Revision submitted May 9th, 2015

A Further Look at Postview Effects in Reading:
An Eye-movements Study of Influences From the Left of Fixation

Timothy R. Jordan[1]

Victoria A. McGowan[2]

Stoyan Kurtev[2]

&

Kevin B. Paterson[2]

1. Department of Psychology, Zayed University, Dubai, UAE

2. College of Medicine, Biological Sciences and Psychology, University of Leicester, UK

Running title: Postview Effects in Reading

ABSTRACT

When reading from left to right, useful information acquired during each fixational pause is widely assumed to extend 14-15 characters to the right of fixation but just 3-4 characters to the left, and certainly no further than the beginning of the fixated word. However, this leftward extent is strikingly small and seems inconsistent with other aspects of reading performance and with the general horizontal symmetry of visual input. Accordingly, two experiments were conducted to examine the influence of text located to the left of fixation during each fixational pause using an eye-tracking paradigm in which invisible boundaries were created in sentence displays. Each boundary corresponded to the leftmost edge of each word so that, as each sentence was read, the normal letter content of text to the left of each fixated word was corrupted by letter replacements that were either visually similar or visually dissimilar to the originals. The proximity of corrupted text to the left of fixation was maintained at 1, 2, 3, or 4 words from the left boundary of each fixated word. In both experiments, relative to completely normal text, reading performance was impaired when each type of letter replacement was up to two words to the left of fixated words but letter replacements further from fixation produced no impairment. These findings suggest that key aspects of reading are influenced by information acquired during each fixational pause from much further leftwards than is usually assumed. Some of the implications of these findings for reading are discussed.

Key Words: Reading, perceptual span, eye-movements

Normal reading relies on making saccadic eye-movements along lines of text and ending each movement with a brief fixational pause, during which time information is acquired (for a review, see Rayner, 2009). However, the area of text from which the information acquired at each fixational pause actually influences reading (the *perceptual span*) appears to be quite limited. In particular, assessments of the perceptual span are typically obtained using eye-tracking techniques in which areas of text extending leftwards or rightwards from each point of fixation are displayed normally during reading while text outside these areas is deliberately corrupted (e.g., by substituting different letters for the originals). Since these techniques were first introduced (McConkie & Rayner, 1975, 1976), it has become reported as standard that the findings show that skilled reading of languages read from left to right (such as English) is influenced by information from an asymmetric area that extends 14-15 characters to the right of fixation but no more than 3-4 characters to the left, and certainly no further leftwards than the beginning of each fixated word. Indeed, this standard view continues to be reported widely in the literature (e.g., Blythe, 2014; Rayner, 2014; Rayner, Yang, Schuett, & Slattery, 2014; Veldre & Andrews, 2014; Risse, Hohenstein, Kliegl & Engbert, 2014; Yan, Zhou, Shu, & Kliegl, 2015), indicating that the perceptual span to the right of fixation is relatively large whereas the perceptual span to the left of fixation is strikingly small.

It seems likely that the rightward perceptual span for rightwards-read languages reflects forward-directed processes that are aligned to the general direction of reading (e.g., Jordan, Almabruk, Gadalla, McGowan, White, Abedipour, & Paterson, 2014; Paterson, McGowan, White, Malik, Abedipour, & Jordan, 2014; Pollatsek, Bolozky, Well, & Rayner, 1981).[1] Indeed, acquiring information from words to the right of each fixation is likely to be driven by attentional influences and by the importance of previews of words that have yet to be identified, both of which appear to contribute considerably to efficient and effective reading (e.g., Rayner, 2009). But the view that reading is influenced by information acquired from only 3-4 characters to the left of fixation and no further than the beginning of the fixated word is worthy of closer inspection. In particular, when considering the general properties of human vision, the visual system shows clear bilateral symmetry in the horizontal extent of visual input to the right and left of fixation, and this symmetry extends across the entire visual field (for reviews and discussion, see Jordan & Paterson, 2009, 2010; Jordan, Paterson, & Kurtev, 2009; Jordan, Paterson, & Stachurski, 2008, 2009). Consequently, although there is general agreement that the perceptual span extends rightwards for some distance, the same spatial extent of visual input that provides this rightward area of information during reading will also be available for providing information from text to the left of fixation. Moreover, it seems that information supporting the recognition of individual words to the left of fixation can be acquired from areas substantially further away than the 3-4 characters widely reported for the perceptual span. In particular, in a study investigating the recognition of single words at various distances from fixation, Jordan, Patching and Thomas (2003) presented words randomly at different locations to the right and left of a central fixation point. The random nature of the presentations helped avoid the systematic allocation of attentional resources to each location, left or right, and, crucially, an eye-tracker was used to control the location of each presentation precisely. In line with numerous other studies, words generally showed an identification advantage when presented to the right of fixation due to their projection to the language-dominant left hemisphere (for reviews, see Gazzaniga, 2000; Jordan, Patching, & Milner, 2000). However, identification was better than chance for words at all distances to the right *and* left of fixation, even at distances which, in the Jordan et al. study, corresponded to approximately 14 characters from fixation. Clearly, the task of single word recognition is different from reading a line of text (for discussions, see Jordan & Thomas, 2002) and, indeed, forward-directed attention and previews of upcoming text are likely to be components of the rightward extent of the perceptual span when reading (e.g., Rayner, 2009). Nevertheless, the findings of Jordan et al. and the general symmetrical nature of vision suggest that useful information may well be acquired during reading from words in locations much further to the left of fixation than is generally accepted.

At first sight, the notion of a much larger leftward perceptual span may seem odd because of the diminutive leftward perceptual span that has been reported as standard for many years in the literature. However, this standard view is actually based on only a small set of studies that addressed the influence of information from words to the left of fixation many years ago (McConkie & Rayner, 1975, 1976; Rayner, Well, & Pollatsek, 1980; Underwood & McConkie, 1985), and knowledge about the leftward extent of the perceptual span is still far from complete. For example, in the study by McConkie and Rayner (1975), the letter content of words outside a window of normal text was replaced during each fixational pause but the areas of replacement were symmetrical either side of fixation and so the role of text to the left of fixation required closer investigation. This was addressed in a follow-up study (McConkie & Rayner, 1976) where the area of replacement letters to the left was either 4 or 20 characters from fixation. No differences in performance were found between these two conditions, and this finding helped form the view that the perceptual span does not extend leftwards beyond 4 characters. But in contrast to the original study (McConkie & Rayner, 1975), all letter replacements in this follow-up study were selected specifically to be visually confusable with the original letters of words. So, without knowing what information is actually acquired from text to the left of fixated words during reading, it isn't clear that letters selected specifically to be visually confusable will be visually distinguishable from the leftward letters they replace. Moreover, it is well-established that the visual confusability of letters is heightened in words viewed away from fixation due to influences of crowding and retinal eccentricity (e.g., Pelli & Tillman, 2008), and the considerable vagaries of display quality and eye-tracking accuracy that were present at the time of these studies (for details, see McConkie & Rayner, 1975, 1976) are likely to have added to the problem of revealing the real leftward extent of the perceptual span.

Subsequently, when the leftward perceptual span was investigated by Rayner et al. (1980), normal letter content was replaced by *x*s and square-wave gratings, and normal text extended various distances to the left of the fixated word. The pattern of significant effects observed with these manipulations has been highly influential for the view that the leftward perceptual span does not extend beyond the beginning of the fixated word. But this study also showed that extending normal letter content further leftwards than this often produced additional (albeit non-significant) improvements in reading performance. Indeed, when normal letter content extended leftwards beyond the beginning of the fixated word, reading times and fixation durations were considerably reduced relative to when normal letter content extended just 3 characters to the left of fixation or only to the beginning of the fixated word. Finally, while the study by Underwood and McConkie (1985) is also cited frequently as a source of support for a small leftward perceptual span, the conditions actually used in this study make the leftward extent of the perceptual span difficult to determine. In particular, different-sized increments in normal text were made simultaneously to the left and right of fixation when reading, and the analyses reported prevent a clear indication of the influence of leftward text on performance. Indeed, very few significant effects generally are reported in this study and the conclusions drawn rely largely on visual inspection of the data, which creates further difficulties for an accurate interpretation of the findings. Consequently, although this small number of longstanding studies has provided vital contributions to knowledge of the perceptual span and are cited regularly to support the view that the perceptual span to the left of fixation is strikingly small, the findings these studies actually report do not preclude the possibility that key aspects of reading are influenced by information acquired from further to the left of fixation than is generally accepted.

Indeed, some support for the view that the perceptual span extends leftwards beyond the beginning of the fixated word can be found in a small number of more recent studies of reading. For example, Binder, Pollatsek, and Rayner (1999) changed the identity of a word after it had been passed by a saccade and was now to the left of fixation (see also Starr & Inhoff, 2004). Binder et al. found that although this change was only ever present to the left of the currently fixated word (and so further away than the widely accepted leftward extent of the perceptual span), reading performance was affected relative to when the identity of the word remained unchanged. In a similar vein, Rayner, Castelhano, and Yang (2009) studied the perceptual span of young and older adults by using rows of *x*s to replace words in a line of text. Compared to when only the fixated word was visible during each fixational pause, reading performance improved in both age groups when the word immediately to the left of the fixated word could also be seen. Most recently, Apel, Henderson, and Ferreira (2012) found that regression performance with normal text was disrupted when the letters of the word immediately to the left of each fixated word had been replaced. Thus, despite the widely-cited diminutive parameters of the leftward component of the perceptual span, some useful indications already exist to suggest that information from the word immediately to the left of a fixated word can influence reading performance.

The picture now developing, therefore, is of a perceptual span that is fundamentally different from that in which key aspects of reading are influenced by information acquired during each fixational pause from no further leftwards than the beginning of the fixated word. However, the extent of the leftward component of the perceptual span is still far from clear and, indeed, may extend further than the single word suggested by the more recent studies we have described. For example, in the study by Binder et al (1999), a word was changed as it was passed by a saccade and the subsequent fixation is likely to have fallen on the next word along. However, since determining the actual leftward extent of the perceptual span was not the focus of the study, the exact number of words present between the fixated word and the word that was changed was not controlled. Rayner et al (2009) did control this aspect of their study but only the letters of the word immediately to the left of the fixated word were replaced and influences of words further to the left of fixation were not investigated. Apel et al. (2012) replaced letters up to 2 words to the left of each fixation but found influences only for the word immediately to the left of the fixated word, and only for regressions. However, these findings were obtained using garden path sentences containing a syntactic anomaly part way through each sentence that was designed specifically to induce regressions to particular locations, and this constraint may have restricted the influences of leftward text. [2]

Against this background, the purpose of the present research was to throw new light on the extent of the area of text to the left of fixation from which information acquired at each fixational pause influences reading. To do this, we adopted the same logic and procedures as previous investigations of the perceptual span in order to now systematically corrupt the normal letter content of words at various distances to the left of each fixated word while sentences were read. This manipulation was achieved using the gaze-contingent boundary paradigm (see, e.g., Binder et al., 1999; Cutter, Drieghe, & Liversedge, 2014; Rayner, Castelhano, & Yang, 2010; Rayner, Schotter, & Drieghe, 2014; for a review, see Schotter, Angele, & Rayner, 2012) in which a series of invisible boundaries was created for each sentence display. Each boundary corresponded to the leftmost edge of each word in a sentence so that, as each sentence was read, the normal letter content of areas of text to the left of each fixated word was corrupted by letter replacements. Corrupted text extended from the beginning of each sentence up to one of four distances (1, 2, 3, or 4 words) from the left boundary of each fixated word (word n). In the n-1 condition, the letter content of all words from the beginning of the sentence was corrupted up to and including word n-1 (the word immediately to the left of the fixated word). In the n-2 condition, the letter content of all words from the beginning of the sentence up to and including word n-2 was corrupted, and so on for the n-3 and n-4 conditions. In this way, as each sentence was read, the proximity of corrupted text was always maintained at 1, 2, 3, or 4 words away from each fixated word, and so enabled the leftward extent of the area in which the properties of words influenced reading to be determined.

If the letter content of text to the left of fixated words influences reading, reading should be affected when this letter content is corrupted. More specifically, the leftward extent of this influence should be revealed by the distance from each fixated word (1, 2, 3, or 4 words) at which corrupted letter content affects reading performance. For example, if influences from text to the left of fixation extend no further than the beginning of each fixated word (as the widely reported view of the perceptual span assumes), normal reading performance should not be affected by the letter content of words at *any* distance to the left of fixated words. However, if leftward influences of letter content extend beyond the fixated word, increasing the distance from fixation at which corrupted letter content is present should reveal the extent of these influences. Of particular importance is that the symmetrical nature of vision and the acquisition of information from words displayed individually to the left of fixation (Jordan et al., 2003) suggest that useful information may be acquired during reading from words much further to the left of fixation than is widely accepted. But although some evidence exists to suggest that influences from words to the left of fixation can occur during reading (Apel et al., 2012; Binder et al., 1999; Rayner et al., 2009), the actual extent and nature of these influences are not clear and seem to involve only the word (n-1) immediately to the left of each fixated word. Accordingly, if influences from the letter content of text extend leftwards to word n-1 but no further, this limit should be confirmed by the present research. In contrast, if influences extend leftwards to words further away than n-1, the extent of these influences should be revealed.

Experiment 1

Two types of letter replacement were used. In one condition (visually similar), replacement letters were selected to have the same overall shape (ascender, descender, or neutral) as the letters they replaced but were not selected to be visually confusable with the originals (cf McConkie & Rayner, 1976). This avoided using replacements that were simply indistinguishable from the original letters in the text. In the other condition (visually dissimilar), replacement letters with a different shape (ascender, descender, or neutral) from the originals were used. Both types of replacement have been used extensively to investigate the rightward perceptual span (although the effects are rather mixed; see Rayner, 2009) but the effects of replacement-letter similarity on the leftward span are so far unknown. Accordingly, if the information provided by the letter content of words to the left of fixation corresponds to the overall shapes of letters, only replacement letters that corrupt the shapes of the original text should have an effect on normal reading performance. In contrast, if the information acquired from words to the left of fixation is sufficient to distinguish between letters of the same overall shape, both types of letter replacement should show effects on reading performance.

Method

Participants. Thirty six participants, aged 18-25, were recruited from the University of Leicester and local community. All participants were native speakers of English, were not fluent in a second language, and had normal or corrected to normal vision, as determined by Bailey-Lovie (Bailey & Lovie, 1980), ETDRS (Ferris & Bailey, 1996), and Pelli-Robson (Pelli, Robson, & Wilkins, 1988) assessments.

Design and Materials. The experiment was conducted using two separate letter replacement conditions. In one (visually similar), replacement letters had the same shapes as the originals they replaced (ascender, descender, or neutral). In the other (visually dissimilar), replacement letters had different shapes from the originals they replaced. For example, ascending letters (e.g., f) were replaced by letters with either a descending (e.g., g) or neutral (e.g., e) shape, neutral letters were replaced by letters with either an ascending or descending shape, and so on. To avoid cross-interference from each type of replacement, participants were randomly allocated to either the visually similar or visually dissimilar replacement condition, so that 18 participants took part in each replacement condition.

The experiment used a total set of 144 sentences, and each sentence was presented as a single line of text. Sentences were 54-68 characters in length, of various structures, and did not include any syntactically anomalous items. Sentences contained an average of 11.1 words (SD=1.2) and average word length was 4.6 characters (SD=0.7). For each participant, 80 sentences were selected pseudorandomly from the set of 144 and each of these 80 sentences was displayed in one of the 5 display conditions (normal, n-1, n-2, n-3, n-4), 16 sentences in each. For each participant, the 80 sentence displays were selected for each display condition using a pseudorandom process which ensured that each participant saw any sentence only once but which also ensured that all 144 sentences were shown equally often in each display condition across all participants, for each letter replacement condition (visually similar, visually dissimilar).

In the n-1 condition, all letters from the start of the sentence were replaced up to and including the word immediately to the left of the fixated word (n-1). In the n-2 condition, all letters from the start of the sentence were replaced up to and including word n-2 but no closer; and so on. An illustration of the types of displays used in the experiment are shown in Figure 1. All interword spaces were preserved in all conditions. Practice sentences were presented at the start of each session.

Figure 1 about here

Apparatus and Procedure. Sentences were displayed as black text on a white background in Courier font on a 19 inch monitor with a screen refresh rate of 120Hz, and 4 letters subtended approximately 1.25°. Eye movements were recorded using an Eyelink 2K eye-tracker, using the tower mount, with a spatial resolution of .01° and the position of each participant's right eye was sampled at 1000 Hz using corneal reflection and pupil tracking. An invisible boundary was located at each screen coordinate that corresponded exactly to the leftmost edge of each word in the sentence. As the eyes passed each invisible boundary, letters in all words at the required distance to the left of the invisible boundary were replaced. As with previous research using the boundary paradigm, letters were replaced during a saccade (when perception of visual information in reading is greatly suppressed; e.g., Ishida & Ikeda, 1989; Wolverton & Zola, 1983) so that the actual implementation of corrupted text was not apparent to participants. Given that an invisible boundary was present for every word in a sentence, replacement text could be displayed consistently at the appropriate number of words to the left of each fixated word. The time between crossing an invisible boundary and changing the sentence display was 5-9ms, as determined at the screen using an optical sensor and the BlackBox Toolkit (e.g., see Plant & Quinlan, 2013) and this is very similar to other studies using this technique (e.g., Binder et al., 1999; Cutter et al., 2014; Rayner et al., 2010, 2014). When a progressive saccade was made, the newly-fixated word, all letters at the appropriate distance to the left of this word, and all letters to the right, were displayed as normal.

When a regression was made, the display was changed in the same way as for progressive saccades, so that the newly-fixated leftward word, letters at the appropriate distance to the left of this word, and all letters to the right, were displayed as normal. To help determine that the change in letter content could not be detected when it was implemented during a saccade, an exploratory study was conducted in which the experimental displays were presented to a separate group of 6 participants from the same population as those taking part in the experiment. Participants were asked to read each line of text and to report if they could see any change in the display as it was made. At the end of the study, all participants reported that the implementation of these changes could not be detected.

At the beginning of the experiment, each participant was instructed to read normally and for comprehension. The eye-tracker was then calibrated. At the start of each trial, a fixation square (equal in size to 1 character) was presented at the left of the screen. Once the participant fixated this location accurately for 250 ms, a sentence was presented, with the first letter of the sentence replacing the square. Participants pressed a response key as soon as they finished reading each sentence. The sentence was then replaced by a comprehension question, to which participants responded. Calibration was checked between trials and the eye-tracker was recalibrated as necessary. When questioned at the end of the experiment, no participant indicated that they had noticed any change taking place when reading each line of text. To provide a comprehensive measure of the influence of leftward text on reading, reading performance was assessed by recording overall sentence reading time, mean fixation durations (the average length of fixational pauses), total number of fixations (the number of these fixational pauses), progressive saccade count (the number of forward movements in the text), regressive saccade count (the number of backward movements in the text), and the length of progressive and regressive saccades.

Results

Eye movement measures were analyzed using a linear mixed-effects model (Baayen, Davidson, & Bates, 2008) and the accuracy of responses to comprehension questions was analyzed using a logistic mixed-effects model (Jaeger, 2008) using R (R Development Core Team, 2013). The mixed effects model approach has advantages over other approaches based on more traditional Analyses of Variance by simultaneously taking account of the separate sources of error variance associated with participants and stimuli in the same model (for further discussion, see Baayen, 2008). Both models specified participants and stimuli as crossed random effects. Fixed factors were letter replacement condition (visually similar, visually dissimilar) and display type (normal, n-1, n-2, n-3, n-4), and contrasts were computed that compared the normal display condition with letter replacements at each offset from the fixated word. Models computed using log-transformed and untransformed eye movement data produced the same patterns of findings, and so findings are reported for the untransformed data. P-values for the eye movement data were estimated using posterior distributions for model parameters obtained by Markov chain Monte Carlo sampling (Baayen et al., 2008). For each measure of reading performance, a mean was calculated for each display type and these means are shown in Tables 1a and 1b. Participants showed high levels of sentence comprehension (>97% correct) and no differences in comprehension across display type (normal, n-1, n-2, n-3, n-4), all *z*s<1.4, all *p*s>.15, indicating that all types of display were processed normally.

Compared to normal text, reading times were longer for n-1, b=1042.68, SE=57.96, *t*=17.99, *p*<.001, and n-2, b=188.97, SE=57.98, *t*=3.26, *p*<.01, fixation durations were longer for n-1, b=13.83, SE=1.76, t=7.87, *p*<.001, and n-2, b=3.93, SE=1.75, *t*=2.24, *p*<.05, and number of fixations was greater for n-1, b=2.89, SE=.18, *t*=16.01, *p*<.001, and n-2, b=.52, SE=.18, *t*=2.87, *p*<.01. In addition, compared to normal text, more progressive saccades were made for n-1, b=1.36, SE=.11, *t*=12.77, *p*<.001, and n-2, b=1.36, SE=.11, *t*=2.38, *p*<.05, and more regressive saccades were made for n-1, b=1.35, SE=.10, *t*=14.02, *p*<.001, and n-2, b=.22, SE=.10, *t*=2.37, *p*<.05. Compared to normal text, progressive saccade length was shorter for n-1, b=.09, SE=.03, *t*=3.45, *p*<.001, and regressive saccade length was shorter for n-1, b=1.35, SE=.15, *t*=8.82, *p*<.001, and n-2, b=.62, SE=.15, *t*=4.08, *p*<.001. No other effects were reliable (all *p*s>.10). [3]

Discussion

The findings of Experiment 1 indicate that, in sharp contrast to the standard view of the leftward extent of the perceptual span, the area of text to the left of fixation from which information acquired at each fixational pause influences reading performance extends considerably further than the beginning of the fixated word. In particular, both letter-replacement conditions (visually similar, visually dissimilar) produced significant effects on reading time, fixation duration, number of fixations, number of progressive and regressive saccades, and regressive saccade length that extended two words to the left of the fixated word (n-2), and significant effects on progressive saccade length that extended one word to the left of the fixated word (n-1).

Experiment 2

To avoid contamination from accompanying changes made to other areas of text in a display, the procedure adopted in Experiment 1 used displays in which only the leftward area of each sentence was manipulated. This approach follows that of many previous investigations in which the rightward extent of the perceptual span was the focus of research (for a review, see Rayner, 2009). However, it could be argued that, over an experiment, this procedure may inspire an unnatural bias (e.g., attentional) towards areas of text to the left of fixation, which may then produce the effects we observed. Accordingly, we conducted a further experiment in which the same uncontaminated approach was maintained by using displays in which only the leftward area of text was manipulated but now these displays were randomly intermingled with an equal number of matched, filler displays in which only the rightward area of text was manipulated. If the findings showing a substantial leftward component of the perceptual span obtained in Experiment 1 were due to the exclusive use of leftward-manipulated displays, these effects should be absent in Experiment 2.

Method

Participants. Thirty six participants, aged 18-25, were recruited from the same population as Experiment 1 and screened in the same way. No participant had taken part in the previous experiment. As in Experiment 1, participants were randomly allocated to either the visually similar or visually dissimilar replacement condition, so that 18 participants took part in each condition.

Design, Materials, and Procedure. Experiment 2 used the same set of 144 sentences as Experiment 1, for both leftward- and rightward-manipulated displays. The replacement letters used in Experiment 2 followed the same procedures used in Experiment 1; namely, the shapes of replacement letters were either the same as or different from the originals. The boundary procedure for producing changes to the left of the fixated word in each experiment was also the same as in Experiment 1, and the procedure for producing changes to the right of the fixated word mirrored this approach exactly. Accordingly, in Experiment 2, sentences were displayed either entirely as normal or in one of 8 offset conditions: n-1, n-2, n-3, n-4, n+1, n+2, n+3, and n+ 4. The n-1, n-2, n-3, and n-4 conditions were identical to those of Experiment 1. In the n+1 condition, all letters from the end of the sentence up to and including the word immediately to the right of the fixated word (n+1) were replaced. In the n+2 condition, all letters from the end of the sentence up to and including word n+2 were replaced; and so on. For each participant, 16 sentences were shown in each of the 9 display conditions: normal, 4 leftward experimental displays, 4 rightward filler displays. Sentences were assigned pseudorandomly to each display condition for each participant so that each participant saw any sentence only once but all 144 sentences were shown equally often in each display condition across all participants for each letter replacement condition (visually similar, visually dissimilar). All remaining aspects of Experiment 2 were identical to those of Experiment 1. When questioned at the end of each experiment, no participant indicated that they had noticed any change taking place when reading each line of text.

Results

As in Experiment 1, eye movement measures were analyzed using a linear mixed effects model (Baayen et al., 2008) and the accuracy of responses to comprehension questions was analyzed using a logistic mixed-effects model (Jaeger, 2008) using R (R Development Core Team, 2013). Both models specified participants and stimuli as crossed random effects. Fixed factors were letter replacement condition (visually similar, visually dissimilar) and display type (normal, n-

1, n-2, n-3, n-4), and contrasts were computed that compared the normal display condition with letter replacements at each offset from the fixated word. Models computed using log-transformed and untransformed eye movement data produced the same patterns of findings, and so findings are reported for the untransformed data. P-values for the eye movement data were estimated using posterior distributions for model parameters obtained by Markov chain Monte Carlo sampling (Baayen et al., 2008). The means for all measures are reported in Tables 2a and 2b. Participants showed high levels of sentence comprehension (>96% correct) and there were no differences in comprehension across each display type (normal, n-1, n-2, n-3, n-4), *z*s<1.65, *p*s>.10, indicating that all types of display were processed normally.

For displays in which changes were made to the left of the fixated word, reading times were longer than normal for n-1, b=1086.50, SE=51.63, *t*=21.04, *p*<.001, and n-2, b=204.93, SE=51.63, *t*=3.97, *p*<.001, fixation durations were longer than normal for n-1, b=23.38, SE=1.87, *t*=12.50, *p*<.001, and n-2, b=8.98, SE=1.87, *t*=4.80, *p*<.001, number of fixations was greater than normal for n-1, b=2.77, SE=.17, *t*=16.71, *p*<.001, and n-2, b=.42, SE=.17, *t*=2.54, *p*<.05, and more progressive saccades than normal were made for n-1, b=1.32, SE=.10, *t*=13.62, *p*<.001, and n-2, b=.30, SE=.10, *t*=3.07, *p*<.01. In addition, compared to normal text, more regressive saccades were made for n-1, b=1.01, SE=.08, *t*=12.13, *p*<.001, progressive saccade length was shorter for n-1, b=.07, SE=.03, *t*=2.41, *p*<.05, and regressive saccade length was shorter for n-1, b = .71, SE=.13, *t*=5.48, *p*<.001. No other differences were reliable (all ps>.10).

The focus of this experiment was the leftward extent of the perceptual span but analyses of filler items were also conducted. These showed effects of letter corruption extending to n+1 and n+2, and this matches the extent of the rightward perceptual span reported in previous research (for reviews, see Rayner, 2009; Schotter et al., 2012). In particular, reading times were longer than with normal text for n+1, b=1115.93, SE=53.56, *t*=20.83, *p*<.001, and n+2, b=320.69, SE=53.61, *t*=5.98, *p*<.001, fixation durations were longer than normal for n+1, b=24.75, SE=1.82, *t*=13.53, *p*<.001, and n+2, b=5.76, SE=1.83, *t*=3.15, *p*<.01, and the number of fixations was greater than normal for n+1, b=2.04, SE=.17, t=17.49, p<.001, and n+2, b=.89, SE=.17, t=5.07, p<.001. Compared to normal text, more progressive saccades were made for n+1, b=2.14, SE=.11, t=19.81, p<.001, and n+2, b=.67, SE=.11, t=6.18, p<.001, more regressive saccades were made for n+1, b=.45, SE=.08, t=5.50, p<.001, progressive saccade length was shorter for n+1, b=.33, SE=.03, t=12.60, p<.001, and n+2, b=.13, SE=.03, t=5.07, p<.001, and regressive saccade length was shorter for n+1, b=.41, SE=.13, t=3.12, p<.01. Interaction effects with letter replacement condition (visually similar, visually dissimilar) occurred rarely and were observed only for fixation durations; for n+1, b=11.07, SE=3.66, t=3.03, p<.01, and n+2, b=10.79, SE=3.66, t=2.95, p<.01. In both cases, this was due to smaller effects for visually similar than visually dissimilar letter replacements. No other effects were reliable (all ps>.10).

Discussion

The findings of Experiment 2 showed again that key aspects of reading were influenced by replacement letters that were either visually similar or dissimilar to the originals located up to two words to the left of the fixated word. This underscores the findings of Experiment 1 that the area of text from which information acquired at each fixational pause influences reading extends leftwards considerably further than the beginning of the fixated word. Moreover, as the findings of Experiment 2 were obtained under conditions in which leftward and rightward manipulations of text were randomly intermingled, it seems unlikely that the leftward extent of the perceptual span shown by these findings (and, accordingly, by the findings of Experiment 1) was inspired by an unnatural bias towards areas of text to the left of fixation. Indeed, the finding that the extent of the widely-reported influence of rightward manipulations on reading was also obtained in Experiment 2 for displays in which the rightward area of text was manipulated provides an important indication that the general procedure of Experiments 1 and 2 is consistent with the wider body of research previously conducted on the parameters of the perceptual span.

Despite the addition of rightward displays in Experiment 2, the same leftward perceptual span as Experiment 1 was observed for five of the seven measures of reading performance used, and only the extent of influences on the number and length of regressive saccades was affected (changing from n-2 to n-1). It seems, therefore, that the influence of the leftward perceptual span on reading identified in this study is robust, and only a slight change was produced when leftward manipulations were used consistently in an experiment (Experiment 1), and then only for influences on oculomotor control of regressive saccades before a fixation was made. It may be the case, therefore, that influences of leftward text on decisions concerning the backward movement of the eyes are susceptible to variations in the areas of text that are manipulated in experiments. However, even for these influences, the leftward extent of the perceptual span that was observed consistently exceeded that reported as standard in the literature.

General Discussion

The major indication provided by the findings of this study is that changing the normal letter content of words to the left of fixation influenced reading performance even when this change was two words away from the fixated word. Thus, in contrast to the widely-adopted view that the perceptual span does not extend leftwards beyond the beginning of the fixated word, reading speed and major components of eye guidance were influenced by the properties of words located considerably further to the left during each fixational pause. Indeed, while any part of these words may influence reading, two words to the left of fixation extended, on average, more than 11 characters from the left boundary of fixated words, which is a distance considerably closer to the well-established rightward extent of the perceptual span than previously assumed.

The range of effects on performance that were observed suggest that the influences on reading produced by information acquired to the left of fixated words are not trivial. In particular, compared to normal text, corrupted letter content produced longer reading times, longer and more fixations, more regressive and progressive saccades, and shorter amplitudes for both types of saccade. Moreover, the quality of information acquired from these leftward words was sufficient not only to determine the overall shapes of letters (and, presumably therefore, the overall shapes of whole words) but also to differentiate between letters (and words) of the same shape. Indeed, reading time, which is often regarded as the most comprehensive measure of reading performance, was slowed substantially when the letter content of text two words away from the fixated word was replaced by letters matched to the shapes of the originals, suggesting that somewhat detailed information can be acquired from text to the left of fixation during reading and that this information influences reading performance.

The influence of text to the left of fixated words may play a number of important roles in reading. In particular, when considering the overall direction of reading from left to right, words to the left of each fixation are spatially well placed to help supplement information acquired previously from words as readers progress along a line. For example, although it is well established that, as English text is read, information is acquired from the fixated word and from text to the right (Rayner, 2009; Schotter et al., 2012), a progressive saccade may often be initiated before lexical processing of these words is completed, so that fixations shift before these word identities have been fully determined (e.g., Rayner & Duffy, 1986; Reichle, Liversedge, Pollatsek, & Rayner, 2009; Reichle, Rayner, & Pollatsek, 2003; Reichle, Tokowicz, Liu, & Perfetti, 2011). However, the findings obtained in the present study show that when a new rightward fixation is made, information from text to the left of fixation is still available to the reader and is well positioned to help complete or confirm the identification of words that have now been passed. Moreover, from the findings we report, these *postview* influences at each fixational pause are available from text up to two words to the left of the fixated word, and involve information about the overall shapes of letters (and words) as well as more detailed contributions.

The finding that reading is influenced by text up to two words to the left of the fixated word also provides important empirical support for suggestions that words passed by a forward saccade, and so which are now to the left of fixation, contribute cues to the location of each new fixation within the same line (e.g., Reichle et al., 2009). In a similar vein, other researchers (e.g., Kennedy, Brooks, Flynn, & Prophet, 2003) have proposed that maintaining a record of the identities of words passed by forward saccades helps assimilate information acquired at each new fixation with that acquired previously (see also Mitchell, Shen, Green, & Hodgson, 2008). Consequently, and in line with these views, corrupting the letter content of leftward text during a saccade (as in the present study) should increase the difficulty with which information acquired across successive fixations can be assimilated, and this is consistent with the increased reading time, the increased duration and frequency of fixational pauses, and the disruption to saccades that were observed in this study. But while some previous studies have suggested that *spatial memory* is available for words located several words to the left of the word currently fixated (e.g., Baccino & Pynte, 1994; Frazier & Rayner, 1982; Kennedy et al., 2003; but see Inhoff & Weger, 2005; Weger & Inhoff, 2007), our findings suggest that fluent reading and eye-movement behaviour are influenced by perceptual information that is acquired from up to two words to the left of fixation but no further (although it may be the case that information about interword spaces extends slightly further than this; see Jordan et al., 2013).

The findings of both experiments revealed influences not only on the duration and frequency of fixations but also on the frequency and targeting of saccades, indicating that the leftward letter content of text during fixational pauses affected decisions about where to move the eyes next. But although changes in letter content in these displays were made only to words in locations to the left of each fixation, both regressive *and* progressive saccades were affected. Indeed, the frequency of progressive saccades was affected in both experiments when replacement letters were one or two words to the left of the fixated word. Thus, information up to two words to the left of fixation influenced saccadic behaviour but this influence of leftward text was clearly not restricted to situations involving leftward eye movements. As a result, although it is well-established that changing letter content to the right of fixation disrupts normal forward progression through text (e.g., Rayner, 2009; Schotter et al., 2012; see also Experiment 2 of the present study), our findings show that forward progression is also disrupted by letter manipulations to the left of fixation, despite their “backwards” location. Accordingly, and following our previous arguments, a reader’s progression through text appears to be influenced not only by information falling to the right of fixation but also by information acquired during each fixational pause from text to the left of fixated words.

The finding that both regressive *and* progressive saccades were affected by text changes to the left of fixation suggest that influences of leftward text do not depend on leftward shifts of attention when reading, and this is supported by the saccadic behaviour observed when leftward and rightward manipulations of text were randomly intermingled in Experiment 2. In contrast, when influences of text to the left of fixation have been observed in other research, one indication is that these influences occur only with regressive saccades (Apel et al., 2012; see also Binder et al., 1999), and so may occur only when a greater allocation of attention has been made to the left of fixation prior to a saccade being made in that direction (although see Rayner et al., 2009). Thus, it seems that while some aspects of eye movement behaviors may be associated with shifts in attention, the influences of leftward letter content observed in the present study do not rely on such shifts.[4] Nevertheless, we wished to determine more clearly whether the influence of leftward text we observed relied at all on the incidence of leftward shifts in attention, and so looked more closely at a measure of reading performance that could reveal this influence; namely, fixation durations. To do this, analyses of fixation durations were conducted as previously in our study but these now excluded all fixations made immediately before a regressive saccade, when attention is likely to be directed leftwards. If effects of leftward text require leftward saccades, no effects of leftward text on fixation duration should be observed when these saccades were removed from the analyses. For Experiment 1, an ANOVA showed that fixation durations were longer than normal for n-1, $F(1,34)=63.37$, $p<.001$, $\eta_p^2=.65$, and n-2, $F(1,34)=5.44$, $p<.05$, $\eta_p^2=.14$, with no significant interactions, Fs<3.5, ps>.07. In a similar vein, for Experiment 2, fixation durations were also longer than normal for n-1, $F(1,34)=31.76$, $p<.001$, $\eta_p^2=.48$, and n-2, $F(1,34)=6.02$, $p<.05$, $\eta_p^2=.15$, with no significant interactions, Fs<2.5, ps>.07. These findings underscore the general indication provide by the present study (including the findings when filler displays were used in Experiment 2) that influences on reading behaviour produced by information acquired from leftward text at each fixational pause are extensive and do not rely on leftward shifts in attention.

The principal aim of this investigation of the leftward perceptual span was to shine new light on the extent to which reading is influenced by information acquired at each fixational pause from text to the left of fixation. To do this, we adopted the same logic as other studies that have used gaze-contingent displays and letter replacement to investigate effects of textual information to the right of fixation. In particular, when studies have found effects of letter replacement to the right of fixation, these studies have concluded, quite reasonably, that information acquired from these areas is normally used for reading, and information outside these areas is not. In a similar vein, the indication from the findings we report is that the area of text from which information acquired at each fixational pause influences reading extends up to two words to the left of fixation, and so extends considerably further than the beginning of the fixated word. But although substantial and closer in size to the rightward span than previously realised, it seems unlikely that this leftward area is used for reading in precisely the same way as text to the right of fixation. As we have already discussed, a major requirement of forward-directed processes that drive the progression of the eyes along a line of text is to obtain new information about words yet to be identified. Consequently, as part of this process, forward-directed attention and previews of upcoming text are important components of the rightward extent of the perceptual span (e.g., Rayner, 2009). In contrast, the requirements for reading placed on information from words to the left of fixation are likely to be rather different. In particular, leftward text may serve to provide information which helps complete lexical processing after a word has been passed, and maintains an important record of the identities and locations of words which, in turn, helps preserve the spatial and linguistic context of words as a line of text is read. Moreover, since attentional resources are likely to be assigned most often in the direction of reading, these roles of leftward text may generally operate in a more passive (non-attentive) way, but be available for attentional processing when required. For example, guidance of regressions generally is likely to benefit from maintaining information about the identities and locations of words in leftward text, but this textual information may also help attentional resources to be directed to a leftward location when making a regression to resolve a specific semantic or syntactic anomaly (as in the study of Apel et al., 2012).

The findings of the research reported in this study provide a new perspective for understanding the role of information acquired during fixational pauses and for implementing this role in models of reading. Currently, two models of reading are widely referred to in the literature (EZ Reader, SWIFT) and both models provide frameworks for understanding how visual processing, word identification, and oculomotor control jointly determine when and where the eyes move during reading. For example, the E-Z Reader model (e.g., Pollatsek, Reichle, & Rayner, 2006; Reichle, Pollatsek, Fisher, & Rayner, 1998; Reichle, Pollatsek, & Rayner, 2006) is a serial-processing account that proposes that visual processing provides sensory information from across the page on each fixation. But the area of text from which information acquired at each fixational pause influences reading reflects the serial allocation of attention to words, coupled with the assumption that this produces asymmetry in the perceptual span which extends 14-15 characters to the right of fixation but leftwards no further than the beginning of the fixated word. In contrast, the SWIFT model is a parallel-processing account that contains capabilities for influences from postviewed text within its core principles (e.g., Engbert, Longtin, & Kliegl, 2002; Engbert, Nuthmann, Richter, & Kliegl, 2005) as processing can be distributed across several words at each fixation. Thus, according to this model, words to the right and left of fixation can be processed concurrently with words at fixation, and so information from text to the left of fixation can influence reading. However, when implementing the model (Engbert et al., 2005), the parameters used to define the leftward extent of the perceptual span have been motivated by the conventional view on rightward asymmetry, and the actual leftward extent of the perceptual span is determined to be no more than 5 letters, which is substantially less than indicated by the findings of the present study. Therefore, both these models provide important bases for accommodating influences from text to the left of fixation, but the influences on reading time, fixations, and saccadic behaviour revealed by the present research can now help these (and other) models capture more fully the influences of leftward text on human reading performance. In particular, as we have argued, leftward text may serve to provide information which helps complete lexical processing after a word has been passed, and maintains an important record of the identities and locations of words which, in turn, helps preserve the spatial and linguistic context of words as a line of text is read. While E-Z Reader will only rarely shift attention to the next word before lexical processing of the currently fixated word is completed, SWIFT does not have these restrictions. Indeed, in SWIFT, such a situation occurs whenever a neighboring word produces higher lexical activation and is likely to win the saccade target-selection competition. However, in SWIFT, fixation durations depend only on processing the fixated word (although more words are processed in parallel) and the remaining lexical activation for words to the left of fixation has no influence on SWIFT's fixation durations. The findings we report suggest that this may not be the case for human reading. Moreover, since attentional resources are likely to be assigned most often in the direction of reading, the roles of leftward text may operate in a more passive (non-attentive) way, but yet also be available for attentional processing when required (e.g., when guiding regressions). Indeed, while current eye movement models of provide good accounts of forward-directed eye movements, they don’t account well for regressions and re-reading. Following the findings we report in this study, further research can now address these issues more directly.

Finally, it should be emphasised that although previous research has led to the standard view that the leftward extent of the perceptual span does not extend beyond the left boundary of the fixated word, the actual evidence supporting this view is limited. In fact, and as we have described earlier in this article, the standard view is based on only a small set of studies conducted many years ago (McConkie & Rayner, 1975, 1976; Rayner et al., 1980; Underwood & McConkie, 1985) and the evidence they report concerning the leftward parameters of the span could not be regarded as conclusive. This is certainly not a criticism of the studies concerned, which have all provided crucial breakthroughs in our understanding of reading. But it does serve to show that, rather than contradicting a wealth of previous evidence supporting the diminutive leftward extent of the perceptual span, the findings we report in the present study address an important aspect of reading that has previously been under-investigated in the literature. Indeed, even when a number of more recent studies have shown that effects may extend leftwards to n-1 (Apel et al., 2012; Binder et al., 1999; Rayner et al., 2009), these findings have been widely ignored in the literature, and even portrayed as possible anomalies (e.g., Rayner, 2014). But the findings we report now make the case emphatically for a sizable leftward component of the perceptual span when reading English. In particular, rather than readers relying on an area to the left of fixation that is remarkably small, these new findings reveal that the area of text from which the information acquired at each fixational pause influences reading extends up to two words to the left of fixated words, and so indicate a perceptual span that is more symmetrical than is generally reported and widely assumed.

Footnotes

1. It seems likely that this directional influence is reversed for languages read from right to left (e.g., Jordan, Almabruk, Gadalla, McGowan, White, Abedipour, & Paterson, 2014; Paterson, McGowan, White, Malik, Abedipour, & Jordan, 2014; Pollatsek, Bolozky, Well, & Rayner, 1981) although the precise parameters and nature of the left and right components of the perceptual span in such languages remain to be determined.

2. Although not directly related to the role of *words* to the left of fixation, the findings of a study by Jordan, McGowan, and Paterson (2013) are worthy of mention. In their study, Jordan et al. showed that reading is affected by interword spaces to the left of fixation, and that the effect of obscuring these spaces extends as far as 3 interword spaces (i.e., just over 2 words) to the left of each fixated word.

3. In line with previous research investigating the perceptual span, statistical analyses were conducted using data from across each entire sentence, even when replacement letters were not currently present on the screen (as in a regression to the start of a sentence). The benefit of this unrestricted approach is that it does not impose temporal restrictions on when the influence produced by replacement letters can occur as progressive and regressive eye movements are made along each line of text, and so provides a more comprehensive assessment of these influences. However, for completeness, analyses using data only from those points in each experimental display (n-1, n-2, n-3, n-4), and the same points in each associated normal display, at which replacement letters were actually present on the screen were also conducted for each experiment. For each experiment, these analyses showed the same pattern of effects as observed in the original, unrestricted analyses.

4. The findings of Apel et al. (2012) are particularly interesting because they show no influences of leftward text on progressive saccades, and this differs from the findings of the present study. However, the study by Apel et al. used sentences designed specifically to induce regressions by containing a deliberate syntactic anomaly part way through which altered the meaning of the overall

sentence. In contrast, the sentences used in the present study contained no syntactic anomalies, and this may explain the wider range of influences from leftward text that was observed.

Acknowledgements

This research was supported by the Ulverscroft Foundation and a Professorial Fellowship from the Economic Research Foundation awarded to Tim Jordan, and a Mid-Career Fellowship from the British Academy awarded to Kevin Paterson.

REFERENCES

Apel, J.K., Henderson, J.M., & Ferreira, F. (2012). Targeting regressions: Do readers pay attention to the left? *Psychonomic Bulletin & Review, 19*, 1108-1113.

Baayen, H.R. (2008). *Analyzing linguistic data: A practical introduction to statistics using R*. Cambridge University Press: Cambridge, UK.

Baayen, H.R., Davidson, D.J., & Bates, D.M. (2008). Mixed-effects modeling with crossed random effects for subjects and items. *Journal of Memory and Language, 59*, 390-412.

Baccino, T., & Pynte, J. (1994). Spatial coding and discourse models during text reading. *Language & Cognitive Processes, 9*, 143-155.

Bailey, I.L., and Lovie, J.E. (1980). The design and use of a new near-vision chart. *American Journal of Optometry and Physiological Optics, 57*, 378-387.

Binder, K.S., Pollatsek, A., & Rayner, K. (1999). Extraction of information to the left of the fixated word in reading. *Journal of Experimental Psychology: Human Perception and Performance, 25*, 1162-1172.

Blythe, H.I. (2014). Developmental changes in eye movements and visual information encoding associated with learning to read. *Current Directions in Psychological Science, 23*, 201-207.

Cutter, M.G., Drieghe, D., & Liversedge, S.P. (2014). Preview benefit in English spaced compounds. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 40*, 1778 - 1786.

Engbert, R., Longtin, A., & Kliegl, R. (2002). A dynamical model of saccade generation in reading based on spatially distributed lexical processing. *Vision Research, 42*, 621-636.

Engbert, R., Nuthmann, A., Richter, E., & Kliegl, R. (2005). SWIFT: A dynamical model of saccade generation during reading. *Psychological Review, 112*, 777-813.

Ferris, F.L., & Bailey, I.L. (1996). Standardizing the measurement of visual acuity for clinical research studies. *Ophthalmology, 103*, 181-182.

Frazier, L., & Rayner, K. (1982). Making and correcting errors during sentence comprehension:

Eye movements in the analysis of structurally ambiguous sentences. *Cognitive Psychology, 14*, 178-210.

Gazzaniga, M.S. (2000). Cerebral specialization and interhemispheric communication: Does the corpus callosum enable the human condition? *Brain, 123*, 1293-1326.

Inhoff, A.W., & Weger, U.W. (2005). Memory for word location during reading: Eye movements to previously read words are spatially selective but not precise. *Memory & Cognition, 33*, 447-461.

Ishida, T., & Ikeda, M. (1989). Temporal properties of information extraction in reading studied by a text-mask replacement technique. *Journal of the Optical Society A: Optics and Image Science, 6*, 1624-1632.

Jaeger, T.F. (2008). Categorical data analysis: Away from ANOVAs (transformation or not) and towards logit mixed models. *Journal of Memory and Language, 59*, 434-446.

Jordan, T.R., Almabruk, A.A.A., Gadalla, E.A., McGowan, V.A., White, S.J., Abedipour, L., & Paterson, K.B. (2014). Reading direction and the central perceptual span: Evidence from Arabic and English. *Psychonomic Bulletin & Review, 21*, 505-511.

Jordan, T.R., McGowan, V.A., & Paterson, K.B. (2013). What's left? An eye-movement study of the influence of interword spaces to the left of fixation during reading. *Psychonomic Bulletin & Review, 20*, 551-557.

Jordan, T.R., Patching, G.R., & Milner, A.D. (2000). Lateralized word recognition: Assessing the role of hemispheric specialization, modes of lexical access and perceptual asymmetry. *Journal of Experimental Psychology: Human Perception and Performance, 26*, 1192-1208.

Jordan, T.R., Patching, G.R., & Thomas, S.M. (2003). Assessing the role of hemispheric specialization, serial-position processing and retinal eccentricity in lateralized word perception. *Cognitive Neuropsychology, 20*, 49-71.

Jordan, T.R., & Paterson, K.B. (2009). Re-evaluating split-fovea processing in word recognition: A critical assessment of recent research. *Neuropsychologia, 47*, 2341-2353.

Jordan, T.R., & Paterson, K.B. (2010). Where is the evidence for split fovea processing in word recognition? *Neuropsychologia, 48*, 2782-2783.

Jordan, T.R., Paterson, K.B., & Kurtev, S. (2009). Re-evaluating split-fovea processing in word recognition: Hemispheric dominance, retinal location, and the word-nonword effect. *Cognitive, Affective, & Behavioral Neuroscience, 9*, 113-121.

Jordan, T.R., Paterson, K.B., & Stachurski, M. (2008). Re-evaluating split-fovea processing in word recognition: Effects of retinal eccentricity on hemispheric dominance. *Neuropsychology, 22*, 738-745.

Jordan, T.R., Paterson, K.B., & Stachurski, M. (2009). Re-evaluating split-fovea processing in word recognition: Effects of word length. *Cortex, 45*, 495-505.

Jordan, T.R., & Thomas, S.M. (2002). In search of perceptual influences of sentence context on word recognition. *Journal of Experimental Psychology: Learning, Memory and Cognition, 28*, 34-45.

Kennedy, A., Brooks, R., Flynn, L.-A., & Prophet, C. (2003). The reader's spatial code. In J. Hyönä, R. Radach, & H. Deubel (Eds.), *The mind's eye: Cognitive and applied aspects of eye movement research (pp. 193–212)*. Oxford: Elsevier.

McConkie, G.W., & Rayner, K. (1975). The span of the effective stimulus during a fixation in reading. *Perception & Psychophysics, 17*, 578-586.

McConkie, G.W., & Rayner, K. (1976). Asymmetry of the perceptual span in reading. *Bulletin of the Psychonomic Society, 8*, 365-68.

Mitchell, D.C., Shen, X., Green, M.J. & Hodgson, T.L. (2008). Accounting for regressive eye-movements in models of sentence processing: A reappraisal of the Selective Reanalysis hypothesis. *Journal of Memory and Language, 59*, 266-293.

Paterson, K.B., McGowan, V.A., White, S.J., Malik, S., Abedipour, L., & Jordan, T.R. (2014). Reading direction and the central perceptual span in Urdu and English. *PLoS ONE, 10.1371/journal.pone.0088358*.

Pelli, D.G., Robson, J.G., Wilkins, A.J. (1988). The design of a new letter chart for measuring contrast sensitivity. *Clinical Vision Science, 2*, 187-199.

Pelli, D.G., & Tillman, K.A. (2008). The uncrowded window of object recognition. *Nature Neuroscience, 11*, 1129-1135.

Plant, R.R. & Quinlan, P.T. (2013). Could millisecond timing errors in commonly used equipment be a cause of replication failure in some neuroscience studies*?* *Cognitive, Affective, & Behavioral Neuroscience*, *13*, 598-614.

Pollatsek, A., Bolozky, S., Well, A.D., & Rayner, K. (1981). Asymmetries in the perceptual span for Israeli readers. *Brain and Language, 14*, 174-180.

Pollatsek, A., Reichle, E.D., & Rayner, K. (2006). Tests of the E-Z Reader model: Exploring the interface between cognition and eye-movement control. *Cognitive Psychology, 52*, 1-56.

R Development Core Team. (2013). *R: A language and environment for statistical computing*. R Foundation for Statistical Computing. Available from: http://www.r-project.org.

Rayner, K. (2009). The Thirty Fifth Sir Frederick Bartlett Lecture: Eye movements and attention during reading, scene perception, and visual search. *Quarterly Journal of Experimental Psychology, 62*, 1457-1506.

Rayner, K. (2014). The gaze-contingent moving window in reading: Development and review. *Visual Cognition, 22*, 242-258.

Rayner, K., Castelhano, M.S., & Yang, J. (2009). Eye movements and the perceptual span in older and younger readers. *Psychology and Aging*, *24*, 755-760.

Rayner, K., Castelhano, M.S., & Yang, J. (2010). Preview benefit during eye fixations in reading for older and younger readers. *Psychology and Aging*, *25*, 714-718.

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

Rayner, K., Schotter, E.R., & Drieghe, D. (2014). Lack of semantic parafoveal preview benefit in reading revisited. *Psychonomic Bulletin & Review, 21*, 1067-1072.

Rayner, K., Well, A.D., & Pollatsek, A. (1980). Asymmetry of the effective visual field in reading. *Perception & Psychophysics, 27*, 537-544.

Rayner, K., Well, A.D., Pollatsek, A., & Bertera, J.H. (1982). The availability of useful information to the right of fixation in reading. *Perception & Psychophysics, 31*, 537-550.

Rayner, K., Yang, J., Schuett, S., Slattery, T.J. (2014). The effect of foveal and parafoveal masks on the eye movements of older and younger readers. *Psychology and Aging, 29*, 205-212.

Reichle, E.D., Liversedge, S.P., Pollatsek, A., & Rayner, K. (2009). Encoding multiple words simultaneously in reading is implausible. *Trends in Cognitive Sciences, 13*, 115-119.

Reichle, E.D., Pollatsek, A., Fisher, D.L., & Rayner, K. (1998). Towards a model of eye movement control in reading. *Psychological Review, 105*, 125-157.

Reichle, E.D., Pollatsek, A., & Rayner, K. (2006). E-Z Reader: A cognitive-control, serial attention model of eye-movement control during reading. *Cognitive Systems Research, 7*, 4-22.

Reichle, E.D., Rayner, K., & Pollatsek, A. (2003). The E-Z Reader model of eye-movement control in reading: Comparisons to other models. *Behavioral and Brain Sciences, 26*, 445-526.

Reichle, E.D., Tokowicz, N., Liu, Y., & Perfetti, C.A. (2011). Testing an assumption of the E-Z Reader model of eye-movement control during reading: Using event-related potentials to examine the familiarity check. *Psychophysiology, 48*, 993-1003.

Risse, S., Hohenstein, S., Kliegl, R., & Engbert, R. (2014). A theoretical analysis of the perceptual span based on SWIFT simulations of the n + 2 boundary paradigm. *Visual Cognition, 22*, 283-308.

Schotter, E.R., Angele, B., & Rayner, K. (2012). Parafoveal processing in reading. *Attention Perception & Psychophysics, 74*, 5-35.

Starr, M.S., & Inhoff, A.W. (2004). Attention allocation to the right and left of a fixated word: Use of orthographic information from multiple words during reading, *European Journal of Cognitive Psychology, 16*, 203-225.

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

Veldre, A., & Andrews, S. (2014). Lexical quality and eye movements: Individual differences in the perceptual span of skilled adult readers. *The Quarterly Journal of Experimental Psychology, 67*, 703-727.

Weger, U.W., & Inhoff, A.W. (2007). Long-range regressions to previously read words are guided by spatial and verbal memory. *Memory & Cognition, 35*, 1293-1306.

Wolverton, G.S., & Zola, D. (1983). The temporal characteristics of visual information extraction during reading. In K. Rayner (Ed.), *Eye movements in reading: Perceptual and language processes (pp. 41-52)*. New York: Academic Press.

Yan, M., Zhou, W., Shu, H., & Kliegl, R. (2015). Perceptual span depends on font size during reading of Chinese sentences. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 41*, 209-219.

Figure Legend

Fig. 1. An illustration of the types of display that were used to investigate the leftward extent of the perceptual span. The | symbol denotes the location fixated in this example (the symbol and the sentence are shown here for illustrative purposes and were not used in the experiment).

Figure 1

An example of visually-similar letter replacements

```
Normal    letters on the left of fixation are extremely useful for reading
                                   |
n-1       kahlozn eu bko hstl zd fixation are extremely useful for reading
                                   |
n-2       kahlozn eu bko hstl of fixation are extremely useful for reading
                                   |
n-3       kahlozn eu bko left of fixation are extremely useful for reading
                                   |
n-4       kahlozn eu the left of fixation are extremely useful for reading
                                   |
```

An example of visually-dissimilar letter replacements

```
Normal    letters on the left of fixation are extremely useful for reading
                                   |
n-1       akzoylh hj nsk xtuj ls fixation are extremely useful for reading
                                   |
n-2       akzoylh hj nsk xtuj of fixation are extremely useful for reading
                                   |
n-3       akzoylh hj nsk left of fixation are extremely useful for reading
                                   |
n-4       akzoylh hj the left of fixation are extremely useful for reading
                                   |
```

Table 1a: Eye Movement Measures for Each Display Condition Using Visually Similar Letter Replacements in Experiment 1.

			Replacement Condition		
	Normal	n-1	n-2	n-3	n-4
Reading time	2454 (113)	3749 (308)	2637 (137)	2565 (135)	2472 (119)
Fixation duration	236 (4)	253 (5)	239 (4)	237 (4)	236 (4)
Number of fixations	10.6 (.4)	14.1 (.8)	11.3 (.5)	10.7 (.5)	10.6 (.5)
Number of progressive saccades	7.4 (.3)	9.1 (.5)	7.7 (.3)	7.5 (.3)	7.4 (.3)
Number of regressive saccades	2.3 (.2)	2.5 (.3)	2.5 (.3)	2.3 (.3)	2.3 (.3)
Progressive saccade length	2.4 (.1)	2.2 (.1)	2.3 (.1)	2.4 (.1)	2.4 (1.)
Regressive saccade length	4.5 (.4)	3.0 (.3)	4.0 (.4)	4.4 (.5)	4.4 (.4)

Durations are in ms, lengths are in degrees, and Standard Errors of the Mean are in parentheses.

Table 1b: Eye Movement Measures for Each Display Condition Using Visually Dissimilar Letter Replacements in Experiment 1

		Replacement Condition			
	Normal	n-1	n-2	n-3	n-4
Reading time	2589 (182)	3379 (262)	2884 (213)	2606 (179)	2596 (184)
Fixation duration	244 (7)	255 (7)	251 (7)	248 (7)	244 (7)
Number of fixations	10.6 (.6)	12.9 (.8)	11.2 (.7)	10.6 (.6)	10.7 (.6)
Number of progressive saccades	7.6 (.4)	8.7 (.5)	8.0 (.4)	7.7 (.4)	7.7 (.4)
Number of regressive saccades	2.1 (.3)	3.2 (.4)	2.3 (.3)	2.0 (.3)	2.1 (.3)
Progressive saccade length	2.4 (.1)	2.2 (.1)	2.3 (.1)	2.4 (.1)	2.4 (.1)
Regressive saccade length	4.1 (.4)	2.9 (.3)	3.5 (.4)	4.3 (.4)	4.4 (.4)

Durations are in ms, lengths are in degrees, and Standard Errors of the Mean are in parentheses.

Table 2a: Eye Movement Measures for Each Display Condition Using Visually Similar Letter Replacements in Experiment 2.

		Replacement Condition							
	Normal	n-1	n-2	n-3	n-4	n+1	n+2	n+3	n+4
Reading time	2573 (195)	3656 (297)	2736 (233)	2688 (117)	2569 (219)	3723 (337)	2955 (324)	2754 (242)	2731 (239)
Fixation duration	241 (4)	261 (6)	247 (5)	244 (4)	243 (5)	260 (6)	245 (5)	242 (5)	240 (5)
Number of fixations	11.0 (.6)	13.8 (.8)	11.3 (.7)	11.1 (.7)	11.0 (.7)	14.2 (.9)	12.2 (1.1)	11.4 (.7)	11.3 (.7)
Number of progressive saccades	7.5 (.4)	9.0 (.5)	7.8 (.4)	7.6 (.4)	7.4 (.4)	9.6 (.5)	8.3 (.6)	7.8 (.4)	7.7 (.4)
Number of regressive saccades	2.0 (.3)	2.9 (.4)	2.2 (.4)	2.2 (.3)	1.9 (.3)	3.9 (.4)	2.4 (.3)	2.4 (.3)	2.3 (.3)
Progressive saccade length	1.6 (1)	1.5 (.1)	1.6 (.1)	1.6 (.1)	1.6 (1.)	1.3 (.1)	1.5 (.1)	1.6 (.1)	1.6 (1.)
Regressive saccade length	3.0 (.2)	2.4 (.2)	3.0 (.3)	3.0 (.2)	3.3 (.3)	2.4 (.1)	2.8 (.2)	2.8 (.2)	3.0 (.3)

Durations are in ms, lengths are in degrees, and Standard Errors of the Mean are in parentheses.

Table 2b: Eye Movement Measures for Each Display Condition Using Visually Dissimilar Letter Replacements in Experiment 2.

		Replacement Condition							
	Normal	n-1	n-2	n-3	n-4	n+1	n+2	n+3	n+4
Reading time	2073 (113)	3146 (171)	2326 (106)	2164 (120)	2116 (117)	3168 (142)	2331 (137)	2184 (106)	2143 (121)
Fixation duration	247 (8)	273 (8)	259 (6)	250 (7)	251 (6)	277 (7)	257 (7)	252 (7)	249 (6)
Number of fixations	8.9 (.4)	11.6 (.5)	9.5 (.4)	9.1 (.4)	8.8 (.4)	11.7 (.5)	9.4 (.4)	9.1 (.4)	9.0 (.4)
Number of progressive saccades	6.4 (.3)	7.6 (.3)	6.8 (.3)	6.5 (.3)	5.4 (.3)	8.5 (.3)	6.9 (.3)	6.6 (.3)	6.5 (.3)
Number of regressive saccades	1.5 (.3)	2.6 (.3)	1.6 (.3)	1.5 (.3)	1.4 (.3)	2.0 (.2)	1.6 (.2)	1.5 (.2)	1.4 (.2)
Progressive saccade length	2.1 (.1)	2.0 (.1)	2.1 (.1)	2.1 (.1)	2.1 (1.)	1.7 (.1)	1.9 (.1)	2.0 (.1)	2.0 (1.)
Regressive saccade length	3.2 (.2)	2.4 (.3)	3.3 (.3)	3.3 (.3)	3.4 (.3)	2.8 (.3)	3.5 (.3)	3.4 (.3)	3.2 (.3)

Durations are in ms, lengths are in degrees, and Standard Errors of the Mean are in parentheses.