**Pre-print authors’ copy QJEP accepted 20-7-17**

**Reading comprehension and its relationship with working memory capacity when reading horizontally scrolling text.**

Hannah Harvey and Robin Walker

Department of Psychology, Royal Holloway University of London, Egham, UK

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

**Reading comprehension and its relationship with working memory capacity when reading horizontally scrolling text.**

The horizontally scrolling format, where text is presented in a single line drifting right to left, is relatively commonly used to display text on digital screens. This format presents a potentially challenging reading situation, as the text must be followed smoothly to the left (to track individual words) whilst rightward eye-movements are made as usual to progress through the text. This conflict may reduce attention allocated to upcoming text. Returning to previously encountered text is also more difficult with this format. Here, a sustained reading comprehension task was used to compare performance with horizontally scrolling and multiline static text formats. Results showed that literal comprehension can be reasonably well-maintained with scrolling text, although small decrements are seen at faster scrolling rates. However, they indicated that this format makes it more difficult to answer questions requiring an inference to be made. The contribution of working memory capacity and the impact of display speed on these effects was considered. These findings have implications for the application of this format in digital media, and also more widely for the conditions required for successful in-depth reading comprehension with any text format.

Keywords: reading; comprehension; working memory;dynamic text; digital media

**Introduction**

The dynamic horizontally scrolling text display format has a number of applications including on LED announcement boards, in mobile apps, and on smart-watches. Understanding how dynamic formats affect reading comprehension is increasingly important as exposure to print becomes more digitised; particularly given increasing use of mobile devices such as smart phones and tablets for learning (so-called ‘m-learning’; Al-Fahad, 2009; Dahlstrom, 2012; Gikas & Grant, 2013; Pegrum, Oakley, & Faulkner, 2013; Wallace, Clark, & White, 2012), and the potential of these formats as low vision aids (Bowers, Woods, & Peli, 2004; Walker, Bryan, Harvey, Riazi, & Anderson, 2016).

Scrolling text presents a particular profile of challenges for the reading process. Firstly, the movement of text may modulate the way attention is deployed during reading. Visual attention and eye movements are thought to be closely coupled (Rizzolatti, Riggio, Dascola, & Umilta, 1987; Rizzolatti, Riggio, & Sheliga, 1994). This means that scrolling text produces an apparent attentional conflict, between smooth pursuit programs to track the text leftwards and saccadic programmes to make progress left to right through the text. This potential conflict results in a reduced forward deployment to upcoming text for scrolling text (Fine, Woods, & Peli, 2001). Similar restriction of advance processing of text has been associated in other reading situations with difficulty in understanding text, i.e. with poor or developing comprehenders, and for more difficult reading material (e.g. Henderson & Ferreira, 1990; Patberg & Yonas, 1978; Rayner, 1986; Smith, 1971; White et al., 2005). Furthermore, the opportunity for and ease of making long-range regressions, known to support good understanding of text when reading normally (Schotter, Tran, & Rayner, 2014), is reduced in reading of scrolling text (Harvey, Godwin, Fitzsimmons, Liversedge, & Walker, 2017). Keeping track of the moving text may also reduce available working memory capacity (cf. Kerzel & Ziegler, 2005), important for holding pieces of information from the text for integration with later information. Given all of these factors, it may be expected that text comprehension may be impacted with the scrolling text format (compared to typical static text).

Text comprehension is achieved across several levels of textual analysis: processing perceptual characteristics; combining words into meaningful clause units; building an interrelated network of these units for gist formation; and incorporating the reader’s relevant existing knowledge (Kintsch & Rawson, 2007; Kintsch & van Dijk, 1978; Kintsch, 1988, 1998; van Dijk & Kintsch, 1983). To produce this highest level of comprehension, units of information acquired from the text must be sufficiently processed to activate relevant parts of existing knowledge, and both must be maintained in working memory whilst the passage is read (van den Broek & Young, 1998). The reduction in forward allocation of attention with scrolling text means that text is encountered in smaller and therefore more numerous sections, as the amount of information that can be processed from the upcoming text is reduced (see e.g. Rayner, 2014 for a full explanation of the role of forward allocation of attention in text processing). This will increase the processing burden for maintaining these units of information in the working memory. This may leave fewer resources to be allocated to completion of higher levels of processing (i.e. gist analysis and integration with existing knowledge). The consequences of not completing all levels of analysis on reading comprehension are demonstrated for example by findings from skim reading, where readers swiftly scan a text performing only a gist level of analysis (Coke, 1976; Huckin, 1983), and are consequently unable to achieve a high level of text comprehension (Rayner, Schotter, Masson, Potter, & Treiman, 2016).

Working memory is therefore one important factor involved in supporting effective text comprehension under typical reading conditions. Working memory is regarded as 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, 1992; Baddeley & Hitch, 1974). The involvement of working memory in supporting good comprehension is clear in the models of text comprehension (Ericsson & Kintsch, 1999; Kintsch & van Dijk, 1978; van den Broek & Young, 1998), and this relationship has been supported by the development of a complex reading span task by Daneman and Carpenter (1980). In this task, participants are asked to recall the last word for a series of sentences, and report all of these words after all sentences have been read. The working memory span is defined using this task as the number of these final target words a participant is able to recall. This measure has been found to correlate with reading comprehension scores across a number of different measures, with higher working memory scores associated with better text comprehension (Daneman & Carpenter, 1980). The increased demands placed on the oculomotor and attentional systems when reading moving text (Harvey et al., 2017), combined with the loss of the sustained availability of the text with this format, may result in lower working memory capacity scores; and correspondingly poorer text comprehension.

Some previous studies have investigated scrolling text comprehension (e.g. Dyson & Haselgrove, 2000, 2001; Kang & Muter, 1989; Öquist & Lundin, 2007; So & Chan, 2013), however, many of these have been carried out in languages using a logographic orthography, and the role of working memory has never before been investigated in this context. Furthermore, previous studies have focused on the impact of dynamic formats with digital displays, and have not included a comparison with normal static text or reported the effects on comprehension. Comparisons with other dynamic presentation methods such as rapid serial visual presentation (RSVP; where words are presented sequentially for a short duration) have variably suggested better (Kang & Muter, 1989), comparable (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). A study of RSVP indicated poorer comprehension in a sustained reading comprehension task than with static text (Benedetto et al., 2015). Although scrolling text shares some similarities with RSVP (such as a reduced ability to make long-range regressions to earlier parts of the text), there are also some key differences: crucially, the lack of any parafoveal preview information with RSVP, contrasting with a preserved preview available with scrolling text, and the ability to adjust the duration spent fixating a word depending on the processing demands (as occurs during normal reading; e.g. fixation durations inflated for less frequently encountered words and reduced for easily predictable words; Rayner, Ashby, Pollatsek, & Reichle, 2004). Scrolling text should therefore allow better preservation of reading comprehension than RSVP, when compared to static text.

This is supported to some extent by reports comparing scrolling and static text directly which have shown no difference in text comprehension between these two formats on a simple two-alternative forced choice assessment of comprehension (Harvey et al., 2017; Valsecchi, Gegenfurtner, & Schütz, 2013). However, such questions can rely on recognition memory for the presence or absence of certain key words or may be answerable solely on the basis of the reader’s existing knowledge (Rayner & Pollatsek, 1989) resulting in a ceiling effect that could 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.

The present study therefore examined reading comprehension with scrolling and static text using a sustained reading comprehension task based on one sustained reading of a long passage, rather than multiple short trials of single or very few sentences, adapted from a test battery specifically designed to investigate reading comprehension ability (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, two scrolling speeds are compared to performance when reading static text: one of around the same rate as the approximate average reading speed for normal static text (250 wpm; Rayner, 1998), and half this speed. 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 students 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. The study had approval from the RHUL ethics committee.

#### Stimuli and apparatus

Stimuli were displayed in Experiment Builder (SR Research, Ontario, Ca) 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 (horizontal character extent 11 pixels, corresponding to 0.4o). Static text was displayed in paragraph format (approximately 15 lines), and scrolling text in a single line moving across the page, with the faster condition moving atthreepixels per screen refresh (approximately 240 wpm; following Harvey et al., 2017, chosen to be approximately equivalent to an average static reading speed of around 250 wpm; Rayner, 1998) and the slower condition atthreepixels pertwoscreen refreshes (approximately 120 wpm). This slower speed is similar to that used in real life applications, such as news tickers (as used e.g. by Sky News) and announcement boards (e.g. on trains).

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). Literal questions in this battery are designed to require only knowledge of facts explicitly stated in the passage: e.g. Q: *According to the passage, what does Norman usually do in the evening? A: Schoolwork*. Inferential questions require knowledge that is not literally stated in the passage, and relying on integration for instance with prior knowledge: e.g. for the question *How do you think Norman feels about the summer holidays?,* participants can infer from the text that the character Norman does not like the holidays, but this information is not explicitly stated in the text (Stothard et al., 2010).

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. These were randomly allocated to three groups of 64 sentences with broadly comparable average numbers of words and characters (group one: 15.3 words and 86.2 char; group two: 15.0 words and 85.6 char; group three: 15.5 words and 86.3 char), there was no significant difference in the number of words or characters contained in the sentences for each group (p > 0.1 for all comparisons). The 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. Participants did not report perceiving any blurring or unevenness in the text motion for either speed. 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) that enabled reading speed to be calculated for this format.

A reduced list of comprehension questions was given to participants directly following 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 1.

[Table 1 near here]

The working memory task was carried out following Daneman and Carpenter’s (1980) procedure, with participants asked to first read 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 further sentence longer to ensure that performance was at ceiling). 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 highest set size that they could correctly respond to on two out of three trials in a block. In the fast scrolling condition, a third of participants were unable to reach this level (two out of three trials correct) 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* = .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 =* .98 (mean working memory score 2.6 SE 0.2 for all three blocks).

*Analysis*

Analyses were carried out with R 3.0.3 (R Core Team, 2016). 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 1) was modulated by the display type *F*(2, 58) = 77.60, *p* < .001, with the speed for the faster scrolling text (mean 200.4 wpm, SE 3.5) being quicker than for static text (*t*(29) = -3.19, *p* = 0.01 mean 173.7 wpm, SE 9.1), which was read significantly faster than the slower scrolling text (mean 111.5 wpm, SE 1.4*, t*(29) = 7.01, *p* <0.001). There was no significant association found between reading speed and any comprehension score measure for any of the three formats (-0.20 < *r* < 0.20, *p* > .05). In order to confirm that reading speed was not a confounding factor in the rest of the results, subgroup analyses were carried out for each measure to compare participants with similar reading speeds for fast scrolling and static text (less than 30wpm difference, mean 16.8 wpm, SE = 1.6, n = 15) with those with a larger difference in speed between these conditions (mean 67.0 wpm, 7.0 SE, n = 15). There was no significant effect of group, or interaction between group and display type, on any measure (global comprehension score, comprehension score as a function of question type, or working memory score, see Table 2).

[Figure 1 near here]

[Table 2 near here]

To compare 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 2a) across the three display types *F*(2, 58) = 32.33, *p* < .001, with pairwise comparisons indicating that static text allowed significantly better comprehension than both slow (t(29) = 4.00, p = .001) and fast (*t*(29) = 8.89, *p* < .001) scrolling text, and slow scrolling text better than fast scrolling text (*t*(29) = 3.73, *p* = .003).

[Figure 2 near here]

The comprehension scores were also examined 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 2b), there was again an effect of display type *F*(2, 58) = 6.63, *p* = .003, with static text and slower scrolling text producing significantly better comprehension than faster scrolling text (*t*(29) = 4.64, *p* < .001 and *t*(29) = 2.83, *p* = .03 respectively). There was no significant difference between slower scrolling and static text (*t*(29) = 0.02, *p* = .99).

For inference-based questions only (see Figure 2c) there was again an effect of display type on comprehension scores *F*(2, 58) = 12.37, *p* < .001. Static text resulted in a higher level of comprehension than fast or slow scrolling text (*t*(29) = 4.78 and *t*(29) = 4.14 respectively, both *p* < .001), with no difference between the scrolling speeds (*t*(29) = 0.73, *p* = .47).

The number of points recalled in the summaries produced (see Figure 2d) was also affected by display type *F*(2, 58) = 15.39, *p* < .001. Participants included more points with static text than with faster scrolling (*t*(29) = 5.92, *p* < .001) and slower scrolling (*t*(29) = 2.58, *p* = .045) text. There was also a difference between scrolling speeds, with better performance with the slower scrolling rate (*t*(29) = 2.80, *p* = .027).

Display type also had a significant effect on working memory scores *F*(2, 58) = 73.17, *p* < .001, with significant differences between all conditions (*p* < .001; see Figure 3). 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 two 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 four items.

[Figure 3 near here]

Correlations between working memory score and overall comprehension score indicated that there was a significant association between these for static text only (static *r* = .77, *p* < .001; slow scroll *r =* .27, *p* = .15; fast scroll *r* = .29, *p* = .12).

### Discussion

This study examined text comprehension with scrolling text in a sustained reading task, and the relationship between comprehension and working memory capacity. The results indicate that comprehension is reduced when reading scrolling text (compared to reading normal paragraph-form static text), although this outcome is mediated by scrolling speed and the level of processing required to answer the question.

The overall comprehension score was significantly reduced for scrolling text (cf. static text), and furthermore was significantly worse for faster scrolling text than slower scrolling text. The faster scrolling rate of 240 wpm was approximately comparable to that of a typical reading speed with staic text (Rayner, 1998), and the slower rate of 120 wpm was similar to that used in real-world displays such as the Sky News breaking news ticker (used in live broadcasts), and train announcement boards. An examination of the three question types indicated that the difference between the two scrolling speeds 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 significantly reduced for scrolling text, with the faster scrolling speed showing a particular decrement: performance in the working memory task with this display format was 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). This reduction in working memory capacity may in part be explained by entrainment of attention to the left in order to fixate on each word (which can reasonably be expected to become stronger at faster text speeds), producing a conflict with the normal deployment of attention along to the right (following the premotor model of visual attention; e.g. Rizzolatti et al., 1987). This conflict 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 comprehension 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 for the dynamic formats; i.e. with reduced working memory capacity compared to static text leading to reduced comprehension. This association is not replicated for scrolling text, with no significant correlationbetween working memory score~~s~~ and comprehension scores within display type for either of the display speeds. This lack of association is likely due to the floor effect seen with the scrolling format. The reduction in working memory capacity with scrolling text may be particularly problematic given the reduction in sustained availability of the text: with static text it has been found 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).

For static text, reading speed was calculated as the number of words in the passage divided by total reading duration for the passage indicated by the participants’ keypress. This method was adopted to standardise for differences in passage lengths. It is possible that this may have resulted in 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 participants may have made more than one pass of some or all of the text, whereas the faster average cited by Rayner is likely derived from studies of reading single sentences where this kind of rereading would be less necessary. However, there was no correlation between reading speed and comprehension score, and the average reading speed for the static text condition fell between the average speeds for each scrolling text condition. Reading speed does not, therefore, appear to be a factor in modulating the levels of text comprehension, at least at the moderate range of speeds investigated in this study. This lack of a relationship between reading speed and comprehension 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, & Luebker, 1989).

The most striking finding from this study was that the inference-based comprehension score was the only measure which did not show some improvement with a slower scrolling speed (compared to the faster display speed). Working memory may be the factor that can explain the apparent difficulty with making inferences (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 (retrieval failure due to storage difficulty) is likely 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 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.

The most likely unifying factor underlying the reduction in inference reduction across both scrolling text speeds is the restricted text availability for both scrolling formats, compared to the sustained availability of the whole passage for static text that allows re-inspection. The importance of sustained availability to support comprehension in this way has recently been supported by a backwards masking study of reading single static sentences (White, Lantz, & Paterson, 2017). Given the increased availability of the text for re-reading in both the static and slower scrolling conditions (although to a lesser extent with the scrolling format), this potentially allows more time to establish and remember the key concepts from the text as they are encountered: especially as the questions were all presented after the passage had been read and was no longer available, increasing the reliance on memory for the facts. The forced extended exposure to restricted portions of the text with the slower scrolling rate may confer an advantage for recalling specific individual ideas 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. However, the process of integrating the ideas across the text and with existing knowledge is less likely to gain an advantage from this delay. A factor in common to both scrolling conditions is the restriction on the amount of text displayed at any one time, which 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, Beker, & Oudega, 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.

The lack of sustained availability and the reduced working memory span with scrolling text may 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 that 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, are doubly constrained by working memory capacity and text availability and are therefore 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 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 employed to read scrolling text; Buettner, Krischer, & Meissen, 1985; Harvey et al., 2017; Valsecchi et al., 2013) may introduce interference, disturbing the integration of individual propositions (Kintsch & van Dijk, 1978; Rapp & van den Broek, 2005). Finally, 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 organise 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).

Despite the limitations for comprehension of scrolling text highlighted by these findings, a good level of literal comprehension was achieved even with a faster display speed, and some gist analysis and even higher-level inference production clearly is possible. Consequently, whilst this presentation format may not be suitable in situations where in-depth sustained reading comprehension is key (e.g. for m-learning applications), it may be an adequate format for displaying text where continuous linking of information with earlier ideas and existing knowledge is not as crucial (e.g. for news tickers); especially as the slower speed in this study is more representative of the display speed used in such real-world applications. In situations where this continuity is important, it may be possible to improve comprehension by making thematic links more explicit in the text, rather than relying on the reader to infer these links for themselves. This is particularly relevant to facilitate use of scrolling text in domains of application where the potential benefits of this format override the limitations identified in this report. For instance, for populations with certain visual impairments such as age-related macular degeneration, active oculomotor navigation of a multi-line page of static text can become a significant challenge (Deruaz, Whatham, Mermoud, & Safran, 2002); the scrolling format can help to reduce this, with findings suggesting that scrolling may im**p**rove peripheral acuity (Venkataraman, Lewis, Unsbo, & Lundström, 2017), with a subjective preference for this format and improved accuracy compared to static text reported in this population (e.g. Bowers et al., 2004; Harvey & Walker, 2014; Walker, 2013; Walker et al., 2016).

**Conclusion**

This study has shown that 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. This highlights the importance of these aspects of the reading situation in supporting good understanding of the content. However, comprehension is maintained at sufficient levels to allow use of this format in situations where highly detailed recall and integration with existing knowledge are not primary goals of the reading task.

Acknowledgements: We thank Dr Jessie Ricketts and Dr Rebecca Lucas for helpful discussion regarding sustained reading comprehension assessments. The study was funded by a Royal Holloway Reid Studentship to the first author.

The authors report no conflicts of interest.

**References**

Al-Fahad, F. (2009). Students’ attitudes and perceptions towards the effectiveness of mobile learning in King Saud University, Saudi Arabia. *The Turkish Online Journal of Educational Technology*, *8*(2), 1–9.

Baddeley, A. (1992). Working memory. *Science*, *255*(5044), 556–559. http://doi.org/10.1126/science.1736359

Baddeley, A., & Hitch, G. (1974). Working memory. In G. H. Bower (Ed.), *The Psychology of Learning and Motivation Vol. 8* (pp. 47–89). London: Academic Press, Inc.

Benedetto, S., Carbone, A., Pedrotti, M., Le Fevre, K., Bey, L. A. Y., & Baccino, T. (2015). Rapid serial visual presentation in reading: The case of Spritz. *Computers in Human Behavior*, *45*, 352–358. http://doi.org/10.1016/j.chb.2014.12.043

Bowers, A. R., Woods, R. L., & Peli, E. (2004). Preferred retinal locus and reading rate with four dynamic text presentation formats. *Optometry and Vision Science*, *81*(3), 205–13.

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

Burton, C., & Daneman, M. (2007). Compensating for a limited working memory capacity during reading: evidence from eye movements. *Reading Psychology*, *28*(2), 163–186. http://doi.org/10.1080/02702710601186407

Chien, Y.-H., Chen, C.-H., & Wei, W.-L. (2008). Effects of dynamic display, presentation method, speed, and task type on reading comprehension of wristwatch screens. *Displays*, *29*(5), 471–477. http://doi.org/10.1016/j.displa.2008.03.005

Christie, J., & Just, M. A. (1976). Remembering the location and content of sentences in a prose passage. *Journal of Educational Psychology*, *68*(6), 702–710.

Coke, E. (1976). Reading rate, readability, and variations in task-induced processing. *Journal of Educational Psychology*, *68*, 167–173.

Dahlstrom, E. (2012). *ECAR study of undergraduate students and information technology*. *Undergraduate Students and IT*. Louisville.

Daneman, M., & Carpenter, P. A. (1980). Individual differences in working memory and reading. *Journal of Verbal Learning and Verbal Behavior*, *19*(4), 450–466. http://doi.org/10.1016/S0022-5371(80)90312-6

Deruaz, A., Whatham, A. R., Mermoud, C., & Safran, A. B. (2002). Reading with multiple preferred retinal loci: implications for training a more efficient reading strategy. *Vision Research*, *42*(27), 2947–2957.

Dyson, M., & Haselgrove, M. (2000). The effects of reading speed and reading patterns on the understanding of text read from screen. *Journal of Research in Reading*, *23*(2), 210. http://doi.org/10.1111/1467-9817.00115

Dyson, M., & Haselgrove, M. (2001). The influence of reading speed and line length on the effectiveness of reading from screen. *International Journal of Human-Computer Studies*, *54*(4), 585–612. http://doi.org/10.1006/ijhc.2001.0458

Engle, R. W., & Kane, M. J. (2004). Executive attention, working memory capacity, and a two-factor theory of cognitive control. In B. Ross (Ed.), *The Psychology of Learning and Motivation* (pp. 145–199). Elsevier. http://doi.org/10.1016/S0079-7421(03)44005-X

Ericsson, K. A., & Kintsch, W. (1999). The role of long-term working memory in text comprehension. *Psychologia*, *42*(4), 186–198.

Fine, E. M., Woods, R. L., & Peli, E. (2001). Is there a preview benefit when reading scrolled text ? *Vision Science and Its Applications*, *FC5*-*4*, 55–58.

Gikas, J., & Grant, M. M. (2013). Mobile computing devices in higher education: Student perspectives on learning with cellphones, smartphones & social media. *The Internet and Higher Education*, *19*, 18–26. http://doi.org/10.1016/j.iheduc.2013.06.002

Harvey, H., Godwin, H., Fitzsimmons, G., Liversedge, S. P., & Walker, R. (2017). Oculomotor and linguistic processing effects in reading dynamic horizontally scrolling text. *Journal of Experimental Psychology: Human Perception and Performance*. http://doi.org/10.1037/xhp0000329

Harvey, H., & Walker, R. (2014). Reading with peripheral vision: a comparison of reading dynamic scrolling and static text with a simulated central scotoma. *Vision Research*, *98*, 54–60. http://doi.org/10.1016/j.visres.2014.03.009

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

Huckin, T. N. (1983). A cognitive approach to readability. In P. Anderson, R. Brockmann, & C. Miller (Eds.), *New essays in technical and scientific communication: Research, theory, practice* (pp. 90–108). NY: Baywood: Farmingdale.

Juola, J. F., Tiritoglu, A., & Pleunis, J. (1995). Reading text presented on a small display. *Applied Ergonomics*, *26*(3), 227–9.

Kang, T., & Muter, P. (1989). Reading dynamically displayed text. *Behaviour and Information Technology*, *8*(1), 33–42.

Karimi, H., & Ferreira, F. (2015). Good-enough linguistic representations and online cognitive equilibrium in language processing. *The Quarterly Journal of Experimental Psychology*, *218*(July), 1–28. http://doi.org/10.1080/17470218.2015.1053951

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

Kintsch, W. (1988). The role of knowledge in discourse comprehension: a construction-integration model. *Psychological Review*, *95*(2), 163–182.

Kintsch, W., & van Dijk, T. A. (1978). Toward a model of text comprehension and production. *Psychological Review*, *85*(5), 363–394.

Legge, G. E., Ross, J. A., Maxwell, K., & Luebker, A. (1989). Psychophysics of reading. VII. Comprehension in normal and low vision. *Clinical Vision Sciences*, *4*, 51–60.

Mcvay, J. C., & Kane, M. J. (2012). Why does working memory capacity predict variation in reading comprehension? On the influence of mind wandering and executive attention. *Journal of Experimental Psychology: General*, *141*(2), 302–320. http://doi.org/10.1037/a0025250

Ntim, S. K. (2015). Comprehension skill differences between proficient and less proficient reader in word-to-text integration processes: implications for interventions for students with reading problems. *International Journal of Learning, Teaching and Educational Research*, *13*(3), 41–61.

Öquist, G., & Lundin, K. (2007). Eye movement study of reading text on a mobile phone using paging, scrolling, leading, and RSVP. *Proceedings of the 6th International Conference on Mobile and Ubiquitous Multimedia - MUM ’07*, 176–183. http://doi.org/10.1145/1329469.1329493

Patberg, J. P., & Yonas, A. (1978). The effects of the reader’s skill and the difficulty of the text on the perceptual span in reading. *Journal of Experimental Psychology. Human Perception and Performance*, *4*(4), 545–52. http://doi.org/10.1037/0096-1523.4.4.545

Paterson, D. G., & Tinker, M. A. (1940). *How to make type readable.* New York: Harper and Row.

Pegrum, M., Oakley, G., & Faulkner, R. (2013). Schools going mobile: A study of the adoption of mobile handheld technologies in western australian independent schools. *Australasian Journal of Educational Technology*, *29*(1), 66–81. http://doi.org/10.1234/ajet.v29i1.64

Perfetti, C. (2007). Reading ability: lexical quality to comprehension. *Scientific Studies of Reading*, *11*(4), 357–383. http://doi.org/10.1080/10888430701530730

Perfetti, C., & Hart, L. (2001). The lexical basis of comprehension skill. In D. Gorfein (Ed.), *On the consequences of meaning selection: Perspectives on resolving lexical ambiguity* (pp. 67–86). Washington: American Psychological Association.

Perfetti, C., & Hart, L. (2002). The lexical quality hypothesis. In L. Verhoeven, C. Elbro, & P. Reitsma (Eds.), *Precursors of functional literacy* (pp. 67–86). Amsterdam: John Benhamins.

R Core Team. (2016). R: A language and environment for statistical computing. Vienna: R Foundation for Statistical Computing.

Rapp, D., & van den Broek, P. (2005). Dynamic text comprehension. *Current Directions in Psychological Science*, *14*(5), 276–279.

Rayner, K. (1986). Eye movements and the perceptual span in beginning and skilled readers. *Journal of Experimental Child Psychology*, *41*(2), 211–36.

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

Rayner, K. (2014). The gaze-contingent moving window in reading: Development and review. *Visual Cognition*, *22*(3–4), 1–17. http://doi.org/10.1080/13506285.2013.879084

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

Rayner, K., Schotter, E. R., Masson, M. E. J., Potter, M. C., & Treiman, R. (2016). So much to read, so little time: How do we read, and can speed reading help? *Psychological Science in the Public Interest*, *17*(1), 4–34. http://doi.org/10.1177/1529100615623267

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

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

Rothkopf, E. (1971). Incidental memory for location of information in text. *Journal of Memory and Language*, *10*(6), 608–613.

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

Smith, F. (1971). *Understanding Reading*. New York: Holt.

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

Stothard, S. E., Hulme, C., Clarke, P., Barmby, P., & Snowling, M. J. (2010). *YARC York Assessment of Reading for Comprehension: Passage Reading Secondary.* London: GL Assessment.

Tinker, M. A. (1965). *Bases for Effective Reading*. Minnesota: Minnesota Press.

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

van den Broek, P., Beker, K., & Oudega, M. (2015). Inference generation in text comprehension: automatic and strategic processes in the construction of a mental representation. In E. O’Brien, A. E. Cook, & R. F. Lorch (Eds.), *Inferences During Reading* (pp. 94–121). Cambridge: Cambridge University Press.

van den Broek, P., Mouw, J. M., & Kraal, A. (2016). Individual differences in reading comprehension. In P. Afflerbach (Ed.), *Handbook of Individual Differences in Reading* (pp. 138–150). Abingdon: Routledge.

van den Broek, P., Rapp, D., & Kendeou, P. (2005). Integrating memory-based and constructionist processes in accounts of reading comprehension. *Discourse Processes*, *39*(2), 299–316. http://doi.org/10.1207/s15326950dp3902&3\_11

van den Broek, P., & Young, M. (1998). The landscape model of reading: Inferences and the online construction of a memory representation. In H. van Oostendorp & S. R. Goldman (Eds.), *The construction of mental representations during reading* (pp. 71–98). Hove: Psychology Press.

Venkataraman, A., Lewis, P., Unsbo, P., & Lundström, L. (2017). Peripheral resolution and contrast sensitivity: Effects of stimulus drift. *Vision Research*, *133*, 145–149.

Verhoeven, L., & Perfetti, C. (2008). Advances in text comprehension: Model, process and development. *Applied Cognitive Psychology*, *22*(3), 293–301.

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

Walker, R., Bryan, L., Harvey, H., Riazi, A., & Anderson, S. J. (2016). The value of Tablets as reading aids for individuals with central visual field loss: An evaluation of eccentric reading with static and scrolling text. *Ophthalmic & Physiological Optics*, *36*(4), 355–512. http://doi.org/10.1111/opo.12296

Wallace, S., Clark, M., & White, J. (2012). “It”s on my iPhone’: attitudes to the use of mobile computing devices in medical education, a mixed-methods study. *BMJ Open*, *2*(4), e001099–e001099. http://doi.org/10.1136/bmjopen-2012-001099

White, S. J., Lantz, L., & Paterson, K. B. (2017). Spontaneous Rereading Within Sentences: Eye Movement Control and Visual Sampling. *Journal of Experimental Psychology: Human Perception and Performance*, *43*(2), 395–413.

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

Zechmeister, E., & McKillip, J. (1972). Recall of place on the page. *Journal of Educational Psychology*, *63*(5), 446–453.

**Tables**

Table 1. Composition of different question types for comprehension passages used.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Passage title** | **Literal questions** | **Inference questions** | **Summary (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 |

Table 2. Subgroup analysis\*.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  |  | **Static** | **Scroll fast** | **Scroll slow** |
| **Measure** |  | Group 1 | Group 2 | Group 1 | Group 2 | Group 1 | Group 2 |
| **Overall comprehension** | Mean (SE) | 66.53 (3.72) | 74.13 (3.39) | 46.76 (3.00) | 50.46 (4.13) | 55.15 (4.26) | 64.55 (2.83) |
|  | Group | F(1,28) = 2.98, *p* = 0.10 |  |  |  |
|  | Display type | F(2, 56) = 31.85, *p* < 0.001 |  |  |  |
|  | Group \* display type | F(2, 56) = 0.57, *p* = 0.57 |  |  |  |
| **Literal comprehension** | Mean (SE) | 67.43 (5.06) | 69.33 (5.46) | 48.95 (4.44) | 55.81 (6.41) | 63.62 (7.92) | 72.95 (3.10) |
|  | Group | F(1,28) = 1.30, *p* = 0.26 |  |  |  |
|  | Display type | F(2, 56) = 6.47, *p* = 0.003 |  |  |  |
|  | Group \* display type | F(2, 56) = 0.27, *p* = 0.76 |  |  |  |
| **Inferential comprehension** | Mean (SE) | 68.89 (6.22) | 77.78 (5.50) | 39.44 (4.84) | 52.22 (7.02) | 48.33 (8.30) | 52.78 (6.33) |
|  | Group | F(1,28) = 2.12, *p* = 0.16 |  |  |  |
|  | Display type | F(2, 56) = 12.05, *p* < 0.001 |  |  |  |
|  | Group \* display type | F(2, 56) = 0.24, *p* = 0.79 |  |  |  |
| **Summary score** | Mean (SE) | 65.68 (5.39) | 77.53 (3.86) | 48.57 (4.06) | 46.83 (5.04) | 55.13 (5.06) | 64.96 (5.46) |
|  | Group | F(1,28) = 1.95, *p* = 0.17 |  |  |  |  |
|  | Display type | F(2, 56) = 15.65, *p* < 0.001 |  |  |  |
|  | Group \* display type | F(2, 56) = 1.49, *p* = 0.23 |  |  |  |
| **Working memory** | Mean (SE) | 3.73 (0.21) | 3.73 (0.27) | 1.73 (0.15) | 1.80 (0.17) | 2.20 (0.11) | 2.40 (0.13) |
|  | Group | F(1,28) = 0.30, *p* = 0.59 |  |  |  |  |
|  | Display type | F(2, 56) = 71.09, *p* < 0.04 |  |  |  |
|  | Group \* display type | F(2, 56) = 0.18, *p* = 0.84 |  |  |  |

\*Group 1: at least 30wpm difference in speed between these faster scrolling and static text conditions; Group 2: participants with similar reading speeds for fast scrolling and static text.

**Figures**

Figure 1.Average number of words read per minute for each display type (text scrolling at the faster speed of ~240 wpm, scrolling at the slower speed of ~120 wpm, or presented as static paragraphs). Error bars show standard error here and in all following.

Figure 2. Average comprehension scores by display type: a) overall comprehension scores, b) literal questions only, c) inference-based questions only, d) summary only.

Figure 3. Average working memory capacity scores across the three types of text displays; pairwise comparisons showed all significantly different, fast vs. slow scrolling *t*(29) = 4.65, *p* < 0.001, fast scroll vs. static *t*(29) = 10.42, *p* < 0.001, slow scroll vs. static *t*(29) = 7.55, *p* < 0.001.