Evidence for a Reduction of the Rightward Extent of the Perceptual Span when Reading Dynamic Horizontally Scrolling Text.

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Abstract

The dynamic horizontally scrolling text format produces a directional conflict in the allocation of attention for reading, with a necessity to track each word leftwards (in the direction of movement) concurrently with normal rightward shifts made to progress through the text (in left-to-right orthographies such as English). The gaze-contingent window paradigm was used to compare the extent of the perceptual span in reading of scrolling and static sentences. Across two experiments, this investigation confirmed that the allocation of attentional resources to the right of fixation was compressed with scrolling text. There was no evidence for a reversal of the direction of asymmetry or a confounding shift of landing position.

Keywords: reading; eye-movements; scrolling text; attention; perceptual span

Public significance statement

Horizontally scrolling text is commonly used in digital media in situations where extended passages of text need to be displayed in a limited space; e.g. for rolling news tickers. Reading scrolling text requires the additional task of tracking the words as they move across the screen, making this a challenging reading situation, but little is known about its impact on text processing and comprehension. Here we report two experiments showing that one important change that readers make to cope with the additional tracking requirement is a reduction in the amount of attention allocated to process upcoming text. This may have implications for understanding the processing adjustments that need to be made when reading in different kinds of challenging reading situations, as well as for the application of this specific text presentation format.

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The dynamic horizontally scrolling text format (i.e. text that is displayed in a single-line, pixel-stepped motion from right to left) has a number of possible applications, including in digital media to display unlimited text in a spatially limited window and as a reading aid for populations with visual impairments (e.g. Ong et al., 2012; Sharmin, 2015; So & Chan, 2013; Walker, 2013; 2016). It is also of theoretical interest, providing an unusual and challenging reading situation potentially comparable to other paradigms that similarly manipulate text characteristics such as the *disappearing text* and *transposed letter* paradigms (Acha & Perea, 2008a, 2008b; Johnson, Perea, & Rayner, 2007; Liversedge et al., 2004; Rayner, Liversedge, & White, 2006; Rayner, Liversedge, White, & Vergilino-Perez, 2003). Relatively little research has been carried out on normal reading of this format, but one study has demonstrated 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 (inferred from the absence of the usual early facilitation effect for highly predictable words with this format; Harvey, Godwin, Fitzsimmons, Liversedge, & Walker, 2017). A further study also showed the consequences of this difficulty for detailed text comprehension (Harvey & Walker, 2018). One factor that may help to explain these findings is a reduction in the cognitive resources available to be allocated to text processing, arising from the more challenging reading situation involved with scrolling text. In particular, the movement of the text may disrupt the allocation of attention (characterised in the literature as the *perceptual span*; Rayner, 1975) around the point of fixation, with the typical allocation of attention to the right (in English) to begin processing of upcoming text conflicting with leftward pursuit tracking in order to maintain a steady ‘fixation’ of each targeted scrolling word enabling cognitive processing.

The perceptual span is an important concept to consider in relation to the deployment of attention during reading, describing 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 the perceptual span is 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 has been established using the gaze-contingent ‘moving window’ paradigm first developed by McConkie and Rayner (1975, 1976), wherein only a fixed 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, 1986; Rayner, Slattery, & Bélanger, 2011). At the point at which the amount of visible text 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, 1986; Rayner et al., 2009; Sperlich, Meixner, & Laubrock, 2016), the reader's language ability (Choi et al., 2015; Sperlich et al., 2016), whether reading is silent or oral (Ashby, Yang, Evans, & Rayner, 2012), reading speed (Rayner et al., 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, the observed modulation of the perceptual span by such factors as those described above demonstrate that the main constraint on the extent of the perceptual span derives from 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, that is, to the right of fixation in writing systems written horizontally left to right across a page (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 that can be written vertically from top to bottom of a page (e.g. Japanese; Osaka & Oda, 1991). Furthermore, one study replicated the same asymmetric span under conditions in which compensatory magnification of letters in the parafoveal preview was used to reduce the acuity consideration (Miellet, O'Donnell, & Sereno, 2009), demonstrating 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. The horizontally scrolling movement introduces a conflict for the allocation of attentional and oculomotor control, with leftward pursuit tracking for 'fixation' on the text required in addition to the normal rightward shifts of gaze and attention required for reading (see Figure 1), as shown in previous studies of the global oculomotor pattern employed for reading scrolling text (Buettner, Krischer, & Meissen, 1985; Valsecchi, Gegenfurtner, & Schütz, 2013). This directional conflict may 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, e.g., 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).

Figure 1. Schematic illustration of the source of a directional conflict in the deployment of attention during reading of scrolling text, with leftward pursuit periods to track, that is, ‘fixate’, each word interspersed with rightward saccades to make progress through text. Hypothetical eye positions during fixations are indicated by the grey dots.

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, Riggio, Craighero, & Rizzolatti, 1995; Sheliga, Riggio, & Rizzolatti, 1994). The amount of attention allocated to the left of fixation approximately 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). Under these assumptions, 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. This may, therefore, be expected to reduce the rightward extent of the perceptual span for scrolling text, as the conflict may reduce available resources for allocation to the parafoveal area.

An alternative prediction is that the perceptual span might be increased with scrolling text: longer fixation durations with this format (Buettner et al., 1985; Harvey et al., 2017; Valsecchi et al., 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). This means that if the increased fixation durations were a result of increased difficulty in perceiving the words, this may similarly be expected to result in 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 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°/s; Ludvigh & Miller, 1958). Rather, analysis of the global oculomotor pattern used to read scrolling text indicates 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, findings suggest that there is very little difference in processing difficulty at this single word level (Harvey et al., 2017).

A further possibility is that the asymmetry of the attentional window could be affected by scrolling text, with the perceptual span more resembling the allocation of attention observed in studies of simple pursuit tracking. Attention has been shown to be allocated symmetrically around the pursuit target, with a window of around 1° either side of the target outside of which performance for example on discrimination tasks falls to chance level (Lovejoy, Fowler, & Krauzlis, 2009). There is some evidence that this may be modulated with attentional resources being voluntarily allocated up to around 2^{o} ahead of the target (but not equivalently behind the target; Lovejoy et al., 2009; Van Donkelaar & Drew, 2002). However, the deployment of attention is primarily driven by the stimulus, not the specific oculomotor strategy (e.g. Watamaniuk & Heinen, 2015), and therefore the adaptive asymmetric allocation of resources towards upcoming text should be maintained with scrolling as with static text.

Few studies have investigated reading of scrolling text, and fewer still the allocation of attention during this task. Harvey et al. (2017) found that scrolling text elicited significantly shorter average progressive saccade amplitudes than static text (with progressive saccade length linked to word identification span extent in static text; Jacobs, 1986; Rayner, 1998), supporting a hypothesised reduction in the attentional window. By contrast, 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 both static and scrolling text. However, taking into consideration the significant difference in their reported intercepts (their Figure 8, p.11), this relationship appears to show that fixation periods of equivalent durations were associated with longer preceding saccades for static than scrolling text. This supports the idea of a smaller perceptual span with the scrolling format: according to the prevailing models of attention allocation in reading, matched fixations should be preceded by saccades of equal length if the preview was equivalent (Engbert, Nuthmann, Richter, & Kliegl, 2005; Reichle, Rayner, & Pollatsek, 2003). Furthermore, their conclusion does not take into account any movement of the continuously scrolling text occurring between selecting a saccade target and fully executing the saccade programme, 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 perceptual span 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, Niefind, Sommer, & Dimigen, 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) more in normal static text reading than in passive reading. This is suggestive of a reduced perceptual span with passive reading, as a similar amount of processing is required on a word regardless of whether it has been available prior to its direct fixation. Whilst it should be noted that passive reading constitutes a distinct reading situation and the parafoveal preview may be affected by factors specific to this presentation method used - such as the sudden onset of each word at fixation. This paradigm does, however, 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 we propose will be the case for scrolling text here.

Two studies have previously investigated the perceptual span with scrolling text (Fine & Peli, 1996; Fine, Woods, & Peli, 2001), reporting a reduced span of around 4-7 characters, compared to the normal rightward 12-15 characters established for static text (Rayner, 1998). This supports the hypothesis of a reduced perceptual span resulting from the directional conflict in scrolling text, but the use of an ageing sample in these studies (Fine & Peli, 1996) and a fixed (i.e. as opposed to gaze-contingent) restriction window significantly limits the generality of the results of this study. Furthermore, as gaze position was not monitored, there is a possibility that participants were not necessarily maintaining the assumed preview extent that the symmetric application of these fixed 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). Finally, as characterisation of the normal perceptual span was not the goal of these studies, there was no investigation of the asymmetry of the span, and no direct comparison with static text.

The present study, therefore, sought to go beyond existing work, to characterise changes to the deployment of attention around the point of fixation when reading dynamic horizontally scrolling text (compared to static text) in the general adult population. Two experiments were carried out, using the gaze-contingent moving window paradigm (McConkie & Rayner, 1975, 1976), to establish whether there were any changes in the extent and asymmetry of the perceptual span with this format.

Experiment 1

Experiment 1 sought to compare the effect of a series of window sizes on reading speed and oculomotor measures (average fixation duration, fixation count, and average saccade amplitude) with scrolling and static text. This method allows the determination of the critical window size; that is, 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. We therefore expected that there would be no significant recovery in any measure of reading performance, in either display format (static or scrolling), with the leftward asymmetry conditions compared to the smallest (symmetrical 4 character) window. 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 due to a directional conflict in the allocation of attention. To examine this, we included two rightward asymmetry conditions, with 8 and 12 characters available to the right of fixation. We expected that to see more stability in reading performance (across four different measures) under the 8-character and 12-character windows and the unrestricted full view condition with scrolling text than with static text.

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.

To establish that this sample size was appropriate, the effect sizes seen for the measures of interest when comparing static and scrolling text (Harvey et al., 2017) and for comparable comparisons of perceptual span extent (using the comparison of 8-character and 12-character windows from Choi et al., 2015) were used in a power calculation. The smaller of these two effect sizes for each measure were entered into power calculations using the PANGEA tool for ANOVA designs of the kind used in this experiment, aiming for statistical power of at least 0.8 in all measures (Westfall, 2016). For example, for reading speed the effect sizes from the literature were d_z[1] = 0.26 for scrolling vs. static text, and $d_z = 0.82$ for a comparison between two gaze-contingent window sizes in static text reading), so the display type effect size (d_z = 0.26 was used for the power calculation. This was done similarly for all four measures of interest – using an estimated effect size of $d_z = 0.57$ for fixation count, $d_z = 0.52$ for fixation duration, $d_z = 1.09$ for saccade amplitude, and $d_z = 0.26$ for reading speed.

Stimuli and apparatus. Stimuli were 240 narrative 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*. All sentences were of a similar syntactic structure and complexity, and were around grade level 6, with a Flesch Reading Ease score of 79.5 (Flesch, 1948). 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 (96 DPI) CRT monitor running at a 100Hz refresh rate. Participants were seated at a viewing distance of 70 cm from the monitor, maintained with a table-mounted head and chin rest. Eye movements were

[1] d_z was calculated using the spreadsheet provided as supplementary material by Däniel Lakens in (Lakens, 2013)

recorded using an SR Research EyeLink 1000 eye-tracker (remote desktop mount), taking one sample of pupil and corneal reflection position every millisecond. This was used 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). It should be noted that although the scrolling rate does constrain reading speed, the sustained availability of around 93 characters (under the present display conditions) on the screen means that it is possible to read the text both more slowly and faster than the display rate (235 wpm here). Furthermore, it can easily be seen from inspecting the eye movement traces whether the reading speed for scrolling text is problematically too fast (in which case eye movements are clustered at the left edge of the screen, where the text disappears) or too slow (in which case eye movements are clustered at the right edge of the screen, waiting for text to appear). The scrolling rate for this study was determined on the basis of pilot studies detailed in a previous report (Harvey et al., 2017).

Procedure. The procedure was based on the gaze-contingent moving window paradigm developed by McConkie and Rayner (1975, 1976). Participants read sentences either with full view of the sentence (as in normal reading) or with only a fixed window 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 2).

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 2 for examples of each window size 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. Display types were presented blocked so that participants either completed all window conditions for static text and then scrolling text or vice versa, the order of which were counterbalanced across participants (18 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?*).

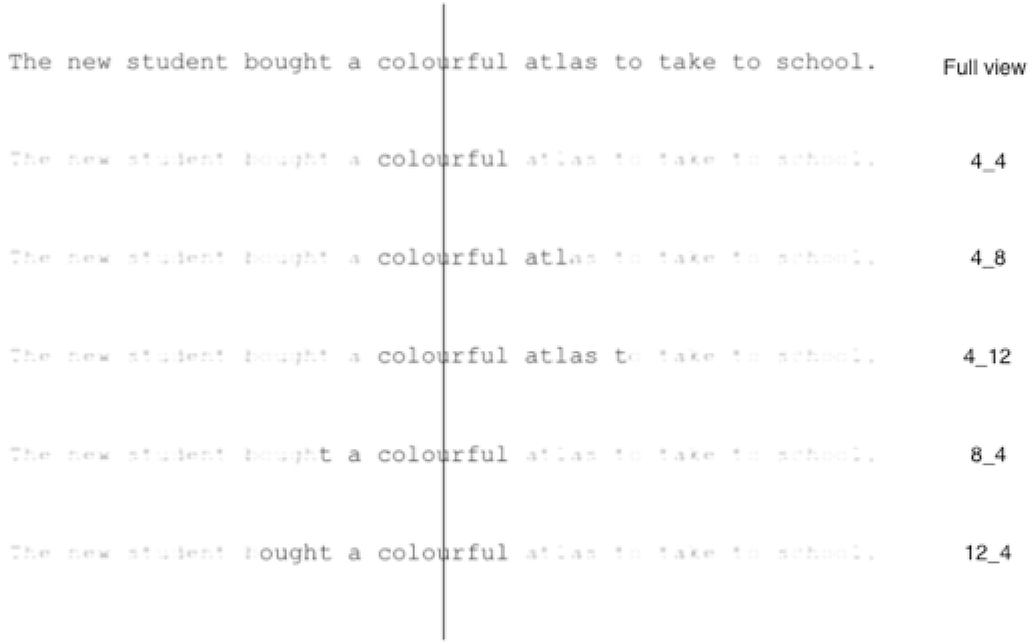

Figure 2. Examples of each window size (with the vertical line representing a hypothetical fixation on letter ‘u’ in the word ‘colourful’, from top to bottom of pane displaying: full unrestricted view of sentence; 4 characters available symmetrically either side of fixation; rightward asymmetry with 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.

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 gaze-contingent square (of 0.8^{o} width) displayed, with the beginning of the trial triggered when participants made a stable fixation within this square. Both the drift correction and gaze-contingent square were positioned where the first word of the text would be displayed; 80 pixels from the left edge of the screen for static text and centrally on the screen for scrolling text (both centred vertically). The scrolling text did not begin moving until 12 screen refreshes (120ms) after the onset of the sentence, as we have previously found that participants often need to make an immediate regressive saccade to the first word if the movement of text begins without this delay. On average, the pixel extent of a sentence was around two-thirds of the full pixel extent of the screen; following the initial display of the sentence from the centre of the screen, the entire sentence would pass through the screen at some point as the text drifted to the left, and text would disappear as it reached the screen's left edge. Termination of each trial was controlled by participant button-press, and it was explained clearly to participants during the practice phase that this button-press should be made as soon as possible after they had read and understood the sentence.

Statistical analyses were carried out using R 3.4.3 (R Core Team, 2018). Data processing followed the approach taken by Harvey et al. (2017): briefly, reading under both text display conditions was analysed and processed identically, with pursuit periods in scrolling text treated as equivalent to fixations. Where these pursuit periods spanned two words, these were either allocated as separate fixations on each word (if both words were fixated for more than 80 ms) or allocated to the word where more time was spent (if one of the words was fixated for less than 80 ms). Fixations of less than 80 ms and more than 1200 ms fixations were removed (as standard in reading research), resulting in a loss of 2.5% of fixations. Data were also cleaned for 2.5 standard deviations for each participant and conditions, and trials were 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. As our predictions were based in part on the absence of effects between specific window conditions (i.e. no significant difference between the 4_8 and full view conditions in scrolling text), equivalence tests were carried out in order to check that any null effects were not due to a lack of statistical power (i.e.

that they were significantly smaller than a meaningful effect size). These analyses were carried out using the TOSTER package (Lakens, 2017), with equivalence bounds set in relation to typical effect sizes for detecting the critical window size in a similar gaze-contingent window paradigm experiment (Choi et al., 2015); $d_z = 0.6$ for fixation count and fixation duration, $d_z = 1.1$ for saccade amplitude, and $d_z = 0.8$ for reading speed.

Results

Comprehension questions resulted in a mean comprehension score of 93.6% (SD 4.5%), with no significant difference between static and scrolling sentences ($t(35) = 0.04$, $p = .96$). This is in line with previous findings of 2AFC assessments for these text formats, and serves only to indicate that there was a high level of task engagement for both formats.

To establish the critical extent of the available window on the text, the following measures were compared with 2 (Display Format: scrolling vs. static text) x 6 (Window Extent) within-subject ANOVAs: reading rate (words per minute), average fixation duration, the number of fixations employed to read a sentence (fixation count), and average saccade amplitude. Average landing position (character position within targeted word) following a saccade was also computed in order to ensure that a shift in this parameter did not account for any change in the determined perceptual span. Planned contrasts were carried out to compare the following critical comparisons within each display format: each leftward asymmetry window vs. the symmetrical 4_4 window, each rightward asymmetry window vs. the full view comparison, and the smaller vs. the larger rightward asymmetry window. Effect sizes are reported using generalised eta squared for all ANOVAs and Cohen's d_z for t-tests.

Reading rate. The average reading rate (words per minute) was calculated for each window width and display type combination read by each participant. An ANOVA indicated that there was a main effect of window extent only on reading rate $F(5, 175) = 34.21$, $p < .001$, $\eta_G^2 = 0.15$ (with no significant effect of display type, $p = .73$, $\eta_G^2 < 0.001$). However, there was also an interaction of window extent and display type $F(5, 175) = 2.42$, $p = .04$, $\eta_G^2 = 0.01$, suggesting that the effect of window extent was modulated by the text display format. Planned contrasts were computed to test the critical contrasts of interest; comparing, within each display type, each leftward asymmetry window with the symmetric 4-character window, and each rightward asymmetry window with each other and the full view condition. These contrasts indicated no reallocation of resources to the left of fixation with scrolling text, confirming the prediction that there would be no reversal of the span with the scrolling format. There did however appear to be a reduction of resources allocated to the right of fixation with scrolling text, with a significant decrease in reading speed with the 8-character window compared to the full view condition in the static but not scrolling text conditions. This indicates a compression of the perceptual span for scrolling text to the right of fixation.

To confirm this pattern of results, we carried out equivalence tests for each contrast to determine whether any of the null effects were actually statistically meaningful (i.e. greater than the smallest meaningful effect, set equivalent to standard effect sizes in previous perceptual span literature as outlined previously in *Methods*. The only evidence of this was for one additional comparison in static text, with a possible increase in reading speed from the 8-character and 12-character rightward asymmetry windows. Full statistics for the contrasts can be seen in Table 1.

Average fixation duration. There was a significant effect of both window extent F(5, 175) = 12.40, $p < .001$, $\eta_G^2 = 0.06$ and display type $F(1, 35) = 15.32$, $p < .001$, $\eta_G^2 = 0.04$ 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). There was also an interaction of these two factors F(5, 175) = 2.43, p = .04, $\eta_G^2 = 0.01$ (see Figure 4). Planned contrasts (Table 2) indicated that the full view on the sentence was significantly different only from the 8-character rightward asymmetry window, with a significant inflation in fixation duration in this restricted window for both scrolling and static text. However, equivalence testing also indicated that in static text the null effect seen in the significance testing results between the restricted 12-character rightward asymmetry window and full view may not be a true null effect; whereas in scrolling text the null result of the significance testing for this contrast is supported by the equivalence test.

Fixation count. The number of fixations made to read a sentence (see Figure 5) was affected by window condition $F(5, 175) = 39.24$, $p < .001$, $\eta_G^2 = 0.15$. Significantly more fixations were made with static text $F(1, 35) = 19.49$, $p < .001$, $\eta_G^2 = 0.06$ (1.0 extra fixation). The effect of window type was also again mediated by display type $F(5, 175) = 3.94$, $p = .002$, $\eta_G^2 = 0.01$, with a similar pattern as seen in the reading speed measure: for static text, the 8 character rightward asymmetry window elicited significantly more fixations than the 12 character rightward asymmetry window or the full view condition, but there was no significant difference found between these rightward asymmetry conditions or between either of these conditions and the full view condition for scrolling text. There was again no difference for either display type between either leftward asymmetry window condition and the symmetric 4-character window condition. Full statistical details for these planned contrasts are presented in Table 3.

Average saccade amplitude. Window extent had a significant effect on average saccade amplitude $F(5, 175) = 123.07$, $p < .001$, $\eta_G^2 = 0.31$, as did display type $F(1, 35) = 1289.49$, $p < .001$, $\eta_G^2 = 0.81$ (with significantly shorter saccades made with scrolling text). There was again an interaction of these factors $F(5, 175) = 7.50$, $p < .001$, $\eta_G^2 = 0.02$. However, planned contrasts (Table 4) did not show a difference in the pattern of effects across display windows for static and scrolling text. Average saccade amplitude increased between the 8-character rightward asymmetry window and each of the 12-character rightward asymmetry window and the full view on sentence. There was no difference between the 12 character rightward asymmetry window and the full view for either display type.

Table 1. Planned contrasts for reading speed in Experiment 1.

Display type	**Window comparison**	**Mean 1**	**Mean 2**	**[a]SE**	**d_z**	**Est.**	**t**	**p**	**Eq t[b]**	**Eq p**
Scrolling	12_4 vs. 4_4	238.48	234.58	6.30	0.08	3.90	0.49	>.99	-4.18	<.001
	8_4 vs. 4_4	232.07	234.58	4.83	-0.05	-2.51	-0.32	>.99	4.28	<.001
	4_8 vs. 4_12	267.57	275.76	7.64	-0.17	-8.19	-1.03	>.99	3.73	<.001
	4_8 vs. Full view	267.57	281.57	7.02	-0.30	-14.00	-1.77	.78	2.81	.004
	4_12 vs. Full view	275.76	281.57	5.93	-0.12	-5.81	-0.73	>.99	3.82	<.001
Static	12_4 vs. 4_4	235.35	216.80	7.22	0.39	18.55	2.34	.20	-2.23	.02
	8_4 vs. 4_4	227.16	216.80	6.85	0.22	10.36	1.31	>.99	-3.29	.001
	4_8 vs. 4_12	260.99	281.57	5.23	-0.43	-20.58	-2.60	.10	.87	.20[c]
	4_8 vs. Full view*	260.99	293.17	9.99	-0.68	-32.19	-4.06	<.001	1.58	.06[d]
	4_12 vs. Full view	281.57	293.17	9.86	-0.25	-11.61	-1.47	>.99	3.62	<.001

[a] Standard error was calculated using the within-subjects formula provided by (Franz & Loftus, 2012), here and in all following; [b] Eq t and eq p are the values from the equivalence tests and can be interpreted in the opposite way to the significance-testing statistic – a significant p-value indicates that the effect size of that contrast is significantly smaller than the standard set for a statistically meaningful effect – see notes [c] and [d] for examples of how to interpret these results; [c] The static text 4_8 vs. 4_12 window conditions comparison was not statistically significant but the effect size was not statistically smaller than a meaningful effect; [d] The static text 4_8 vs. Full view window conditions comparison was statistically significant and the effect size was statistically meaningful; all other comparisons were not statistically significant and statistically equivalent to zero; * demarks the contrast which shows a significant and statistically meaningful effect.

Table 2. Planned contrasts for fixation duration in Experiment 1.

Display type	**Window comparison**	**Mean 1**	**Mean 2**	**SE**	**d_z**	**Est.**	**t**	**p**	**Eq t**	**Eq p**
Scrolling	12_4 vs. 4_4	217.91	219.07	2.42	-0.07	-1.16	-0.41	>.99	3.12	.002
	8_4 vs. 4_4	217.58	219.07	2.05	-0.09	-1.49	-0.53	>.99	2.88	.003
	4_8 vs. 4_12	216.16	212.22	2.96	0.23	3.94	1.40	>.99	-2.27	.01
	4_8 vs. Full view*	216.16	207.80	3.14	0.50	8.37	2.97	.03	-0.94	.18
	4_12 vs. Full view	212.22	207.80	2.95	0.26	4.42	1.57	>.99	-2.10	.02
Static	12_4 vs. 4_4	208.67	216.03	3.32	-0.44	-7.36	-2.61	.09	1.38	.09
	8_4 vs. 4_4	211.79	216.03	2.52	-0.25	-4.24	-1.50	>.99	1.92	.03
	4_8 vs. 4_12	204.02	202.71	2.14	0.08	1.31	0.47	>.99	-2.99	.003
	4_8 vs. Full view*	204.02	195.52	3.24	0.50	8.50	3.02	.03	-0.98	.17
	4_12 vs. Full view	202.71	195.52	2.69	0.43	7.19	2.55	.11	-0.92	.18[a]

[a] The 4_12 vs. full view contrast for static text was not statistically significant, but equivalence testing indicated that the effect size was not statistically different from a meaningful effect; * demarks statistically significant and meaningful effects.

Table 3. Planned contrasts for fixation count in Experiment 1.

Display type	Window comparison	Mean 1	Mean 2	SE	d_z	Est.	t	p	Eq t	Eq p
Scrolling	12_4 vs. 4_4	0.92	0.92	0.01	0.03	0.01	0.16	>.99	-4.51	<.001
	8_4 vs. 4_4	0.94	0.92	0.01	0.15	0.02	0.89	>.99	-3.18	.002
	4_8 vs. 4_12	0.82	0.79	0.01	0.23	0.03	1.37	>.99	-2.21	.02
	4_8 vs. Full view	0.82	0.80	0.01	0.17	0.03	1.01	>.99	-2.89	.003
	4_12 vs. Full view	0.79	0.80	0.01	-0.06	-0.01	-0.36	>.99	3.94	<.001
Static	12_4 vs. 4_4	1.02	1.07	0.02	-0.34	-0.05	-2.06	.40	2.69	.005
	8_4 vs. 4_4	1.04	1.07	0.03	-0.21	-0.03	-1.28	>.99	3.77	<.001
	4_8 vs. 4_12*	0.93	0.85	0.02	0.57	0.08	3.40	.008	-0.79	.22
	4_8 vs. Full view*	0.93	0.84	0.02	0.67	0.09	4.03	<.001	-0.82	.21
	4_12 vs. Full view	0.85	0.84	0.02	0.11	0.02	0.65	>.99	-4.09	<.001

* demarks statistically significant and meaningful effects.

Table 4. Planned contrasts for saccade amplitude in Experiment 1.

Display type	**Window comparison**	**Mean 1**	**Mean 2**	**SE**	**d_z**	**Est.**	**t**	**p**	**Eq t**	**Eq p**
Scrolling	12_4 vs. 4_4	2.24	2.15	0.09	0.13	0.08	0.75	>.99	-5.68	<.001
	8_4 vs. 4_4	2.14	2.15	0.06	-0.02	-0.01	-0.09	>.99	6.42	<.001
	4_8 vs. 4_12*	2.80	3.24	0.08	-0.65	-0.44	-3.89	.001	1.27	.11
	4_8 vs. Full view*	2.80	3.35	0.10	-0.80	-0.54	-4.80	<.001	0.89	.19
	4_12 vs. Full view	3.24	3.35	0.07	-0.15	-0.10	-0.91	>.99	5.21	<.001
Static	12_4 vs. 4_4[a]	6.07	5.66	0.11	0.61	0.41	3.63	.003	-2.72	.005
	8_4 vs. 4_4	5.88	5.66	0.08	0.32	0.22	1.94	.53	-3.77	<.001
	4_8 vs. 4_12*	6.65	7.34	0.07	-1.02	-0.69	-6.10	<.001	-3.63	>.99
	4_8 vs. Full view*	6.65	7.65	0.16	-1.47	-1.00	-8.84	<.001	0.30	.38
	4_12 vs. Full view	7.34	7.65	0.16	-0.46	-0.31	-2.74	.06	4.64	<.001

[a] This contrast was statistically significant, but equivalence testing indicated that the effect size was not statistically meaningful; * denotes statistically significant and meaningful effects.

Landing position. There was no significant effect of window condition on landing position $F(5, 175) = 1.03$, $p = .40$, $\eta_G^2 = 0.01$, or of of display type $F(1, 35) = 2.73$, $p = .11$, $\eta_G^2 = 0.01$ (see Figure 3), and no interaction of these factors $F(5, 175) = 1.24$, $p = .29$, $\eta_G^2 = 0.01$.

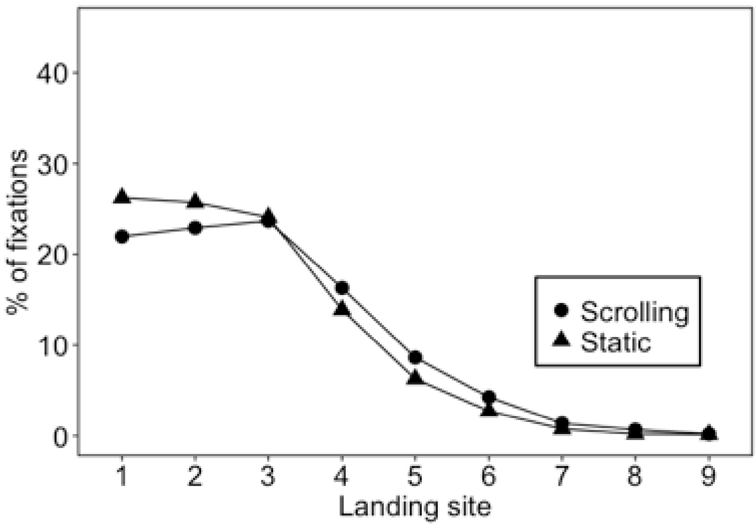

Figure 3. Landing position (character in targeted word) distributions under static and scrolling text conditions.

Discussion

This experiment aimed to characterise changes to the allocation of attention during reading with horizontally scrolling text, using the gaze-contingent moving window paradigm (McConkie & Rayner, 1975, 1976) to compare the extent of the perceptual span with scrolling and static text. As would be expected given the extremely well-established effect of restricting text availability in this way during reading of static text (Clifton et al., 2016; McConkie & Rayner, 1975, 1976; Rayner, 1998), all oculomotor measures investigated here were significantly disrupted in both display conditions (static and scrolling text) by the gaze-contingent window paradigm. 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. Significant differences were observed between the 8 character but not the 12 character rightward asymmetry window and the unrestricted view of the sentence for all four measures reported. By contrast, the rightward extent of the perceptual span appeared to be reduced to around 8 characters with the scrolling text format, 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 and fixation count (contrasting with a significant difference between the 8 character window and full view for static text on both of these measures), and some evidence for a similar pattern in fixation duration. 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 modulate attentional resources in the direction of pursuit. Analysis of landing position in this study showed no significant difference in average landing position between scrolling and static text, 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.

These findings are consistent with a reduction in the rightward extent of the perceptual span when text is horizontally scrolled during reading; i.e., that fewer resources were allocated to the right of fixation when reading text scrolling to the left, and that this finding could not be attributed to a change in saccade landing position.

Experiment 2

Despite slight variability in the different measures of interest in Experiment 1, the results coherently support the conclusion of a compressed perceptual span when reading scrolling text. This finding is most parsimoniously explained by an increased attentional load via the mechanisms discussed previously. However, a further possibility was that the increased reading difficulty that this compression implies for scrolling text results not from a generalised effect over the entire reading period, but from specific difficulties that readers may have in adapting to the movement of the text when it first appears, or in planning oculomotor behaviour when they reach the end of the text[2]. We therefore carried out a second experiment using a sustained reading task to exclude this possibility. The use of paragraph-length stimuli, as opposed to single sentences, enables the exclusion of a portion of the data at reading onset, and a portion prior to reading offset to ensure that the data in our analyses solely reflected "smooth" undisrupted reading without contamination by fixations at, or soon after, the start, and fixations soon before, or at the end of reading. As in Experiment 1, we expected to see more similarity between the 8-character, 12-character and full view conditions in scrolling text than in static text, indicating a reduction in the perceptual span with the scrolling format.

Method

Participants. Participants were 24 undergraduate students from RHUL (16 female, mean age 19.8). 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 at RHUL, and participants gave informed consent accordingly.

Stimuli and procedure. Stimuli were 98 short paragraphs with an average of 64.7 words per passage. These were adapted from short expository news items in the national newspaper The Independent (2006-2011 archive, accessed from Nexis.com,

[2] We thank the reviewers for highlighting this interesting possibility.

16th October 2017). All were similar in structure and had an approximate reading grade level of grade 10, with a Flesch Reading Ease score of 51.9. Scrolling text was displayed in a single continuous line as in the previous experiments. Static text was displayed in multi-line paragraphs across 3-4 lines (average 3.24 lines), with inter-line spacing of 150 pixels in order to ensure good vertical accuracy of the gaze-contingent windows. The window conditions compared were two rightwardly asymmetric windows, with 4 characters to the left and 8 or 12 to right of fixation (4_8 and 4_12) and a full view condition, with no restriction on the availability of text. These windows were chosen as those identified as the critical widths of interest by Experiment 1, with other windows excluded in order to allow us to maximize statistical power. All participants viewed all conditions, as before, as both static and scrolling text (presented in counterbalanced blocks with 16 cells per condition, with sentences rotated in a Latin Square design as previously). The window restrictions were applied as previously (windows implemented as spatial filtering of text). Participants were asked to briefly summarize the paragraph that they had just read at the end of six randomly chosen trials throughout each block, in order to ensure adequate task engagement. All participants were able to provide these accurately on all occasions.

In order to exclude any oculomotor behaviour elicited specifically by the onset and offset of the moving text stimulus, we removed the first and last 10% of each trial (mean 1492.86 ms, SE 1.62; from mean total trial length 14928.55 ms, SE 16.25). Procedure and data analyses were otherwise as for previous experiments. Data cleaning resulted in a loss of 2.4% of fixations (80-1200 ms criterion) and 2.1% of trials (trial cleaning). Multiple comparisons were again corrected for using the Bonferroni criterion throughout, and equivalence tests were carried out for all planned contrasts to verify that null effects were not due to a lack of statistical power.

Results

Reading rate. As in Experiment 1, there was a main effect of window extent $F(2, 46) = 29.53$, $p < .001$, $\eta_G^2 = 0.06$ on reading rate, and this was modulated by an interaction of window extent with display type $F(2, 46) = 8.67$, $p < .001$, $\eta_G^2 = 0.02$. There was again no significant main effect of display type, although in this study this was approaching significance ($F(1, 23) = 3.88$, $p = .06$, $\eta_G^2 = 0.06$), with faster reading times for scrolling than static text. This is unsurprising as participants had more opportunity for re-reading with the static paragraphs, increasing their overall reading time. Planned contrasts (Table 5) showed significantly slower reading in both the 8-character and 12-character windows than in the full view condition for static, but no significant differences between reading speed between any of the three viewing conditions for scrolling text; although equivalence tests showed that the effect sizes of each of comparisons between a rightwardly asymmetric window and the full view condition may be statistically meaningful. Nevertheless, there was a clear divergence in results on the comparison of the two asymmetric windows, with a significant decrease in reading speed with the smaller window in static text only.

Average fixation duration. The effects found in Experiment 1 were again replicated with significant main effects of both window extent ($F(2, 46) = 68.07$, $p < .001$, $\eta_G^2 = 0.10$) and display type ($F(1, 23) = 2.20$, $p < .001$, $\eta_G^2 = 0.06$) on average fixation duration, with an interaction between these factors $F(2, 46) = 11.98$, $p < .001$, $\eta_G^2 = 0.03$. Planned contrasts (Table 6) indicated an inflation with both display formats when the window on the sentence was truncated at 8 characters to the right of fixation, and some evidence for a benefit of the 12-character window over the 8-character window (although this contrast was not statistically significant in scrolling text; $p = .32$). However, for static text only there was a significant decrease in fixation duration between the 12-character window and unrestricted view; consistent with a compression of the span for scrolling text.

Fixation count. There were no significant effects of either window extent ($F(2, 46) = 1.66$, $p = .20$, $\eta_G^2 = 0.004$) or display type ($F(1, 23) = 1.39$, $p = .25$, $\eta_G^2 = 0.02$) found for the average number of fixations made by participants to read a passage, and no interaction of these factors ($F(2, 46) = 1.38$, $p = .26$, $\eta_G^2 = 0.002$). This is in contrast to the findings of the first study, where significant effects of display type and window extent were apparent, as well as an interaction between these factors. There was a numerical trend in static text only for increased fixations with the smallest window size (47.8 fixations cf. 45.6 with 4_12 window and 45.1 with full view; scrolling text 43.1, 43.3, 42.6 fixations respectively).

Average saccade amplitude. As in Experiment 1, there were significant effects of window extent $F(2, 46) = 17.61$, $p < .001$, $\eta_G^2 = 0.10$ and display type $F(1, 23) = 207.48$, $p < .001$, $\eta_G^2 = 0.71$, with these effects modulated by a significant interaction

$F(2, 46) = 6.22$, $p = .004$, $\eta_G^2 = 0.02$. Planned contrasts (see Table 7) reveal a significant decrease in saccade amplitude through the three viewing conditions (i.e. shorter saccades made with a 12-character window than when reading with no restrictions, and shorter again with the 8-character window) for static text; whereas there was a reduction in saccade length only for the 8-character window with scrolling text.

Table 5. Planned contrasts for reading speed in Experiment 2.

Display type	Window comparison	Mean 1	Mean 2	SE	d_z	Est.	t	p	Eq t	Eq p
Scrolling	4_8 vs. 4_12	257.07	256.65	2.28	0.02	0.42	0.08	>.99	-3.74	<.001
	4_8 vs. Full view[a]	257.07	270.47	2.31	-0.52	-13.40	-2.57	.07	-1.87	.96
	4_12 vs. Full view[a]	256.65	270.47	2.39	-0.54	-13.83	-2.66	.06	-1.87	.96
Static	4_8 vs. 4_12*	218.20	235.67	5.02	-0.69	-17.48	-3.36	.007	0.44	.33
	4_8 vs. Full view*	218.20	261.30	8.73	-1.69	-43.10	-8.28	<.001	-1.02	.84
	4_12 vs. Full view*	235.67	261.30	6.71	-1.00	-25.63	-4.92	<.001	0.10	.46

[a]These contrasts were not statistically significant, but the equivalence tests indicated that the effect sizes may be statistically meaningful; * denotes statistically significant and meaningful effects.

Table 6. Planned contrasts for fixation duration in Experiment 2.

Display type	Window comparison	Mean 1	Mean 2	SE	d_z	Est.	t	p	Eq t	Eq p
Scrolling	4_8 vs. 4_12[a]	220.33	216.15	1.51	0.40	4.18	1.95	.32	-1.14	.13
	4_8 vs. Full view*	220.33	213.42	1.82	0.66	6.91	3.23	.01	-0.13	.45
	4_12 vs. Full view	216.15	213.42	1.66	0.26	2.73	1.27	>.99	-2.28	.02
Static	4_8 vs. 4_12*	218.12	208.81	1.34	0.89	9.31	4.35	<.001	3.04	.98
	4_8 vs. Full view*	218.12	194.88	3.00	2.21	23.25	10.85	<.001	3.84	>.99
	4_12 vs. Full view*	208.81	194.88	2.90	1.33	13.93	6.51	<.001	0.88	.81

[a]This contrast was not statistically significant, but the equivalence test indicated that the effect size may be statistically meaningful; * denotes statistically significant and meaningful effects.

Table 7. Planned contrasts for saccade amplitude in Experiment 2.

Display type	Window comparison	Mean 1	Mean 2	SE	d_z	Est.	t	p	Eq t	Eq p
Scrolling	4_8 vs. 4_12	4.26	4.53	0.12	-0.36	-0.27	-1.23	>.99	1.61	.06
	4_8 vs. Full view*	4.26	4.94	0.21	-0.79	-0.68	-3.05	.02	0.72	.24
	4_12 vs. Full view	4.53	4.94	0.19	-0.42	-0.41	-1.82	.43	1.75	<.05
Static	4_8 vs. 4_12*	8.19	8.82	0.17	-0.61	-0.63	-2.81	.04	0.24	.41
	4_8 vs. Full view*	8.19	9.72	0.33	-1.26	-1.53	-6.86	<.001	-0.79	.78
	4_12 vs. Full view*	8.82	9.72	0.26	-0.65	-0.91	-4.05	<.001	0.49	.31

* denotes statistically significant and meaningful effects.

Discussion

The results of Experiment 2 confirmed that the compression of the perceptual span observed with scrolling text in the first experiment was not due to the short stimuli length, or an artefact of any difficulty in beginning pursuit of the text with this format. As in Experiment 1, the crucial finding of an interaction between text display format and window extent was significant for the reading speed, saccade amplitude, and fixation duration measures. Planned contrasts across these three measures again supported our conclusion of a compressed perceptual span to the right of fixation when reading scrolling text. The only measure which did not replicate in Experiment 2 was the number of fixations made per word, although numerical trends indicated a similar pattern.

Pooled data for both experiments 1 and 2

Given the slight differences seen in patterns of pairwise comparisons in some of the measures across the two experiments, and in order to maximise statistical power as far as possible, we performed further analyses that combined the datasets from both experiments. These analyses included the data relating to the common window sizes of 4 characters to the left and 8 or 12 to the right of fixation, and the full view conditions. ANOVAs were carried out described previously, with within-subjects factors of display type (scrolling/static) and window size (4_8, 4_12, and full view). There was also an additional between-subjects factor of experiment (1 or 2). In order to allow direct comparison between the studies regardless of the average word length of stimuli, we report a standardised measure of fixation count as average number of fixations per word instead of raw fixation count as previously.

Reading rate. There was a significant main effect of window extent $F(2, 116) = 21.07$, $p = .04$, $\eta_G^2 = 0.03$. The main effect of display type did not reach significance $F(1, 58) = 1.82$, $p = .18$, $\eta_G^2 = 0.01$, but as in both previous studies there was a significant interaction of these two critical factors $F(2, 116) = 11.43$, $p < .001$, $\eta_G^2 = 0.01$. This confirms the compression of the perceptual span apparent in both experiments. There was a significant effect of experiment $F(1, 58) = 46.42$, $p < .001$, $\eta_G^2 = 0.05$, with slowest reading speeds in Experiment 2, and an interaction of experiment and window condition $F(2, 116) = 3.25$, $p = .04$, $\eta_G^2 = 0.001$; both of which may be expected due to the more complex scientific topic of the stimuli in the second experiment. Importantly though, there was no interaction of experiment with display type ($F(1, 58) = 3.42$, $p = .07$, $\eta_G^2 = 0.01$), and no three-way interaction of the three factors ($F(2, 116) = 1.11$, $p = .33$, $\eta_G^2 = 0.0004$). Planned contrasts comparing the rightward asymmetry windows to the full view on the sentence for each display type again showed that the critical window size was smaller for scrolling text, with no significant or statistically meaningful difference between any of three window conditions with this display type, but an increase in reading speed through the increasing text availability windows for static text (see Table 8). This confirms that the finding of a compressed perceptual span with scrolling text was consistent across both experiments.

Average fixation duration. As for reading speed and again supporting our hypothesis, there were significant main effects of display type $F(1, 58) = 30.45$, $p < .001$, $\eta_G^2 = 0.06$ and window extent $F(2, 116) = 32.09$, $p < .001$, $\eta_G^2 = 0.05$; and a significant interaction of these factors $F(2, 116) = 5.83$, $p = .004$, $\eta_G^2 = 0.01$, again confirming our interpretation of a compressed span with scrolling text. Planned contrasts (Table 9) showed a significant difference between the rightwardly asymmetric 12-character window and the full view on the stimuli in static text only.

There was no significant effect of experiment $F(1, 58) = 1.37$, $p = .25$, $\eta_G^2 = 0.02$, and no interaction of this factor with display type ($F(1, 58) = 0.27$, $p = .61$, $\eta_G^2 = 0.001$) or window extent ($F(2, 116) = 1.58$, $p = .08$, $\eta_G^2 = 0.004$). However, there was a three-way interaction of these factors $F(2, 116) = 4.85$, $p = .01$, $\eta_G^2 = 0.01$. This can be interpreted from the planned contrasts of the separate analyses for each experiment for this measure (Tables 2 and 6), showing that Experiment 2 but not Experiment 1 showed a significant difference between the rightward 12-character window and full view for static text.

Average number of fixations per word. The number of fixations made by each participant to read each sentence/paragraph was divided by the number of words in the passage in order to produce a standardised score of average number of fixations per word which could be compared across experiments. There were significant main effects of window extent $F(2, 116) = 9.75$, $p < .001$, $\eta_G^2 = 0.01$ and display type $F(1, 58) = 6.99$, $p = .01$, $\eta_G^2 = 0.03$, and a significant interaction between these factors $F(2, 116) = 5.60$, $p = .005$, $\eta_G^2 = 0.004$. Planned contrasts (see Table 10) demonstrated no significant difference between any of the window conditions for scrolling text, but a significant increase in number of fixations with the 8-character window compared to both the 12-character and unrestricted view conditions in static text.

There was no significant effect of experiment $F(1, 58) = 0.49$, $p = .49$, $\eta_G^2 = 0.006$, and no significant interactions of experiment with either other factor (window extent $F(2, 116) = 1.70$, $p = .19$, $\eta_G^2 = 0.002$, display type $F(1, 58) = 0.06$, $p = .81$, $\eta_G^2 = 0.0002$, three-way interaction $F(2, 116) = 0.50$, $p = .61$, $\eta_G^2 = 0.004$).

Average saccade amplitude. Finally, there were again main effects of display type $F(1, 58) = 919.79$, $p < .001$, $\eta_G^2 = 0.77$ and window extent $F(2, 116) = 53.07$, p

< .001, η_G^2 = 0.10 on average saccade amplitude, and an interaction of these factors $F(2, 116) = 11.43$, $p < .001$, $\eta_G^2 = 0.01$, confirming the reliability of this finding across the two experiments. Planned contrasts indicated that there were reliable and statistically meaningful effects between the 8-character rightward asymmetry window and the rightward 12-character window and unrestricted view of the stimuli presented in static text only (see Table 11).

There was also a main effect of experiment $F(1, 58) = 46.42$, $p < .001$, η_G^2 = 0.32, with shorter saccades on average in Experiment 1 than in Experiment 2 (Exp 1 mean 5.17 SE 0.13, Exp 2 6.74 SE 0.20). The small margin of difference here means that it seems unlikely to be of functional significance for our question of interest. Finally there was an interaction of experiment and window condition $F(2, 116)$ = 3.25, $p = .04$, $\eta_G^2 = 0.01$, but no interaction with display type $F(1, 58) = 0.77$, p = .38, $\eta_G^2 = 0.003$, and no three-way interaction $F(2, 116) = 1.11$, $p = .33$, $\eta_G^2 = 0.001$.

Table 8. Planned contrasts for reading speed for data pooled across both experiments.

Display type	Window comparison	Mean 1	Mean 2	SE	d_z	Est.	t	p	Eq t	Eq p
Scrolling	4_8 vs. 4_12	263.37	268.12	4.68	-0.10	-3.89	-0.74	>.99	5.18	<.001
	4_8 vs. Full view	263.37	277.13	4.29	-0.34	-13.70	-2.61	.06	2.99	.002
	4_12 vs. Full view	268.12	277.13	3.70	-0.24	-9.82	-1.87	.38	3.76	<.001
Static	4_8 vs. 4_12*	243.87	263.21	3.70	-0.47	-19.03	-3.63	<.001	0.98	.17
	4_8 vs. Full view*	243.87	280.42	6.92	-0.93	-37.65	-7.17	<.001	0.91	.18
	4_12 vs. Full view[a]	263.21	280.42	6.51	-0.46	-18.62	-3.55	<.001	3.55	<.001

[a] This contrast was statistically significant, but equivalence testing indicated that the effect size was not statistically meaningful; * denotes statistically significant and meaningful effects.

Table 9. Planned contrasts for fixation duration for data pooled across both experiments.

Display type	Window comparison	Mean 1	Mean 2	SE	d_z	Est.	t	p	Eq t	Eq p
Scrolling	4_8 vs. 4_12	217.83	213.79	1.86	0.27	4.06	2.06	.24	-2.48	.008
	4_8 vs. Full view*	217.83	210.05	2.01	0.50	7.64	3.88	<.001	-0.773	.221
	4_12 vs. Full view	213.79	210.05	1.88	0.23	3.58	1.82	.42	-2.65	.005
Static	4_8 vs. 4_12*	209.66	205.15	1.47	0.35	5.31	2.70	.04	-1.58	.06
	4_8 vs. Full view*	209.66	195.26	2.45	1.04	15.87	8.07	<.001	1.22	.89
	4_12 vs. Full view*	205.15	195.26	2.02	0.69	10.56	5.37	<.001	0.26	.60

[a] These contrasts were statistically significant, but equivalence testing indicated that the effect sizes were not statistically meaningful; * denotes statistically significant and meaningful effects.

Table 10. Planned contrasts for average number of fixations per word for data pooled across both experiments.

Display type	Window comparison	Mean 1	Mean 2	SE	d_z	Est.	t	p	Eq t	Eq p
Scrolling	4_8 vs. 4_12	0.81	0.79	0.01	0.13	0.01	1.02	>.99	-2.56	.006
	4_8 vs. Full view	0.81	0.79	0.01	0.16	0.02	1.22	>.99	-2.55	.006
	4_12 vs. Full view	0.79	0.79	0.01	0.03	0.01	0.20	>.99	-4.57	<.001
Static	4_8 vs. 4_12*	0.91	0.84	0.01	0.55	0.06	4.29	<.001	-0.30	.38
	4_8 vs. Full view*	0.91	0.83	0.02	0.67	0.07	5.17	<.001	-0.99	.16
	4_12 vs. Full view	0.84	0.83	0.02	0.11	0.01	0.88	>.99	-3.87	<.001

* denotes statistically significant and meaningful effects.

Table 11. Planned contrasts for saccade amplitude for data pooled across both experiments.

Display type	Window comparison	Mean 1	Mean 2	SE	d_z	Est.	t	p	Eq t	Eq p
Scrolling	4_8 vs. 4_12[a]	3.38	3.76	0.07	-0.40	-0.36	-3.13	.01	3.09	.002
	4_8 vs. Full view [a]	3.38	3.98	0.10	-0.69	-0.61	-5.36	<.001	2.64	.005
	4_12 vs. Full view	3.76	3.98	0.09	-0.29	-0.26	-2.24	.16	5.98	<.001
Static	4_8 vs. 4_12*	7.27	7.93	0.08	-0.74	-0.66	-5.77	<.001	0.04	.48
	4_8 vs. Full view*	7.27	8.48	0.16	-1.43	-1.27	-11.10	<.001	1.08	.14
	4_12 vs. Full view[a]	7.93	8.48	0.15	-0.69	-0.61	-5.32	<.001	4.76	<.001

[a] These contrasts were statistically significant, but equivalence testing indicated that the effect sizes were not statistically meaningful; * denotes statistically significant and meaningful effects.

General Discussion

In two experiments we have presented clear evidence that the deployment of attention to upcoming text is altered when reading horizontally 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). The pattern of results across manipulated preview extents in both experiments were suggestive of a compression of the rightward extent of the perceptual span when reading scrolling text, with no change to this preview effect in the leftward direction of the pursuit fixation. Although this pattern was not always evident across all measures, the results clearly demonstrate a consistent overall pattern. It is common in studies using the gaze-contingent window paradigm for there to be some discrepancy in the effect of window manipulation across all measures considered (see e.g. Paterson et al., 2014; Rayner, 1986; Rayner et al., 2009).

Allocation 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 significantly increased 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 attention is allocated predominantly to the right of the point of fixation, in order to maximise engagement in linguistic processing, 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).

The compression of the rightward extent of the perceptual span with scrolling text can then be explained via a generalised mechanism governing deployment of attention in reading, modulated by foveal load (e.g. Reichle et al., 2003; Schad & Engbert, 2012). Foveal load is determined by 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), which 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 does create a conflict (as hypothesised), resulting in fewer available attentional resources for allocation to the parafoveal area.

Conclusion

In sum, the experiments presented here together demonstrate that the deployment of attention to upcoming text is altered when reading horizontally scrolling text. The perceptual span was reduced to the right of fixation with this display format compared to static text, with no change in the leftward span in the direction of pursuit tracking. This has practical implications for the use of this format in digital media, as 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 observed 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 and consequential comprehension decrement seen with scrolling text; Harvey et al., 2017; Harvey & Walker, 2017). The horizontally scrolling format may be best suited to displaying short and simple text, where a deep level of comprehension is not required. Exceptions to this may be situations in which the cost of a compressed perceptual span can be outweighed by the potential benefits of reading in this different way; notably for populations with visual impairments (e.g. Ong et al., 2012; Walker, 2013; Walker, Bryan, Harvey, Riazi, & Anderson, 2016).

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