extensively, and perhaps the most influential methodology, that enables in-depth characterisation of these many processes is the use of eye-tracking technology to measure the impact of different textual manipulations on eye movement parameters such as fixation durations, word-skipping behaviour, and regression probability (for reviews see e.g. Clifton et al., 2016; Liversedge & Findlay, 2000; Rayner & Liversedge, 2011; Rayner, 1998, 2009; Vitu, 2011). However, very few oculomotor studies have been carried out on reading horizontally scrolling text (with the notable exceptions of Buettner et al., 1985; Valsecchi et al., 2013).

The horizontally scrolling format is not only of interest due to its potential for application, but also has theoretical importance as a paradigm for studying challenging 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, Perea, & Rayner, 2007; Johnson, 2009), and the unspaced text paradigm (Rayner et al., 1998). Such methods are able to produce valuable insights into the processes involved in successful reading. There are a number of factors intrinsic to the horizontally scrolling presentation that may impact on text processing during reading, notably: reduced sustained text availability; increased difficulty in mapping the spatial position of any specific part of the text due to its continuous movement; and a potential conflict in the deployment of attention around the point of fixation, with a necessity to track the text as it moves to the left whilst beginning to process and plan saccades to upcoming text to the right (in languages such as English with a left-to-right layout).

One of the most obvious factors that would be expected to be affected by these changes is the global oculomotor pattern used to read the text. The organisation of the retina is such that most individual words need to be directly fixated in order to be perceived in sufficient detail to be identified (Azzopardi & Cowey, 1993; Drieghe, 2011; Wertheim, 1980). This leads to an active visual approach to reading, with frequent saccades made to progress through the text interspersed with brief pauses to allow a stabilised view of words and time to process this information. It was already known from previous reports on reading of scrolling text that stationary fixations are replaced by brief periods of oculomotor pursuit which perform the same function (i.e. providing a stabilised retinal image of a given word and maintaining the correct spatial location in the text whilst processing of this word is completed), and that these periods were generally longer and less frequent than normal fixations (Buettner et al., 1985; Valsecchi et al., 2013). However, findings regarding the impact of this display format on saccade behaviour, including average saccade amplitude, skipping, refixation and regression probabilities, and landing position were more equivocal (or, in some cases, non-existent).

The findings from this investigation have shown that the movement of text at either of the speeds investigated here (around 120 and 240 words per minute) has little impact on landing positions, suggesting that accurate saccadic targeting is not a significant issue in reading with this format. However, the limited availability of the text as it moves out of range of the leftward extent of the screen would appear to have a considerable influence on the reading strategy: especially when the text is moving reasonably quickly (around 240+ words per minute; although this is also a limiting factor with the slower presentation rate, and the additional limitation of the restriction of the rightward preview by the slow appearance of text from the rightward limit of the screen is also a significant factor at this slower speed). Specifically, it seems that readers respond to the knowledge that they have a limited temporal window in which to decode the text by adopting a risky reading strategy. The core feature of this strategy is an paradoxical increase in word skipping, despite evidence (from Chapter 4) for a reduced parafoveal preview: a factor which would ordinarily be expected to result in a reduction in skipping, as the amount of upcoming text for which processing can begin prior to its potential direct fixation is reduced (Schotter et al., 2012). There are also fewer regressions made to skipped words, despite there ostensibly being time for these regressions to be made (with trials reliably being terminated whilst some text was still available on the screen). Given the findings regarding landing positions, it is unlikely that skipping behaviour changes due to an increase in mislocated fixations (Nuthmann, Engbert, & Kliegl, 2005), supporting interpretation of this pattern as a deliberate strategy adoption. The extinction of the increase in the word skipping rate with a slower scrolling rate further suggests that this is a strategic adaptation, rather than an intrinsic characteristic of reading moving text.

These oculomotor changes do not appear to affect processing at the individual word level: Experiment 1 demonstrated comparable effects of word length and word frequency on fixation duration measures in scrolling text as seen in static text. These are two very robust effects which have been well-established in studies of reading static text, identified as reflecting: effective perceptual chunking of the text (into individual words), with longer words taking longer to process (word length effect; Pollatsek, Juhasz, Reichle, Machacek, & Rayner, 2008; Rayner & McConkie, 1975; Rayner, Sereno, & Raney, 1996; Rayner, Slattery, & Drieghe, 2011); and lexical identification of the likely meaning of a word, with less frequent words taking longer to process (word frequency effect; Inhoff & Rayner, 1986; Inhoff, 1984; Just & Carpenter, 1980; Kliegl, Grabner, Rolfs, & Engbert, 2004; Pollatsek et al., 2008; Rayner, Ashby, Pollatsek, & Reichle, 2004; Rayner & Duffy, 1986; Rayner & Raney, 1996; Rayner, 1977). The similar magnitude of these effects in both scrolling and static text suggest that both of these processes can be carried out equally well with either format, with little or no additional difficulty.

However, in the context of the findings regarding the changes to oculomotor behaviour combined with the investigation of the predictability effect in Experiments 2 and 3, this preservation of lexical processing seems to produce a cost to sentence-level integration of information with the scrolling format (i.e. the former is prioritised at the expense of the latter). In static text, there is a well-established effect of target word predictability on eye movements behaviour, with words that can easily be predicted from previous text context eliciting shorter fixation durations and higher levels of word-skipping (Balota et al., 1985; Erlich et al., 1981; Fitzsimmons & Drieghe, 2013; Inhoff, 1984; Kliegl et al., 2004; Rayner et al., 2004; Rayner, Slattery, & Drieghe, 2011). However, in Experiments 2 and 3 this facilitation of processing was reduced or even eradicated, even when the text was presented at a slow speed (~120 wpm). That this effect was compromised suggests that readers were less able to use context information to make predictions about possible upcoming target words, increasing the word-processing burden when these words were encountered.

Furthermore, Experiment 6 found that readers displayed poorer comprehension with scrolling text, with a particular deficit in inference-based comprehension. This finding supports a conclusion of difficulty in integrating context information from the text when it is presenting in the scrolling format. It is also interesting to note that the profile of results here is strikingly similar to that seen in the population of struggling readers known as poor comprehenders (Nation & Snowling, 1998): unlike dyslexic readers, who struggle with word decoding and therefore rely more heavily than normal readers on context information to compensate for this, poor comprehenders are able to decode individual words (as readers of scrolling text are; cf. Experiment 1), but seem less able to use this context information (cf. Experiments 2 and 3), producing poor comprehension (Experiment 6). One factor linked to the decrement in reading comprehension in both cases is reduced working memory capacity (scrolling text: Experiment 6; poor comprehenders e.g. Nation, Adams, Bowyer-Crane, & Snowling, 1999), with this measure representing a reduction in available cognitive resources for deployment to remembering and integrating concepts from text. Interestingly, this reduction in working memory capacity may also help to explain the findings regarding the predictability effect: this robust effect has been shown to break down in very few situations, however one notable example is of readers with early stage Alzheimer’s disease, who also have a specific deficit in working memory (Fernández et al., 2016).

This reduction in working memory may also interact with the changes to the perceptual span seen with scrolling text. It has been suggested that poor comprehension in reading can be the result of a narrow perceptual span: Smith (1971), for instance, suggests that having a narrow span, and thus perceiving smaller groups of words at a time, results in the cognitive processing system having to deal with more "chunks" of information. The integration of these propositions across different parts of the text is an important part of the comprehension process, with each new proposition triggering a cycle of processing to decode the text (Kintsch & van Dijk, 1978; Kintsch, 1988; McNamara & Magliano, 2009; Rapp & van den Broek, 2005; van den Broek, 1990, 1994). In order to carry out this integration, propositions must be held in a working memory buffer (Kintsch, 1988; van den Broek et al., 2015; van den Broek & Kendeou, 2008); the reduced rightward extent of the perceptual span seen in Chapter 4 may therefore also help to explain the decrement in comprehension, via an increased cognitive load.

These findings highlight the importance of a number of factors in successful reading, which may be useful to consider in relation to the prominent models of reading behaviour outlined initially in Chapter 1: the E-Z Reader (Reichle et al., 2003, 2009; Reichle, 2011) and SWIFT (Engbert & Kliegl, 2011; Engbert et al., 2005). Both of these models have been primarily developed in order to account for the typical reading situation: i.e. of static text by the general adult population. As such, neither is necessarily able to adequately account for all of the changes in oculomotor behaviour seen with the dynamic format. On the basis of the reduced perceptual span seen in Chapter 4, SWIFT would predict longer fixation durations due to the reduced capability to begin processing upcoming words (in parallel) prior to their direct fixation. However, this should also result in reduced word skipping, whereas the opposite pattern is observed. In the E-Z Reader, the assumption of serial processing in this model means that the reduced extent of the perceptual span would be expected to have little to no impact on the amount of lexical processing completed ahead of direct fixation; this model may predict increased word skipping if the inflation in average fixation duration is assumed not to reflect a slowing of lexical processing (supported by the findings regarding word length and frequency effects in Experiment 1), but this would leave the increase in duration to be explained by a delay in the programming or execution of a saccade, neither of which would be expected given the similarity of saccade kinematics following periods of pursuit and fixation (Kaminiarz et al., 2009). Furthermore, the reduction of the predictability effect, as seen in Experiments 2 and 3, may be expected to impact on the familiarity check stage of lexical processing proposed by the E-Z Reader model to determine when the decision is made to programme a new saccade (Reichle et al., 2009). However, if the inflation in average fixation duration with scrolling text was accounted for by a delay in the completion of the familiarity check due to this reduced processing advantage for highly predictable words, then the inflation in word skipping cannot be accounted for under this model either.

That neither model can account for increases in both average fixation duration and word skipping probability may be in part due to a difficulty in interpreting the skipping probability as exactly equivalent to skipping probability in reading of static text; some proportion of instances where a word is recorded as being skipped may not accurately reflect how attention is being allocated, as in some cases the pursuit period spanned more than one word. The cut-off for allocating these split pursuit periods, of less than 80 ms on one of these words, was chosen due to the convention in reading research of merging spatially close fixations if one is of less than 80 ms duration. However, it may be that this approach artificially raises the word skipping probability for scrolling text, if sufficient processing is being carried out for this word in less than 80 ms. The possibilities for future work to explore this issue is discussed in *Limitations and Further Work* subsequently. However, further specification of some of the stages of processing in the oculomotor models may also be useful to better account for reading from non-traditional text presentations, such as the scrolling format. For instance, the role of predictability information in E-Z Reader's familiarity check may be less fixed than the current implementation assumes. The current equation adopted to describe this parameter enters frequency and predictability information separately (Reichle et al., 2009); however this may be complicated by the partial dependence of frequency and predictability (Rayner et al., 2004), and it seems clear from the reduced predictability effect with scrolling text established in Experiments 2 and 3 here that the extent to which readers are able to make use of this predictability information may be influenced by the reading situation. As such, a fixed predictability estimate as provided by standard cloze tasks (established under normal conditions of reading static text) may not provide a completely accurate estimate of the time taken to complete the familiarity check. It may therefore be assumed that additional parameters would need to be considered; comparable for example to considerations of how ageing may affect the reading process, for which Rayner and colleagues (2006) suggested that the addition of a certain probability of incorrectly guessing the identity of upcoming words could help the E-Z Reader to more accurately predict the reading behaviour of older readers. Similarly to this, and supported by the different effect of each scrolling speed on the oculomotor behaviour of readers, it may be important to consider how strategic motivations related to the specific reading goal could be incorporated into such models. This addition would be in line with the recognised influence of task demands on oculomotor strategy in scene viewing; a task for which attempts to apply the E-Z Reader as a predictive model of oculomotor behaviour have not been particularly successful so far (Reichle, Pollatsek, & Rayner, 2012). Finding ways in which to increase the flexibility of the model to incorporate such variations may therefore improve its fit not only to the patterns of oculomotor behaviour for reading scrolling text as presented in this investigation, but to a variety of other tasks.

Application Of Scrolling Text As A Reading Aid

One potential application of the dynamic horizontally scrolling presentation format is as a reading aid for people with ocular conditions involving loss of their central visual field, such as age-related macular degeneration. There are at least two ways in which using this format may be able to help improve the oculomotor approach to reading: using the Steady Eye strategy (Watson & Berg, 1983), keeping the eyes steadily fixated at a particular point and allowing the text to scroll past, through the best remaining part of the retina; or allowing the eye to be entrained into a nystagmus-like pattern (as typically employed to read this kind of text), improving gaze stability (a significant problem in reading static text for this population; Crossland et al., 2004). It is also able to capitalise on presentation advantages which are not specific to this format, such as good magnification, high contrast, and single-line presentation (Bowers, Cheong, & Lovie-Kitchin, 2007; Crossland, Macedo, & Rubin, 2010; Crossland & Rubin, 2012; Culham, Chabra, & Rubin, 2009; Deruaz et al., 2002; Legge, Rubin, & Luebker, 1987; Walker et al., 2016; Walker, 2013).

Previous work has shown that scrolling text may indeed be of benefit to some people with central vision loss, with some reports of improved reading speed (Harland et al., 1998), improved accuracy (Harvey & Walker, 2014; Walker et al., 2016), and subjective preference (Bowers et al., 2004; Harland et al., 1998; Walker et al., 2016; Walker, 2013) for this format. The heterogeneous symptomatic profile of this group means that it is unlikely that any one aid will suit all people who suffer from a CVL, and this is reflected in some inconsistency in findings of its efficacy (for example, whereas Harland et al. found improved reading speed with scrolling text, Walker, 2013, 2016 and Bowers et al., 2004 found no improvement on this measure). In consideration of this factor, Experiment 7 used a gaze-contingent CVL simulation to investigate how different scotoma extents might affect reading performance with scrolling text.

In addition to this, Experiment 7 also considered the effect of increasing inter-word spacing, to optimise presentation of the scrolling format. This factor was chosen for consideration in view of its role in decreasing visual crowding, known to be an important contributor to reading difficulty in this population (He et al., 2013; Latham & Whitaker, 1996; Pelli et al., 2007); and it has been demonstrated for static text that reducing visual crowding by altering text spacing parameters can improve reading performance with a CVL (Blackmore-Wright et al., 2013; Chung, 2002). Overall, increased word spacing did have a beneficial effect on reading performance, with increases in memory and accuracy with tripled word spacing, possibly mediated by better adherence to the eccentric viewing strategy. However, this pattern was modulated by scotoma extent, such that there was no improvement with triple spacing in reading time measures with the largest scotoma size (12^{o}), and only marginal improvements in accuracy with the 8^{o} scotoma (although this may be at least partly attributable to low levels of inaccuracy with this condition overall). Participants also appeared to approach the task differently with different scotoma extents, with much better adherence to the facilitative eccentric viewing strategy with the two larger scotoma conditions, and considerably greater benefit to holding this strategy with increased word spacing for these two conditions (with no benefit for adherence with the 5^{o} scotoma condition at all). This emphasises the importance of considering the symptomatic profile of individuals with a CVL who may benefit the most from using the scrolling format, and of how its presentation may need to be altered to maximise improvements for people for example at different stages of disease progression. This was also supported by some attempted pilot work with two patients with real central vision loss: neither showed any advantage for either format (static or scrolling) for accuracy and comprehension (measured with a 2AFC assessment), and one was slightly quicker at reading with the typical static presentation. However, both of these participants were very motivated readers with extensive experience with the eccentric viewing technique (diagnosed 8 and around 40 years previously, and both acting as mentors in the EV technique for other sufferers through the Macular Society's peer training scheme). This therefore does not undermine the possible usefulness of the scrolling format for anyone experiencing central vision loss, but rather again serves to highlight the importance of targeting its use carefully to a particular subset of this population. For instance, it is likely to be most helpful to support the development of an appropriate compensatory oculomotor strategy, rather than for those who have already developed these strategies.

One measure which has previously seemed to show no difference between static and scrolling text is comprehension; this is the case both in Experiment 7 here, and also in other reports with clinical samples (e.g. Walker et al., 2016; Walker, 2013), despite differences in other measures such as reading accuracy. This could, of course, be due to a true lack of difference in readers' ability to understand the text presented in either format. However, as made clear by the more detailed investigation of reading comprehension presented for unimpaired reading in Chapter 5, this can sometimes arise due to the superficiality of the common single sentence 2AFC assessment of understanding. A second experiment using the gaze-contingent scotoma simulation paradigm therefore used a sustained reading comprehension battery to investigate at this issue, and found that there were some modest (but significant) gains in reading comprehension with scrolling text. This provides further evidence in favour of the utility of the horizontally scrolling format as a reading aid for people who have experienced a loss of central vision.

As recognised in the discussion of findings in Chapter 6, these results will clearly need to be verified in a patient sample. This is particularly important given the additional complication of metamorphopsia in some cases of real macular degeneration (Schuchard, 1995), and the age-related nature of most cases of central vision loss; with known changes to the visual profile with age even in the absence of pathology (Owsley, 2011). Notably, the efficiency of smooth pursuit deployment is known to deteriorate with increasing age (e.g. Kanayama et al., 1994). However, given some existing evidence for positive results for this format with a clinical sample (Walker et al., 2016; Walker, 2013), the likelihood of these results being replicable with a clinical sample seems reasonable. In-depth investigation of the full visual profile of patients taking part in further assessments, including scotoma extent, presence of metamorphopsia, acuity, and contrast sensitivity, will be important to best understand which particular subsets of this heterogeneous population may benefit most from using the scrolling text format.

Limitations And Further Work.

Specific methodological limitations, such as those associated with the use of the gaze-contingent scotoma simulation paradigm in Chapter 6, have been discussed in the relevant sections throughout. However, there are also a number of more general limitations to the work presented in this investigation.

Possibly the foremost of these is that, as with any study of dynamic text formats, it is difficult to ascertain how applicable the results are across the whole range of possible display speeds. Although two of the studies (Experiments 3 and 6) did examine the impact of display speed, identifying some similarities and some differences in oculomotor behaviour between the two speeds, there is clearly much more work to be done, investigating a much wider range of processing effects across a much wider range of display speeds. A starting point for these studies could attempt to determine the upper limit of display speeds at which individual word processing can still successfully be carried out (for example via the word length and word frequency effects, as established in Experiment 1 to be replicable in text displayed at around 240 words per minute). In relation to this issue, there is also scope for work investigating the difference between processing with fixed rate, variable rate, and user-controlled displays.

Furthermore, whilst this investigation provides an initial overview of how scrolling text affects the oculomotor, linguistic, and attentional processes involved in reading, there are clearly many more outstanding that would need to be investigated to produce a comprehensive understanding of how the challenges arising from this format affect the reading process. For instance, the linguistic effects investigated in Chapter 3 arguably represent the three core processes involved in successful reading (Clifton et al., 2016), but there is a wide range of additional processes, including syntactic parsing, resolution of lexical ambiguity, and monitoring of discourse plausibility. Similarly in relation to Chapter 4, that investigated the impact on horizontal scrolling on the deployment of attention, further studies investigating the word identification span (N. R. Underwood & McConkie, 1985) and a more in-depth characterisation of the parafoveal preview (cf. for example Angele, Slattery, Yang, Kliegl, & Rayner, 2008; Drieghe, 2011; Gagl et al., 2013; Schotter et al., 2012) are needed to verify and expand the conclusions regarding the compression of the attentional window here. This could be achieved for instance using the gaze-contingent boundary paradigm (Rayner, 1975), and reversal of the direction of scrolling, both in English and for comparison with orthographies arranged from right to left (e.g. Hebrew or Urdu; cf. for example Jordan et al., 2013; Paterson et al., 2014; Pollatsek et al., 1981). It would be particularly useful to develop these paradigms and the gaze-contingent window paradigm (McConkie & Rayner, 1975) employed in Experiments 4 and 5 to allow the extent of the attentional window to be determined when text is displayed at a slower rate than used in these studies: this method as applied here is not viable due to the truncation of the manipulated preview window by the proximity of the average horizontal position of the eyes to the rightward edge of the screen. Finally, there are several other factors that may contribute to poor reading comprehension which were not addressed in Chapter 5's consideration of text comprehension with scrolling text; for instance, a failure to carry out online monitoring of understanding has been demonstrated to be a key contributor to comprehension difficulty (e.g. Cain, Bryant, & Oakhill, 2004; Chrysochoou, Bablekou, & Tsigilis, 2011; Fuchs, Fuchs, & Maxwell, 1988; Johnston, Barnes, & Desrochers, 2008; Oakhill, Hartt, & Samols, 2005; Zinar, 2000). More direct investigation of some of the processes suggested to underlie poorer inference-making, such as the removal of spatial landmarks (such as paragraphs) from the text and reduced ability to identify the key points is also needed to confirm these hypotheses.

A third limitation of this work is the relative novelty of reading with the scrolling format compared to with a typical static presentation. Normal reading is an over-practiced oculomotor skill for the majority of neurotypical, sighted adults in developed countries: participation in the required minimum of formal education in the UK can be estimated to result in the margin of around 10,000 hours of reading and writing. The scrolling format is comparatively rarely encountered, despite being reasonably commonly used in digital media. This relative unfamiliarity may therefore be a significant factor in some of the results here, with clear evidence in the developmental reading literature for increases in the efficiency of the oculomotor strategy (Huestegge, Radach, Corbic, & Huestegge, 2009), the extent of the perceptual span (Marx, Hutzler, Schuster, & Hawelka, 2016; Sperlich, Meixner, & Laubrock, 2016), and the achievable level of reading comprehension (Hulme et al., 2009; Stothard et al., 2010) with increased familiarity. It would therefore be necessary to monitor for improvement in these measures following repeated practice sessions in reading with the scrolling format to rule this out at an explanation.

Carrying out this investigation has highlighted some factors to consider when carrying out further work. Caution may need to be taken when investigating the use of the horizontally scrolling format in applied settings: two of the popular applications for dynamic text formats are as aids for visual impairments (as discussed; e.g. Bowers et al., 2004), and to increase the reading rate to very high speeds (Rayner et al., 2016). However, in both of these cases, some proponents have suggested that the maximum benefit would be achieved by allowing readers to completely suppress saccades; helping readers with visual impairments to improve their oculomotor control (Harvey & Walker, 2014) and removing the temporal cost of making these movements to maximise reading speed (Rayner et al., 2016). Although readers seem able to suppress saccades to some extent with the scrolling format (for instance in response to an instruction to attempt the Steady Eye strategy to read under conditions of simulated central vision loss), it does not seem to be possible to completely eliminate saccades when reading text displayed in this way.

Finally, the analytical approach adopted here was to consider the pursuit periods and saccades made to read scrolling text as being fundamentally equivalent to the usual pattern of fixations and saccades employed for static text. Although, as discussed, this approach undoubtedly has drawbacks – perhaps most notably that the dynamic stimulus and changes in the saccade pattern in relation to this stimulus may mean that word skipping in particular is not as easily interpretable as is the case for static text – it provides the overriding advantage of allowing the findings to be interpreted in the context of the considerable existing literature on reading with static text. As further work is carried out, it may be possible to refine this approach further: for example, investigation using the *disappearing text* paradigm (where words are masked following a fixed interval of being fixated; e.g. Rayner, Liversedge, et al., 2006) in conjunction with scrolling text would allow confirmation of whether readers require the same minimum period of exposure for successful identification with this format. This would be useful for example in defining the appropriate duration limits to be applied during data cleaning (set at 80 – 1200 ms in the studies reported here, as is common in reading studies).

Conclusions

This thesis presents an experimental investigation of reading with the dynamic horizontally scrolling text display format. Experiments 1-6 examined the impact of this format on some of the key processes involved in reading. These studies showed that, despite having no effect on the processing of individual words, scrolling text reduces the ability of readers to use context information and thus produces a decrement in reading comprehension. Two key explanatory factors for these results would appear to be a narrowing of the perceptual span and a diminished working memory capacity. Experiments 7 and 8 used a gaze-contingent scotoma simulation of conditions involving central vision loss (such as age-related macular degeneration) to investigate the scrolling format as a reading aid for this population. Overall, these findings suggest that the scrolling text paradigm may be able to provide insights into factors that may limit reading success with any text display format. They may also be used to optimise application of this format in mainstream digital media and lend further support to the use of a scrolling display for reading aids for people with central vision loss.

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Appendices

Appendix 1: Stimuli For Experiment 4

1. The clumsy waiter dropped the chocolate cake on the floor.
2. The keen athlete trained hard every day before the big race.
3. The small puppy was chewing on a bone three times his size.
4. She loves to listen to their orchestra playing popular tunes.
5. Their mother always hates it when the children start crying.
6. The police needed to talk to the owner about the break in.
7. The couple booked a luxurious hotel for their summer holiday.
8. The children loved playing in the treehouse on summer days.
9. The caretaker had to clean the dirty floor before he left.
10. The ice cream melted because it was left outside in the sun.
11. Sometimes they drive out into the countryside for long walks.
12. They must remember to feed all the animals every single day.
13. The policewoman was first on scene at the terrible accident.
14. Everyone loves travelling to the seaside on warm summer days.
15. The other children laughed when he slipped on the pavement.
16. The midwife was very good at calming expectant parents down.
17. Their ginger cat had a large litter of kittens last year.
18. The graduate student asked his supervisor for an extension.
19. The diner didn't like honey but there was no other choice.
20. The painting was of a lamp perched on top of a red table.
21. The small kitten played with the red ball of wool for hours.
22. The abrasive style of the newscaster made him very unpopular.
23. The activist received an award for her role in the campaign.
24. Some jellyfish are poisonous and can kill you with a sting.
25. The short story competition was won by an unknown author.
26. Everyone loves to study outside on sunny days in the summer.
27. The unusual keyboard solo was the highlight of the concert.
28. They like to swim in the lake to cool off when it is hot.
29. She was woken up by the sun shining through the curtains.
30. The science teacher was very popular with all of her pupils.
31. Her mother was horrified to see a cockroach in the kitchen.
32. They wanted to make bread but someone had finished the flour.

33. There is an impressive tower there that tourists often visit.
34. The government sent some soldiers to stabilise the region.
35. All of the trees have white and pink blossom in the spring.
36. They said that the weather tomorrow would probably be stormy.
37. The teacher wanted both of them to join the debating team.
38. Their cousin is working abroad before he goes to university.
39. The teacher told the children about the science fair contest.
40. He was surprised when the cat jumped down from the branches.
41. Crocodiles hide silently in the water to wait for their prey.
42. The trees in that orchard produced lots of fruit last year
43. The exhausted nurse got told off for falling asleep at work.
44. The fragile old oak tree fell through the roof in the wind.
45. Everyone laughed loudly when the cats followed her to school.
46. Everyone wanted to catch their trains before the light faded.
47. The children were told off for doodling on their desks again.
48. He had to work all through the night to meet the deadline.
49. The young farmer took all of his livestock to the market.
50. The head chef always developed many delicious new recipes.
51. Please phone your parents and inform them you arrived safely.
52. The project will receive funding for the next three years.
53. You should never have told his teachers about his mistakes.
54. The politician was criticised for the vague proposal he made.
55. She always constantly checks her emails in all the meetings.
56. The young girl asked for a new bike for her next birthday.
57. His family lives in the tallest house on the winding lane.
58. The car was so smashed up that the mechanic could not fix it.
59. They were fighting all day about their new favourite toy.
60. The children went with their grandmother to feed the ducks.
61. They planned to take a train to the seaside at the weekend.
62. The young man put on his best shirt to go to the concert.
63. Some cows escaped from their field and ran down the street.
64. They walked to school every morning with my younger brothers.
65. Instead of finishing their homework they went to the concert.
66. The traffic came to a stop when the girl ran into the road.
67. Everyone admired the beautiful dresses that she had made.
68. The brave soldier won many medals for his part in the war.
69. The television company bought exclusive rights to the game.

70. She visits her grandparents at least three times every month.
71. The fisherman went out in his blue boat to catch some fish.
72. The charity worker trained for six months for the marathon.
73. I hope that she will be allowed to come to the show tomorrow.
74. He told his teacher that the book was extremely interesting.
75. There are always lots of dragonflies when we go to the pond.
76. The nurse found it hard to stay awake on the night shift.
77. She always forgets to lock all the doors after she finishes.
78. The newspapers were flying all around the garden in the wind.
79. He cried when they knocked down the enormous tower he made.
80. It was very dark there because the streetlights were broken.
81. They ripped the tent badly when they went camping last month.
82. Everyone was safely rescued from the terrible train crash.
83. Her son made up a silly story to get himself out of trouble.
84. The boxers had to go to hospital after their latest fight.
85. The old man walked down to the field to feed the donkeys.
86. The play was so boring that everyone wanted to leave early.
87. The junior chef needed some pepper to flavour the dishes.
88. The senior analyst told them that the policy was not working.
89. The student received a grant to visit another university.
90. The lecturer was very angry when his lecture was interrupted.
91. The bridge over the stream has been broken for a whole month.
92. They should all stay inside until the thunderstorm has ended.
93. The children chased the leaves blowing around in the wind.
94. Lamb and mint sauce are always a very popular combination.
95. They all wanted to find the treasure hidden in their garden.
96. The boss had to cancel the meeting because his baby was ill.
97. She must put the book away first before starting another one.
98. It was raining too heavily for the children to play outdoors.
99. Her father was a pilot in the air force before she was born.
100. The new father painted a pretty mural on the nursery wall.
101. The newly approved law made the government very unpopular.
102. The worker lost his job after the serious claim was made.
103. The vain pupil refused to wear the required school uniform.
104. He should have closed the window and switched off the light.
105. The school arranges a visit to the war museum once a year.
106. The prodigy trained for the chess competition for a week.

107. The boys accidentally kicked the football through her window.
108. The old guard walked the lost little boy back to his parents.
109. Her grandmother loves when the children bring her chocolates.
110. She wanted to number the stars but she quickly lost count.
111. The hot air balloons were an impressive sight in the sunset.
112. Three horses were galloping around the large field yesterday.
113. The promising artist displayed her work at a big exhibition.
114. The happy dog barked loudly when it saw its owner arriving.
115. The insurance company would not cover the false injury claim.
116. The school was closed for a whole week because of the snow.
117. Their grandfather always loved when the children sang to him.
118. The lorry driver crashed into a ditch after falling asleep.
119. The sky looked very dark and he said it would probably rain.
120. He wants to go swimming but the lifeguard has forbidden it.
121. The road is always too busy for the children to cross safely.
122. He thought it would be nice to sleep for the whole day today.
123. The blue car broke down on the motorway and caused a jam.
124. The medical student was unsure what specialism to choose.
125. His father thought that he should join the football team.
126. Her grandfather fell over the stool and broke his right leg.
127. The new student bought a colourful atlas to take to school.
128. The show was so expensive that he could not afford to go.
129. The applicant was disappointed when he heard their decision.
130. The taste of the bitter flavouring ruined the whole meal.
131. The weather was lovely but he had to stay indoors to revise.
132. The wasps swarmed into the air when their nest was disturbed.
133. We asked them to stay longer but the children were too tired.
134. The whole class visited the university for a special tour.
135. The ladders were not quite long enough to reach the rooftops.
136. The manager asked his accountant to send the final report.
137. The struggling student needed extra help to pass the year.
138. The neighbours wrote two letters to complain about the noise.
139. The popular magazine had a large spread about the wedding.
140. The teachers could not find the important books this morning.
141. They were hungry and hoped the food would arrive quickly.
142. He asked her to take off her shoes as the carpet was clean.
143. The young woman picked up her bag and prepared to go out.

144. His sister did not enjoy the dance class that she had chosen.
145. She wanted to watch their game but the tickets were sold out.
146. The little girl went with her father to the exciting circus.
147. Her parents always have arguments when they go on holiday.
148. The boy scouts were going on a long hike to the mountains.
149. The exhibition at the art gallery this month is very popular.
150. Her husband bought her some perfume for their anniversary.
151. It was so windy that all the apples had fallen off the trees.
152. All children love to visit their grandparents at the weekend.
153. The teacher told the boy that he would have to be patient.
154. He found the bright colours on the poster to be very jarring.
155. His uncle helped them move their furniture to the new house.
156. If you look very carefully you might see the shooting stars.
157. His father likes to watch the birds flying south for winter.
158. The class were surprised when the maths test was announced.
159. The designer transformed the old hall with his alterations.
160. The street vendor offered an unusual snack to the tourist.
161. The old woman had knitted hundreds of socks for the orphans.
162. The competition was won by the child who sang beautifully.
163. He liked to go to the mountain top and look over the city.
164. Their father hates it when the washing gets left in the rain.
165. She thought it must be very difficult to be a mathematician.
166. The teacher said that the entire class had failed their test.
167. He has lost a lot of weight since they saw him last year.
168. All of the children would like to visit the ice cream shop.
169. He put the washing on the line outside to dry in the wind.
170. Most of her friends did not want to see that film yesterday.
171. He liked animals until their dog chased him down the street.
172. The umbrella blew inside out and they got completely soaked.
173. They all wanted biscuits but the packet was totally empty.
174. The judge asked the criminal to give his account of events.
175. His grandmother always knits stripy jumpers for his birthday.
176. A chameleon can change colour to blend in with its habitat.
177. Our horses are quite speedy but your horse is even quicker.
178. The winner was so shy that he did not want to make a speech.
179. The historian found a bone when he was digging at the site.
180. The spiky hedgehog curled into a ball when the light came on.

181. They have been having money problems since he lost his job.
182. The road is always busy so they should never cross it alone.
183. They spotted an unusual green plane flying high in the sky.
184. The medium claimed to have seen a ghost in the old house.
185. There was a long way to go before they arrived at the hotel.
186. Her best friend bought a new orange campervan at the weekend.
187. The book that she needed for the essay was in the library.
188. The children wanted to make snowmen from the winter snowfall.
189. The new play had received many good reviews from critics.
190. The young boy hoped to receive a toy car for his collection.
191. The stars looked unusually bright in the clear night sky.
192. He wanted to go for a bike ride but it was far too windy.
193. The latest trend resulted in large profits for the company.
194. They called the fire engine to come and put out the fire.
195. They should have called an electrician before the weekend.
196. The shop assistant asked the rude teen to leave the store.
197. She wanted to come to their party but she was much too tired.
198. They always hold the biggest football matches at the weekend.
199. He was concerned that the assignments would be too difficult.
200. The tallest tree fell and blocked the road to the lighthouse.
201. A politician launched the campaign by putting a video online.
202. It took them hours to reproduce the intricate new design.
203. The lions are the most popular animals at the safari park.
204. You should walk the dogs again before they go back to sleep.
205. Every Tuesday brass bands come to play in the market square.
206. The oldest boy was told off for scaring the younger children.
207. The children sheltered in a cave until the rain had stopped.
208. He bought his girlfriend some pretty flowers to celebrate.
209. The keen student wrote about space for her final project.
210. The final performance was cancelled when the stage collapsed.
211. The new dentist told him to brush his teeth more carefully.
212. You should always lock the door before leaving at night time.
213. He forgot about the pie until he smelled something burning.
214. He was very angry when he saw the scratch on his new watch.
215. They hate to tidy up but their mother insists that they must.
216. I like feeding carrots to the horses that live in the field.
217. The role was played by the understudy when the star was ill.

218. Most of the parents would enjoy hearing their children sing.
219. Her mother really hated the purple skirt she chose to wear.
220. The lights were so bright that they could not see anything.
221. The ice was not thick enough for people to walk on safely.
222. His blue trousers were completely ruined in the muddy puddle.
223. The tiny mouse scurried back into its nest to avoid the owl.
224. He had to complete his homework before the weekend finished.
225. The unusual blue gecko always attracted lots of attention.
226. Nobody knew that the cats were sleeping inside the big boxes.
227. The eminent professor gave a short talk about the findings.
228. She should not have gone there without telling her parents.
229. My mother wanted to drive to the shops but they were closed.
230. She keeps seven colourful fish in a tank in her bathroom.
231. She received an expensive gem for her eighteenth birthday.
232. The secretary picked up the file on her way to the meeting.
233. Their cats escaped because she forgot to close the windows.
234. The cook made a nice apple pie for the baking competition.
235. The librarian hated his new job in the university library.
236. The firemen were called to fetch the cat down from the tree.
237. All of them should have known better than to go there alone.
238. She was really angry when his dog chewed her phone charger.
239. A scientist went to talk to the schoolchildren about jobs.
240. The zookeeper hoped that the rare tiger would soon have cubs.

Appendix 2: Stimuli For Experiment 6 Working Memory Task

1. In the summer, ants crawl through the crack in the skirting board and run all over the room.
2. The official threatened to take legal action if people kept parking their cars in his allotted space.
3. Shirley refused to talk to the police about the accusation until she had a lawyer.
4. Jenny was sick of hearing her parents arguing every weekend so gladly moved out as soon as possible.
5. Oliver failed his maths exam because he could not remember any of the formulae.
6. The colourful and lively gymnastics display was very popular with the young audience.
7. The windows of the abandoned house were smashed by vandals throwing bricks and stones.
8. He threw away the old trampoline, because the cords were fraying and the springs were rusty.
9. The police arrived at the scene to see the criminal speeding off in a getaway car.
10. Christine and George went for a nice leisurely ride along the lane on their new tandem.
11. Fiona dropped her new phone onto the concrete path and smashed its screen.
12. Piya had to take some documents into the office to secure her accommodation.
13. The ice cream intended for dessert got left in the car and melted in the sun.
14. Natalie decided to train as a nurse after her involvement in the accident.
15. The poet wrote a quick poem on a napkin whilst waiting for his food in the restaurant.
16. Cara hated zoos: she thought that it was cruel to keep an animal in a cage.
17. Sarah sent an email expressing her interest in the opportunity and asking for more details.
18. The children love running along the beach, making elaborate sand castles and collecting unusual shells.
19. The girl wanted to buy a pretty floral dress to wear at her friend's wedding.
20. They drove out into the countryside with their dogs to take a long walk across the hills.
21. The rebellious teenager was sent home because his newly dyed hair was against the school dress code.
22. Kelly opened her notebook to take down some notes, only to find that it was full.
23. Faaizah liked her new job much better than her previous position, although she missed her colleagues.
24. Anthony blew up twenty balloons and made a large banner for the celebration.
25. No matter how many times she changed it, Tara's clock always seemed to be three minutes fast.

26. Kit wanted to make an appointment to discuss her future with her advisor.
27. Athena insisted that they should all be home in time to eat dinner.
28. The doctor told Sonia that the pain in her back was caused by her terrible posture.
29. The university advertised for extra helpers to deal with the volume of admissions enquiries they received in clearing.
30. He thought that his interview had gone well, but they chose to give the position to another applicant.
31. Max promised his mother that he would work harder at school this term.
32. Delia bought her girlfriend an expensive pearl necklace to celebrate their fifth anniversary.
33. Linda asked her neighbour to look after her pets whilst she was on holiday.
34. The important story was on the front page of every newspaper and all of the news channels.
35. The teacher hoped to give his students the best chance of passing their exams.
36. Louis really wished that he had learned to drive when he heard about the third train strike.
37. Antonio took his grandchildren for a day out to the zoo and the circus.
38. The winning photograph captured dolphins swimming in the harbour as the sun set over the scene.
39. There was rubbish strewn all down the street, where the foxes had raided the bins.
40. Jessica was worried that the rickety boat was not safe enough to take out on the lake.
41. The artist advertised for a number of models to sit for a portrait.
42. Simone was worried that her friend might have banged her head and got a concussion.
43. The teacher asked all of the children to draw a picture for the board in the entrance.
44. The disappearance of the old vase from the locked room was puzzling and mysterious.
45. It was an uncomfortably hot day, and ice-cream sales were through the roof.
46. Ben spent the whole weekend clearing out the rubbish from his garage and shed.
47. Mario told his friends that he was planning a sponsored swim and asked them for donations.
48. The cat knocked the glass of water off of the table, sending it smashing onto the floor.
49. The blacksmith had to make forty horse shoes ahead of the important race.
50. Isabel quickly realised that the problem with the cakes was that she had used salt instead of sugar.
51. A girl ran out into the road without looking, causing a driver to swerve onto the pavement.
52. The manor house had been in their family for thousands of years, a legacy from their royal connections.

53. The architect produced a technical drawing of his plans to show to his client.
54. The unexpected vacancy had to be filled quickly by the most suitable candidate.
55. She drove to her office to collect the files, only to find that she had forgotten her key.
56. Matthew decided to have the day off and take his children for a picnic.
57. Miguel decided to bake a pie for his mother's visit: her favourite flavour, cherry.
58. Catherine needed to get a bucket to catch the water leaking into her basement.
59. Henry planned to complete an impressive metalwork project to add to his varied portfolio.
60. The geography students were going on an exciting field trip to the volcanic island.
61. The children could choose between two different after school activities: karate or ballet.
62. Peter was glad when he heard about his new job, but wished that it was a bit closer.
63. Cats are very popular pets because they are good companions but require less attention than dogs.
64. The tapestry that took them three years to complete will hang in the main hall.
65. Alex was stuck in traffic for three hours following the terrible car crash.
66. They wondered what had happened when they saw clouds of billowing black smoke in the distance.
67. Her grandfather tripped over the low wooden stool left in the doorway and broke his right leg.
68. There were several sightings over the village of an eagle who had built her nest in the mountains.
69. The pilot had to make an emergency landing because of the terrible storm.
70. Rachel was excited to be selected as her school's representative at the event.
71. Zoe made some tasty soup with chicken and a range of spices and vegetables.
72. In a controversial response, the government sent a large contingent of soldiers to stabilise the region.
73. The newly promoted manager left the post after only three weeks in the job.
74. They thought that the fire had probably been started accidentally by an unattended candle.
75. The basketball player fell awkwardly after jumping for the ball and broke his femur.
76. Francesca volunteered to help with the production by making the sets and costumes.
77. After a spate of incidents involving poisonous jellyfish, tourists were warned not to swim along the coast.
78. His dream had always been to establish his own restaurant, but unfortunately he was a very bad chef.

79. The magazine had a large spread about the wedding, with exclusive pictures and an interview with the bride.
80. The farmer was pleased to discover a small barn owl nesting in his barn.
81. David wanted to redecorate his room with orange paint and a colourful rug.
82. Graham signed up for a free online course in order to learn a new skill.
83. The medical student was unsure what specialism to choose, as she liked both children and the elderly.
84. The photographer waited for hours to get the perfect shot of the elusive eagle.
85. The shelves were bowed under the considerable weight of all the heavy books.
86. Monica thought that she would probably be late, but Tom showed her a handy shortcut.
87. His father thinks that he should join the football team when he starts senior school.
88. Laura ordered the most spicy dish on the menu in an attempt to impress her friends.
89. Maurice decided that he would like to keep bees and collect his own honey.
90. Emily was very surprised when the doctor told her that she was pregnant with twins.
91. The reporter secured an exclusive interview with the returning astronaut after her space expedition.
92. The company built a barricade around the site to keep out the protestors.
93. Fatima bought some strong magnets to fix the warped doors on her cupboard.
94. John's hard work paid off; he came top of the year in every subject.
95. The dangerous criminal escaped from police custody when they were transferring him to a higher security prison.
96. Andrea mounted a healthy eating campaign, giving up chocolate and cake in favour of nuts and fruit.
97. Helen was very vain and could not resist looking at herself in every available mirror.
98. Ellie's favourite football team won every single one of its matches this season.
99. After seeing the film's bad reviews, Mary decided not to go to see it at the cinema.
100. The firemen were unable to save any of the important records from the building wrecked by the fire.
101. Mark loved the way that his shouts echoed back at him in the cave.
102. His aunt broke her leg last winter, slipping over on some unexpected ice right outside her front door.
103. Liam was very nervous about talking in public because of his pronounced stutter.
104. Maria was planning an exciting holiday abroad with her friends for her birthday.
105. Simon needed to raise the money for a deposit before he could accept the post.
106. Tourists were advised to avoid going onto the pier when the weather was bad.
107. Tina punched a wall in her frustration and broke three of her knuckles.
108. They were all very disappointed when they heard about the committee's final decision.

109. Susan was really surprised when, six weeks after meeting his girlfriend, her brother announced their engagement.
110. Terry thought that he might like to buy a caravan after he retired.
111. Jack hit the ball so hard that he broke the strings of his racket.
112. The heron swooped down into their back garden and ate a fish from their pond.
113. He planned to drive down to see his parents at the weekend and introduce them to his girlfriend.
114. They hired a van for the weekend to take away their old unused furniture.
115. Duncan was almost home when he realised that he had forgotten to buy some eggs.
116. The twins had been saving up for years to buy tickets for the music festival.
117. Rob promised his niece that if she sat quietly for half an hour she could have a lollipop.
118. The keen astronomers were all hoping for nice weather and clear skies ahead of the rare meteor shower.
119. They were surprised when their large ginger cat gave birth to a litter of kittens.
120. Thierry thought that he would become a vegetarian because he worried that eating meat was unethical.
121. Louise had pictures of her favourite singers stuck on every wall in her bedroom.
122. Paul really hated injections: he was very scared of both doctors and needles.
123. The old fisherman takes his blue boat out onto the lake every evening.
124. There were holes in the carpet and the coat hook was hanging off of the wall.
125. The diligent musician was rehearsing for six hours a day to prepare for his important final recital.
126. Florence was going on a holiday of a lifetime to swim with the dolphins.
127. Ken wanted to be a violinist but his parents insisted that engineering would be a better career.
128. The strong wind brought down several power cables, plunging the whole town into darkness.
129. The fire tore through the forest, bringing devastation to the vegetation and wildlife.
130. More than three hundred people gathered to hear the revolutionary speaker.
131. Colin had eaten the same thing for lunch every day for sixty years: a chicken sandwich and a banana.
132. The kitchen was a complete mess, with food and dirty dishes on every available surface.
133. Timothy forgot to cancel the free trial and ended up paying a large bill for an unwanted subscription.
134. Bill decided that he would never get married after his fiancé jilted him at the altar.

135. The ambulance was held up on their way to a call out by a tree lying across the main road.
136. Bella enjoyed explaining things and got on well with young people: she decided to train to be a teacher.
137. James wanted to work abroad, so he went to evening classes to learn a new language.
138. Lee decided to give up on learning to drive after failing his test for the sixth time.
139. The submission deadline for the final report is on the last Friday of the month.
140. The trainee nurse thought that maybe she would rather become a doctor instead.
141. The doctor told her to go straight to the pharmacist to pick up the prescription.
142. Sue sprained her ankle in the street when one of her heels got caught in a drain cover.
143. She promised to bring them each back a special souvenir from her travels.
144. His uncle gave him an expensive watch for his eighteenth birthday, a family tradition.
145. Even though she always suspected that he would, she was devastated when he broke his promise.
146. He loved to set a moth trap out on warm summer evenings, to see the wide variety of species.
147. Eleanor goes to dancing lessons every Wednesday evening and Sunday afternoon.
148. The baker made a mistake when he was piping the message on top of the cake.
149. The young man intended to propose to his girlfriend during a romantic trip.
150. The insurance company refused to cover the damage to her car, leaving her unable to get to work.
151. The women decided to form a running club to make friends and keep fit.
152. The new worker felt completely overwhelmed by all the responsibilities he was given.
153. The election will take place next month, so all the candidates are campaigning vigorously.
154. She got soaked in the heavy rain after her umbrella blew inside out in the wind.
155. Mel always rushed home after school to make sure she didn't miss her favourite soap.
156. Lara was always so tired after lectures that she went home to have a nap.
157. The engineers did not fix the heating system for a week after it broke: the office was freezing.
158. The student didn't know how she could possibly get all of the assignments submitted.
159. Molly's dog jumped up at her when she came downstairs and tore a hole in her new tights.
160. Brian was really upset when his old dog died: he is going out this weekend to look for a new puppy.
161. The new teacher was quite difficult to understand at first, as she had a very strong Scottish accent.

162. He made an elaborate meal with four courses to celebrate their homecoming.
163. Jean was looking forward to seeing her grandchildren again after their long absence.
164. Lorna was very surprised to receive a call from the school to tell her about her son's poor attendance.
165. Bob's wife was taken to hospital in the middle of the night after an allergic reaction.
166. Mary heard about the shortage of physics teachers on the radio and thought that she might apply.
167. The house on the corner was up for sale again: Elsa thought that it must be haunted.
168. Tony was shocked at how much his daughter's dress for her prom cost.
169. Neil's boss still had not read the report that he had produced over a year previously.
170. Kitty thought that she would like to enter the baking competition she'd seen on television.
171. Tom took advantage of the website's free weekend shipping deal to order his new winter wardrobe.
172. Lena was really thirsty but thought that she should finish her final task before going for a drink.
173. There was an ominous crack through the ceiling that seemed to get bigger every week.
174. May bought a smart new jumper dress and some high heels for her university interview.
175. Pete decided that at the weekend he would have to rake up all of the leaves from the lawn.
176. George almost fell off of the ladder when he was fixing the crack in the gutter.
177. Niamh wanted to buy some furniture to furnish her new bungalow.
178. Yvette played her new favourite song on loop and drove her sister absolutely mad.
179. The mayoral candidate got into trouble for bribing people for their votes.
180. The art student sat in the gallery all day, creating a replica of his favourite painting.
181. Everyone who came always thought that the tour guide was the highlight of their visit.
182. The hot wax dripped off of the candle and left a small blemish on the table's varnish.
183. The girls loved to get together on a Friday night for a fun sleepover.
184. The family had been on holiday to a cottage in the Lake District every year for a decade.
185. Diane had an audition for her perfect job, playing the viola in a professional orchestra.
186. Ned was really scared about the prospect of his first annual appraisal.
187. The light pollution was too high for them to see the shooting stars properly.
188. Becca was furious: her mother had promised two hours ago that she was only popping in quickly.

189. They spent a weekend redecorating their house as the paintwork was chipped and scuffed.
190. Her favourite present was the annual photo album that her children made for Christmas.
191. Three of the farmer's sheep had escaped from the flock through a hole in the fence.
192. The couple decided to celebrate their thirtieth wedding anniversary with a photo safari.

Appendix 3: Stimuli for Experiment 7

1. They said that the weather tomorrow would probably be stormy.
2. She could not sleep in the same room as the big scary clown.
3. Everyone loves travelling to the seaside on warm summer days.
4. Everyone he knows likes to play on the little beach at noon.
5. There is a big river to cross before you reach the mountain.
6. We like feeding carrots to the horses that live in that field.
7. He liked animals until their dog chased him down the street.
8. Nobody knew that the cats were sleeping inside the big boxes.
9. The policeman said he would not let us play basketball here.
10. I hope that you will be able to go to the cinema without me.
11. Two kittens played with the toy mouse until it did not work.
12. They always hold the biggest football matches at the weekend.
13. Our mother tells us that we should wear heavy coats outside.
14. She wanted to come to their party but she was much too tired.
15. Everyone went outside after I started the painting task.
16. Have a nice time at the fair and be sure to come home early.
17. You should never have told his teachers about his mistakes.
18. She loves to listen to their orchestra playing popular tunes.
19. Everyone wanted biscuits but the packet was completely empty.
20. The sky looked very dark and he said it would probably rain.
21. Our horses are quite speedy but your horse is even quicker.
22. She likes to read in the morning before going to her school.
23. All of them should have known better than to go outside alone.
24. It is almost impossible to make a decision in that situation.
25. She must put the book away first before starting another one.
26. Three horses were galloping around the large field yesterday.
27. He was surprised when the cat jumped down from the branches.
28. He was so sick that my dad had to pick him up at the office.
29. They were fighting all morning about their new favourite toy.
30. You should walk the dogs again before they go back to sleep.
31. They ripped the tent badly when they went camping last month.
32. Our dogs bark a lot when they see birds walking in the yard.
33. Everyone wanted to go outside when the rain finally stopped.
34. His friend is also involved in the latest charity event.
35. They must remember to feed all the animals every single day.

36. I hope that she will be allowed to come to the show tomorrow.
37. The teacher showed the children how to draw pretty pictures.
38. Their mother always hates it when the children start crying.
39. The neighbours wrote two letters to complain about the noise.
40. The teacher told us that we should read six books this week.
41. My father asked me to help the two men carry the box inside.
42. We never open the window in the winter or summer months.
43. He made plans to go camping and hiking in the mountains.
44. The tallest tree fell and blocked the road to the lighthouse.
45. Sometimes they drive out into the countryside for long walks.
46. You should always lock the doors before leaving at nighttime.
47. His blue trousers were completely ruined in the muddy puddle.
48. He was very angry when he saw the scratches on his new watch.
49. Today we raced our new red cars on the track outside school.
50. She always forgets to lock all the doors after she finishes.
51. It is fun to travel to the beach when we go with our mother.
52. It was so windy that all the apples had fallen off the trees.
53. The car broke down after we drove over the old green bridge.
54. The sounds of the waves and gulls are very peaceful.
55. He looked up at his mother and told her he was really happy.
56. I must always clean my room before the football game starts.
57. Please phone your parents and inform them you arrived safely.
58. I like to read books with my teddy bear before going to bed.
59. She should not have gone there without telling her parents.
60. They were not able to finish playing the game before dinner.
61. One of the students brought a big apple for the new teacher.
62. The bridge over the stream has been broken for a whole month.
63. Students know class will be held outdoors on sunny days.
64. It was very dark there because the streetlights were broken.
65. It was hard to read the sentences because they were so small.
66. The newspapers were flying all around the garden in the wind.
67. The babysitter told me to go to bed before mum came home.
68. She was worried that she would not be able to finish in time.
69. They walked to school every morning with my younger brothers.
70. Our father wants us to wash the clothes before he gets back.
71. Our old clock chimes hourly if I remember to wind it up.
72. Their grandfather always loved when the children sang to him.

73. His blue hat was on the table before we went out for dinner.
74. He wanted to finish his homework before the weekend finished.
75. The boys accidentally kicked the football through her window.
76. In the distance they could just make out our new lighthouse.
77. He was concerned that the assignments would be too difficult.
78. The schools were closed for a whole week because of the snow.
79. They all hoped that he was enjoying his new position there.
80. My sister was going to play the piano but it was broken.
81. My little puppy has a small white patch below her right eye.
82. The delicious new ice cream is not easily obtained here.
83. The boy carried the toy car in one hand for most of the day.
84. My brother wanted a glass of milk with his cake after lunch.
85. Our tiny bird ate the seeds before flying off its perch.
86. The telephone only rang one time before I came inside.
87. The play was so boring that everyone wanted to leave early.
88. It was hard to know whether we were in the correct position.
89. I am making a cake today for my family and friends to enjoy.
90. We asked them to stay longer but the children were too tired.

Appendix 4: Program for simulated scotoma implementation (Experiments 7 and 8)

```
import sreb
import sreb.graphics
import sreb.time
import pylink

class CustomClassTemplate(sreb.EBObject):
        def __init__(self):
                sreb.EBObject.__init__(self)
                self.customResource1 = None;
                self.customResource2 = None;
                self.displayScreenPath="      # store screen path in the experiment
                self.screen=None              # handle for the screen object
                self.finished = 0;            # used to check if the trial has finished;

                #START PARAMETERS FOR EYE AND TEXT
                self.currentX = 387
                self.currentY = 259
                self.currentP = 0
                self.drawingX = 512
                self.drawingY = 384
                #SCROLLING AND SCREEN PARAMETERS
                self.scrollingSpeed = 1;
                self.dynamicScrollingSpeed = 0; # CHANGE TO SET THE SPEED
                self.xStartPosition = 512; # START POSITION IN SCROLL
                self.textBackgroundColor = sreb.EBColor(255, 255, 255)
                self.transparencyColor=sreb.EBColor(195,195,195)
                self.displayType = "NONE" # STATIC OR DYNAMIC
                self.contingentLoc = 0,0 # DRIFT CORRECT POSITION
                self.uid = 0 # UNIQUE IDENTIFIER FOR EACH REFRESH
                self.windowWidth = 250;
                self.windowHeight = 250;
                #STARTING PARAMETERS FOR SCOTOMA CHECKS
                self.pupil = 0
                self.pupil2 = self.pupil
                self.pupil3 = self.pupil
                self.loop = 0
                self.blink = 0
                self.pupilavg = 0
                self.pupilderiv = 0

        def getTextBackgroundColor(self):
                return self.textBackgroundColor
        def setTextBackgroundColor(self, s):
                self.textBackgroundColor = s

        def getTransparencyColor(self):
```

```
        return self.transparencyColor
def setTransparencyColor(self,s):
        self.transparencyColor = s

def getWindowWidth(self):
        return self.windowWidth
def setWindowWidth(self, s):
        self.windowWidth = s

def getXStartPosition(self):
        return self.xStartPosition
def setXStartPosition(self, s):
        self.xStartPosition = s

# These two methods are used to read and set the scrolling speed of the text;

def getScrollingSpeed(self):
        return self.scrollingSpeed
def setScrollingSpeed(self,s):
        self.scrollingSpeed=s

def getDynamicScrollingSpeed(self):
        return self.dynamicScrollingSpeed
def setDynamicScrollingSpeed(self,s):
        self.dynamicScrollingSpeed=s

# These two methods are used to read and set the trial status;
def getFinished(self):
        return self.finished
def setFinished(self,s):
        self.finished=s

def getDriftCorrect(self):
        return self.driftCorrect
def setDriftCorrect(self, x):
        self.driftCorrect =      x

def getContingentLoc(self):
        return self.contingentLoc
def setContingentLoc(self, x):
        self.contingentLoc = x

def getContingentLoc(self):
        return self.contingentLoc
def setContingentLoc(self, x):
        self.contingentLoc = x

# These two methods are used to read and set the screen path;
def getDisplayScreenPath(self):
        return self.displayScreenPath
```

```
def setDisplayScreenPath(self,s):
        self.displayScreenPath=s

# Initialize the custom class graphics.
def initialize(self):
                # Get the handle of the display screen for drawing;
self.screen=sreb.graphics.getScreenFromPath(self.getDisplayScreenPath())
        if self.screen is None:
                raise "EBScreen could not be accessed"
        self.screenWidth, self.screenHeight = self.screen.getSize()
        # Mask/Window image;
        self.foregroundImage=self.screen.getResources()[0]
        self.foregroundImage.setVisible(False)
        self.maskResource = self.screen.getResources()[1]
        self.maskResource.setVisible(False)
        # The custom resource object for background drawing;
        # EBRectangle(0, 0, 1024, 768):
        #resource dimension is 1024 * 768;
        #the topleft position is (0, 0)
        self.customResource1 =
        Self.screen.createCustomResource(sreb.EBRectangle(0, 0 ,1024,
        768),False,-2)
        self.customResource1.setDrawMethodPointer(self.redraw)

self.customResource1.setShouldRedrawMethodPointer(self.shouldRedraw)

        self.lastRedrawDone=0
        self.lastX=0
        self.lastY=0
        self.finished = 0
        self.uid = 0

# Used to reset the trial status
def reset(self, displayType, dynamicDriftX, dynamicDriftY, dynamicSquareX,
dynamicSquareY, staticDriftX, staticDriftY, staticSquareX, staticSquareY):
        self.displayType = displayType
        #DRIFT CORRECTION AND SQUARE LOCS;
        #DIFFERENT FOR STATIC ('s') AND SCROLL ('d')
        if (self.displayType == 'd'):
                self.driftCorrect = sreb.EBPoint(dynamicDriftX,
                dynamicDriftY)
                self.contingentLoc = sreb.EBPoint(dynamicSquareX,
                dynamicSquareY)
        if (self.displayType == 's'):
                self.driftCorrect = sreb.EBPoint(staticDriftX, staticDriftY)
                self.contingentLoc = sreb.EBPoint(staticSquareX,
                staticSquareY)
        self.lastRedrawDone=0
        self.uid = 0
        self.blink = 0
```

```
        self.loop = 0
        #TEXT START POSITION AND MOVEMENT INFO;
        #DIFFERENT FOR STATIC AND SCROLL
        if (self.displayType =='d'):
            self.lastX=self.xStartPosition
            self.lastY=0
            self.scrollingSpeed = self.dynamicScrollingSpeed
            self.finished = 0
            pylink.getEYELINK().sendMessage("current_speed " +
            str(self.scrollingSpeed))
        if (self.displayType == 's'):
            self.lastX=0
            self.lastY=0
            self.scrollingSpeed = 0
            self.finished = 0
            pylink.getEYELINK().sendMessage("current_speed " +
            str(self.scrollingSpeed))
    def redraw(self):
        # do any drawing to the custom resource here
        start = sreb.time.getCurrentTime()
        self.loop +=1
        s=pylink.getEYELINK().getNewestSample()
        if s:
            eyeData = s.getRightEye();
        # Gets current x, y position and determine the interest area in which
        # it belongs to and decides whether the display needs to be redrawn;
            if eyeData:
                self.currentX = int(eyeData.getGaze()[0])
                self.currentY = int(eyeData.getGaze()[1])
                self.currentP = int(eyeData.getPupilSize())
        #NEED 3 LOOPS TO ESTABLISH ENOUGH PUPIL POSITIONS
        #FOR CHECKS (3 SAMPLE MOVING AVERAGE)
        if self.loop ==1:
            self.drawingX = self.currentX - (self.windowWidth/2);
            self.drawingY = self.currentY - (self.windowHeight/2)
            self.pupil = self.currentP
        elif self.loop ==2:
            self.drawingX = self.currentX - (self.windowWidth/2);
            self.drawingY = self.currentY - (self.windowHeight/2)
            self.pupil2 = self.pupil
            self.pupil = self.currentP
        elif self.loop ==3:
            self.drawingX = self.currentX - (self.windowWidth/2);
            self.drawingY = self.currentY - (self.windowHeight/2)
            self.pupil3 = self.pupil2
            self.pupil2 = self.pupil
            self.pupil = self.currentP
        else:
            self.pupilderiv = (self.currentP-self.pupil3)/(2*1)
            if self.blink != 1:
```

```
            self.pupilavg = (self.pupil + self.pupil2 + self.pupil3)/3
            self.pupil3 = self.pupil2
            self.pupil2 = self.pupil
            self.pupil = self.currentP
            if (self.pupil > (0.9*self.pupilavg)):
                self.drawingX = self.currentX –
                (self.windowWidth/2);
                self.drawingY = self.currentY –
                (self.windowHeight/2)
            else:
                self.blink =1
                self.drawingX = self.drawingX
                self.drawingY= self.drawingY
        elif self.blink == 1:
            self.pupil = self.currentP
            if (self.pupil > (0.9*self.pupilavg)):
                self.blink =0
                self.drawingX = self.currentX –
                (self.windowWidth/2);
                self.drawingY = self.currentY –
                (self.windowHeight/2)
            else:
                self.drawingX = self.drawingX
                self.drawingY= self.drawingY
    # Then draws the foveal mask/window on top of the text image
    target1 = self.customResource1
    target1.fill(self.transparencyColor)
    target1.blitArea(self.foregroundImage,[self.lastX, 355],
    [0,0, 6000, self.screenHeight])
    target1.blit(self.maskResource, [self.drawingX, self.drawingY])
    #TRIAL END
    end = sreb.time.getCurrentTime()
    pylink.getEYELINK().sendMessage("REFRESH_COMPLETE: " +
    str(self.uid) + "; " + str(self.lastX))
    self.lastRedrawDone=end
    self.uid = self.uid + 1
    # FINALLY UPDATE TEXT POSITION
    if (self.uid > 12): #WAIT 12 REFRESHES BEFORE TEXT MOVES
        self.lastX = self.lastX - self.scrollingSpeed
    if (self.uid<=12):
        self.lastX = self.lastX-0
    pylink.getEYELINK().sendMessage("drawing x " + str(self.drawingX-
    self.windowWidth/2))
    pylink.getEYELINK().sendMessage("drawing y " +
    str( self.drawingY))
    pylink.getEYELINK().sendMessage("eye x " + str(self.currentX))

def shouldRedraw(self):
    # return True if you want the CustomResource to be redrawn
    #(by calling the DrawMethodPointer) and the screen updated
```

```
        # and display flipped
        # return False to indicate that no redraw is needed for the resource
        if self.screen.getLastUpdateRetraceTime() <
        sreb.time.getCurrentTime() and \
        self.lastRedrawDone < self.screen.getLastUpdateRetraceTime():
                return True
        return False
def clearImage(self):
        self.customResource.fill(self.textBackgroundColor)
```