Is Orthographic Information from Multiple Parafoveal Words Processed in Parallel: An Eye-tracking Study

Michael G. Cutter, Denis Drieghe, and Simon P. Liversedge

University of Southampton

Word Count: 14,385

Author Note

Michael G. Cutter, Denis Drieghe, and Simon P. Liversedge, School of Psychology, University of Southampton, Southampton, England.

Correspondence regarding this article should be addressed to Michael G. Cutter, School of Psychology, Shackleton Building, University of Southampton, Highfield Campus, Southampton SO17 1BJ. E-mail: M.G.Cutter@soton.ac.uk.

Abstract

In the current study we investigated whether orthographic information available from one upcoming parafoveal word influences the processing of another parafoveal word. Across two experiments we used the boundary paradigm (Rayner, 1975) to present participants with an identity preview of the two words after the boundary (e.g. *hot pan*), a preview in which two letters were transposed between these words (e.g. *hop tan*), or a preview in which the same two letters were substituted (e.g. *hob fan*). We hypothesized that if these two words were processed in parallel in the parafovea then we may observe significant preview benefits for the condition in which the letters were transposed between words relative to the condition in which the letters were substituted. However, no such effect was observed, with participants fixating the words for the same amount of time in both conditions. This was the case both when the transposition was made between the final and first letter of the two words (e.g. *hop tan* as a preview of *hot pan*; Experiment 1) and when the transposition maintained within word letter position (e.g. *pit hop* as a preview of *hit pop*; Experiment 2). The implications of these findings are considered in relation to serial and parallel lexical processing during reading.

Keywords; eye movements, reading, parafoveal processing, n+2 preview effects, letter migration effects.

Statement of Public Significance

The findings of the present study suggest that readers of English only process letter information from one word at a time. Participants did not read any faster when two letters had been swapped between two upcoming words prior to participants looking directly at them (e.g. *sit pea* instead of *sip tea*) than when these same two letters had been replaced with alternative letters (e.g. *six sea*). These findings demonstrate that the human language processing system tends to identify words one at a time in serial order, rather than identifying multiple words at the same time.

During reading visual information is simultaneously available from the fixated word, as well as several spatially adjacent words. As such, multiple words are available for processing during a single fixation. However, the manner in which readers make use of the parafoveal information is disputed, both in terms of the spatial extent of parafoveal processing, and the time course with which this processing takes place. According to the serial approach (Reichle, Liversedge, Pollatsek, & Rayner, 2009; Reichle, Rayner, & Pollatsek, 2003) only one word is processed at a time during reading, with the processing of subsequent words not beginning until the fixated word has been fully identified. In contrast, the parallel approach (Engbert, Nuthmann, Richter, & Kliegl, 2005; Schad & Engbert, 2012) proposes that several words around the point of fixation are processed simultaneously. These two approaches make differing predictions with regard to the number of words processed during a single fixation, and the time course of such processing.

One issue which is often not addressed in this debate is how the parallel lexical processing of multiple words may actually operate. Reichle et al. (2009) posed several problems that may arise during reading as a consequence of processing multiple words in parallel. One such issue relates to how orthographic information from multiple words would accurately lead to the activation and identification of each separate lexical item, rather than noisy activation distributed across multiple lexical entries and corresponding precisely to neither word. Reichle et al. argued that there are two levels of processing at which this could become problematic. The first is at the point of encoding the words, when focussed attention is likely to be necessary to bind the features of a visual object together; in the case of words, the constituent letters. Presumably, if attention was divided across multiple words then the letters of the words may not be adequately bound, and as such the activation caused by each letter may not be specific to a particular word. Furthermore, Reichle et al. made the point that most models of word identification involve the orthographic units of a word feeding activation into the lexicon, with these orthographic units causing activation at higher levels of representation. If orthographic units from more than one visually presented word caused activation in the lexicon simultaneously it is unclear what sort of mechanism would prevent the orthographic units of one word interfering with the processing of the other, and vice versa. An implication of both issues (the need to focus attention to bind the constituent letters of a word, and what happens if orthographic units from multiple words cause lexical activation at the same time) is that if two words were lexically processed in parallel then we may expect the orthographic units of one word to influence the processing of another. If evidence of this occurring was to be found it would constitute very strong support for the parallel processing of multiple words. In the current study we explore these issues by investigating whether orthographic information available from one parafoveal word affects the lexical processing of an adjacent parafoveal word.

Before proceeding to outline our own experiments, it is important to discuss how different approaches to lexical processing have been formalized in models of eye movement control, and how these approaches account for prior findings relating to the processing of parafoveal information. It is especially important to understand the parallel approach, with the current study aiming to find evidence in favor of this, and it is also necessary to understand the serial approach in terms of how it is able to explain prior findings that on the surface may already seem to constitute evidence in favor of parallelism.

One of the models that embodies the parallel processing approach is the SWIFT model (Engbert, Nuthmann, Richter, & Kliegl, 2005; Schad & Engbert, 2012). In SWIFT, a perceptual span around the point of fixation is determined by the processing load of the fixated word, with a less cognitively demanding word resulting in a broader perceptual span. The perceptual span will typically contain multiple words, with all of these words being processed in parallel. The serial position is implemented in the E-Z Reader model (Reichle, Pollatsek, & Rayner, 2006; Reichle, Rayner, & Pollatsek, 2003; Reichle, Warren, & McConnell, 2009). In this model lexical processing proceeds in two separate stages (L_1 and L_2). In the first stage (L_1) the orthographic familiarity of a word is assessed; in the second stage (L_2) the word is lexically accessed and its meaning is retrieved. Upon the completion of L_1 the oculomotor control system initiates the programming of a saccade to the next word (word *n*+1), while processing continues upon the fixated word (word *n*). Thus, the programming of a saccade and the later stages of lexical processing (L_2) occur concurrently. Upon word *n* being fully identified attention shifts to word *n*+1, and this word is processed in the parafovea until the saccade program is completed, at which point word *n*+1 is directly fixated. A further important feature of the E-Z Reader model to the current study is the pre-attentive visual processing stage, in which information from the entire visual field is passed to the brain in parallel, prior to attention being allocated to a single word. Due to these assumptions the two models make differing predictions with regard to the processing of parafoveal information.

The processing of parafoveal information during reading has primarily been investigated using the boundary paradigm (Rayner, 1975). In the boundary paradigm an invisible boundary is placed before a target word, and prior to the eye crossing this boundary there is either a correct or incorrect preview of the target word, which changes to the target word as the boundary is crossed (see Figure 1). This technique can be used to investigate a number of issues relating to the processing of parafoveal information, including the extent to which the characteristics of an upcoming word influence the processing of the fixated word, and the extent to which a word is processed prior to direct fixation. Both of these issues are relevant to the current study, and we will explore them in turn.

Parafoveal-on-foveal effects

The issue of whether the orthographic information which is available from one word in the perceptual span can influence the processing of a word that appears earlier in the perceptual span has previously been addressed in experiments investigating parafoveal-on-foveal effects (for a review, see Drieghe, 2011). Parafoveal-on-foveal effects occur when the characteristics of a parafoveal word (typically word *n*+1) affect fixation durations on word *n*. Such effects have been observed in relation to the orthography of an upcoming word, as might be expected in a parallel processing account according to the arguments of Reichle et al. (2009). Several studies have shown that orthographically illegal or unusual information at the start of a parafoveal word can influence fixation times on the foveal word (Drieghe, Rayner & Pollatsek, 2008; Inhoff, Starr, & Shindler, 2000). In these studies participants fixated a target word for longer when the parafoveal word was manipulated to be orthographically illegal (e.g. *pvxforming*) using the boundary paradigm, than when more typical information (e.g. *performing*) was presented. Furthermore, White (2008) observed inflated fixation times on a word when it was followed by an orthographically unfamiliar (e.g. *crypt*) relative to an orthographically familiar word (e.g. *adder*). It should be noted that these orthographic parafoveal-on-foveal effects are not always observed. For example, White and Liversedge (2006) found that participants did not fixate a target word for any longer when the following word was orthographically illegal (e.g. *pwrformer*) than when it was correct (e.g. *performer*). Nonetheless, it remains worthwhile considering whether these effects may be evidence for the parallel processing of multiple words within the perceptual span.

In addition to these detrimental effects of illegal orthographic information, research has demonstrated facilitative effects of parafoveal orthographic information on foveal word processing. Angele, Tran, and Rayner (2013) examined fixation durations on a target word (e.g. *news*) while using the boundary paradigm to manipulate the parafoveal word to be a repetition of the target (e.g. *news*), an orthographically similar non-word (e.g. *niws*), semantically related (e.g. *tale*), an orthographically dissimilar non-word (e.g. *tule*), or the post-boundary word itself (e.g. *once*). They found that readers fixated the target word for less time when it shared orthographic information with the parafoveal preview than in the other conditions (see also Dare & Shillcock, 2013; Inhoff, Radach, Starr, & Greenberg, 2000). Similarly, isolated word recognition studies have demonstrated facilitative effects of repeating the letters of a target word to either side (e.g. *RO ROCK CK*) on lexical decision times relative to a condition in which the target word was flanked by unrelated letters (e.g. *ST ROCK EN*) (Dare & Shillcock, 2013; Grainger, Mathôt, & Vitu, 2014).

These studies seem to suggest that it is indeed possible for orthographic information from one word to influence the processing of another, in a manner similar to what would be predicted for parallel processing according to the arguments of Reichle et al. (2009). Specifically, the facilitative effects of overlapping orthographic information documented above could be due to two sets of identical orthographic information being fed into the mental lexicon at once, leading to the increased activation of that word's orthographic representation, and thus the rapid identification of that word. If this were the locus of this effect, it would certainly suggest a level of parallel lexical processing. Presumably within this framework the inhibitory effects of illegal parafoveal orthographic information would be due to the unusual information being fed into the lexicon having an adverse effect upon attentional resources, and thus the processing of word *n*.

However, there is an alternative explanation for these effects which is in line with a serial processing model, rather than the parallel processing of multiple words. As stated earlier the E-Z Reader model includes a pre-attentive visual processing stage, in which all available visual information is processed in parallel. It has been proposed (Reichle, Pollatsek, & Rayner, 2006) that during this early stage of processing, unusual letter information may pop out due to its visual saliency, and interfere with normal processing. The manipulation of parafoveal information in all of the above studies involved the manipulation of visual (orthographic) configurations. In the case of the studies showing inhibitory parafoveal-on-foveal effects the letter sequences were highly unusual, and thus salient. In the studies showing facilitatory parafoveal-on-foveal effects the repetition of the same visual pattern in close proximity (a very rare occurrence during reading) was highly visually salient. Thus, current observations of orthographic information from one word influencing the processing of another are not necessarily evidence for multiple word forms feeding activation into the lexicon in parallel; rather, these effects may simply be due to the visually unusual nature of the manipulations used in these studies.[1] As such, a stronger test is required of the possibility that orthographic information from multiple words within the perceptual span is fed into the lexicon in parallel, and that the information from one word is able to influence the processing of another word. Furthermore, it is necessary for this test to avoid confounding this orthographic manipulation with increased visual saliency. In the current paper we present such a test across two experiments, by transposing an orthographic unit (i.e. letter) from one word in the parafovea with an orthographic unit from another word in the parafovea. Under the assumption that both of these parafoveal words are processed prior to fixation, and in parallel, we should observe an effect of this manipulation relative to a condition in which these orthographic units are simply replaced by unrelated ones. Thus, it is necessary to establish how prior research (and different theoretical approaches) suggests these two parafoveal words should be processed.

Preview benefits during reading

The boundary paradigm has more typically been used to examine the extent to which a word is processed prior to direct fixation, in terms of the way in which having a correct relative to incorrect preview of an upcoming target word will influence fixation durations on that word. Typically, participants will spend less time fixated on the target word given a correct rather than incorrect preview, an effect known as the preview benefit. In addition to a preview benefit being observed for a correct relative to incorrect preview, it is also reliably observed for previews that share an abstract characteristic such as orthographic, phonological, or semantic information with the target word (see Cutter, Drieghe, & Liversedge, 2015 for a recent review). Preview benefit effects demonstrate that the parafoveal word has been pre-processed, and has activated a candidate set of lexical items, the members of which are congruent with the available parafoveal information. It has long been uncontroversial that when the previewed word appears directly after the boundary (i.e. word *n*+1) participants reliably gain a preview benefit. Both serial and parallel approaches can account for this finding. According to E-Z Reader attention has shifted to word *n*+1 prior to a saccade being made, while in SWIFT word *n*+1 typically falls in the perceptual span and is thus processed prior to direct fixation.

More recent research has investigated whether a preview benefit is obtained when there is an additional word between the boundary and the target word (i.e. the preview manipulation occurs for word *n*+2). This question is viewed as a further testing ground on which to distinguish between serial and parallel approaches. In the E-Z Reader model word *n*+1 should not typically be identified prior to a saccade being made across the boundary, and thus a substantive preview of word *n*+2 should usually not be obtained. In SWIFT word *n*+2 should regularly fall into the perceptual span, and consequently a preview of this word should be obtained regularly from word *n*. As such, large and prevalent effects of an *n*+2 preview would be more in line with a parallel processing account than a serial processing account. However, research has shown that readers only obtain small preview benefits from word *n*+2, and only under restricted circumstances, such as when word *n*+1 is only three letters long (Angele & Rayner, 2011; Kliegl, Risse, & Laubrock, 2007; Radach, Inhoff, Glover & Vorstius, 2013; Risse & Kliegl, 2012; 2014), or when it forms a larger lexical unit with word *n*+1 (Cutter, Drieghe, & Liversedge, 2014). Effects have not been observed when word *n*+1 was longer than three letters (Angele, Slattery, Yang, Kliegl, & Rayner, 2008; Rayner, Juhasz, & Brown, 2007).

This pattern of results is actually compatible with both models. Within E-Z Reader a short word *n*+1 is easy to identify, allowing attention to shift to word *n*+2 prior to a saccade being made across the boundary (see Schotter, Reichle, & Rayner, 2014 for a simulation). Within SWIFT a longer word *n*+1 causes word *n*+2 to be further away from fixation, and thus less likely to fall into the perceptual span. Furthermore, even when it does fall within the perceptual span it is in lower acuity vision, and thus processed less efficiently. As such, efforts to distinguish between serial and parallel accounts of lexical processing through the investigation of *n*+2 preview effects have thus far been inconclusive, with it being unclear whether effects are due to the parallel processing of word *n*+1 and word *n*+2, or the serial processing of these words with the rapid identification of word *n*+1 from word *n*.

The current study

In summary, existing research on both *n*+2 preview benefits and orthographic parafoveal-on-foveal effects is unable to adequately discriminate between serial and parallel processing accounts. With regard to orthographic parafoveal-on-foveal effects it may be that unusual orthographic information in the parafovea is detected at a pre-attentive visual level, rather than that orthographic information from multiple words is being encoded and fed into the lexicon in parallel. In the case of *n*+2 preview effects it is possible that word *n*+1 is fully identified prior to a saccade being made from word *n,* thus leading to the processing of word *n*+2 as a result of a serial attention shift, as opposed to both word *n*+1 and *n*+2 being lexically processed at the same time. In the current paper we investigate both issues simultaneously, by using the boundary paradigm to examine whether orthographic information extracted from word *n*+1 while it is in the parafovea influences the processing of word *n*+2, and vice versa.

In both of our experiments participants received an identity preview of word *n*+1 and word *n*+2 (e.g. *hot pan*), a preview in which a letter had been transposed between these words (e.g. *hop tan*), or a preview in which the same two letters were substituted (e.g. *hob fan*). In Experiment 1 this manipulation always involved the final letter of word *n*+1 and the initial letter of word *n*+2, whereas in Experiment 2 the manipulation was always applied to the same letter position in each word (e.g. *pit hop* and *fit cop* as previews for *hit pop*). We hypothesized that if word *n*+1 and *n*+2 were processed in parallel we may observe a preview benefit for the condition in which letters had been transposed between words rather than substituted. We made this prediction on the basis that parallel processing accounts assume that *n*+2 preview effects are due to the processing of word *n*, *n*+1, and *n*+2 at the same time. Furthermore, the simplest explanation for facilitative orthographic parafoveal-on-foveal effects in a parallel approach is that they are due to the extraction of orthographic information from two spatially adjacent words in parallel, with both sets of orthographic information being fed into the lexicon at the same time. Following the arguments of Reichle et al. (2009), the orthographic information from one word would then influence the processing of the other word. If both of these related contentions are correct, it seems reasonable to propose that participants may gain a benefit from having correct letter identity information from both words in the parafovea, even if that orthographic information is not position specific. Furthermore, unlike studies that have previously observed facilitative orthographic parafoveal-on-foveal effects, our manipulation did not involve the use of visually salient stimulus patterns in the parafovea, and consequently any effects that might be observed could not be due to pre-attentive visual processing. Rather, our manipulation involved participants always viewing two orthographically legal and distinct words (as opposed to word *n*+1 being identical to word *n* as in Angele et al., 2013) in the parafovea. Thus, if we did observe a benefit of the transposition condition relative to the substitution condition, it could only be due to processing of word *n*+1 and word *n*+2 occurring in parallel. In contrast, a serial model would predict no differences between these two conditions, since the processing of information from word *n*+1 and word *n*+2 should be independent. Rather, a serial model would only predict a preview benefit of the identity condition relative to the two alternative preview types. It should, however, be noted that a null effect of our transposition relative to substitution preview would not necessarily provide evidence against parallel lexical processing, so much as a lack of support for this specific position.

Experiment 1

Our parafoveal preview manipulation in Experiment 1 involved making a transposition between the final letter of word *n*+1 and the initial letter of word *n*+2, such that the transposed letter preview for the target words *hot pan* would be *hop tan*, with a substitution preview of *hob fan*. Word *n*+1 was always three letters long, while word *n*+2 could either be three or four letters long. As such, our manipulation was always made between the third and fifth character beyond the end of word *n* (the space after word *n+1* being the fourth character). Furthermore, word *n*+1 was the same length as in prior studies demonstrating *n*+2 preview effects (e.g. Risse, Kliegl, & Laubrock, 2007). The previews always formed two new words, as opposed to non-words. This approach was taken due to the fact that prior research has shown that people do not process word *n*+2 when word *n*+1 is a non-word (Angele & Rayner, 2011). As such, every precaution was taken to ensure that word *n*+2 should typically have been processed from word *n*, regardless of whether this was due to the parallel processing of multiple words or a serial attention shift towards it.

There are obvious parallels of our manipulation in Experiment 1 with the transposed letter effect in word identification (see Frost, 2015 for a recent review and discussion). The transposed letter effect refers to a phenomenon whereby either a prime (e.g. see Perea & Lupker, 2003) or parafoveal preview of a target word (e.g. *judge*) in which two letters are transposed (e.g *jugde*) leads to faster recognition times for the target word than a preview in which the same letters have been substituted (e.g. *jupte*). While we did not set out to specifically investigate the transposed letter effect so much as the processing of multiple words in the parafovea, there are some findings from this literature that are briefly worth discussing in relation to our own study.[2] First, several prior studies have shown that readers gain a greater parafoveal preview benefit from a transposed letter preview relative to a substituted letter preview (Johnson, 2007; Johnson & Dunne, 2012; Johnson, Perea, & Rayner, 2007; Pagán, Blythe, & Liversedge, 2016). Of particular relevance to the current experiment is that Johnson (2007) observed these effects when applying the manipulation to the third and fifth letter in a parafoveal preview of a target word, such that the word *forest* would receive shorter fixations given the parafoveal preview *fosert* as opposed to *fonewt*. In the current experiment our manipulation was always made between these same two letter positions in the parafovea, albeit across a space, rather than within a word. Thus, within a situation in which the parallel processing of letters is uncontroversial prior research suggests that correct letter identity information in the parafovea can provide a preview benefit, even when these letters have been transposed across two character spaces. Clearly, Johnson's study suggests that readers are generally capable of detecting a manipulation of the magnitude used in the current experiment. Furthermore, Johnson and Dunne (2012) observed a transposed letter preview benefit when using words as the previews (e.g. *calm* as a transposition preview of *clam*, with *chum* as a substitution preview), rather than non-word previews, indicating that using words as previews in the current study should not prevent the observation of a transposed letter effect. Thus, any failure to observe an effect in the current experiment would most likely be a result of the way in which people process parafoveal information across two words, relative to within one word.

It is also worth considering whether transposed letter effects occur when the transposition is made between morphemes, with this manipulation representing a middle ground between within word transpositions, and our between word manipulation. In one study Christianson, Johnson, and Rayner (2005) presented participants with a masked prime of an unspaced compound word (e.g. *sunshine*) which was identical to the target, a prime in which a transposition had been made within a morpheme (e.g. *sunhsine*), a prime in which a transposition had been made between two morphemes (e.g. *susnhine*), or a prime in which a single letter had been substituted (e.g. *sunsbine*). While a letter transposition within a morpheme was facilitative relative to the substitution, this was not the case when the transposition was made between morphemes. Thus, this study suggests that even when there is no space, transposition effects do not occur between lexical units. In a more recent study Stites, Federmeier, and Christianson (2016) embedded compound words in a sentence, and either presented these words correctly (e.g. *cupcake*), with a letter transposed within a morpheme (e.g. *cupacke*), or a letter transposed between morphemes (e.g. *cucpake*). The letter transpositions remained even upon direct fixation. Participants read these sentences while having their eye movements monitored, and there was no greater increase in fixation times on the target word when a transposition was made across a morpheme boundary than within a morpheme. While there was no substitution condition in this study, these effects suggest that during natural reading the effect of letter transpositions are not modulated by morpheme or lexeme boundaries. Thus, prior research does suggest that, during natural reading, transposed letter effects are not modulated by morpheme boundaries, although at some point further research may be necessary to test whether this is the case for compound words in the parafovea. However, for now we will proceed under the assumption that during natural reading transposition effects are not necessarily constrained by lexical boundaries, and as such we may observe a benefit of transposing a letter between two parafoveal words, as opposed to substituting these letters.

Method.

Participants. 48 native English speakers with normal or corrected to normal vision participated. An additional 13 participants were tested but removed from the analysis due to noticing more than five display changes. Participants were rewarded with research credits or £4.50.

Apparatus. An SR Research Eyelink 1000 system with a sampling rate of 1000 hertz was used to track participants' eye movements. Sentences were displayed on a single line of a ViewSonic P227f 20 inch CRT monitor with a grey background, running at a refresh rate of 75 hertz.[3] Viewing distance was 70cm, with 1° of visual angle containing 3.2 characters of monospaced courier font.

Materials and Design. Forty-five pairs of words from which two new words could be created by both transposing and substituting the final and initial letter of the first and second words were embedded into sentences. The first word was always three-letters long, and the second either three- of four-letters long. The two target words were embedded beyond an invisible boundary, as word *n*+1 and word *n+2*, and had their parafoveal previews manipulated. Participants received either a correct preview (e.g. *hot pan*), a transposed letter preview (e.g. *hop tan*), or a substituted letter preview (e.g. *hob fan*). An example of the stimuli can be seen in Figure 1, and all items are listed in Appendix A

We faced a large level of constraint when preparing our stimuli. This was due to the fact that we needed to find pairs of words that fit into a sentential context, could be changed into a new pair of words via a single letter transposition, and changed into a further pair of words by substituting the same letters. Due to this, it was not always possible to closely match all three preview types on all possible characteristics for both word *n*+1 and word *n*+2. However, at a minimum it was necessary to ensure that no significant differences were present between the transposition and substitution conditions. In order to ensure that this was not the case we obtained various norms from the SUBTLEX corpus (Brysbaert & New, 2009) which is part of the English Lexicon Project (Balota et al., 2007). We conducted a paired t-test of the preview log frequency per million between the transposition (*n*+1 mean = 2.75, *n*+2 mean = 2.71) and substitution conditions (*n*+1 mean = 2.89, *n*+2 mean = 3.23). No significant differences were present for either the word *n*+1 preview (t (44) = -1.05, p = .30) or the word *n*+2 preview (t (44) = -1.38, p = .17). We also assessed whether our transposed letter previews differed from our substituted letter previews in terms of bigram frequency (*n*+1 transposition mean = 3192, substitution mean = 3108; *n*+2 transposition mean = 3215, substitution mean = 3286) and number of orthographic neighbors (*n*+1 transposition mean = 19.87, substitution mean = 18.87; *n*+2 transposition mean = 16.07, substitution mean = 16.93). There were no significant differences between the transposed letter and substituted letter previews in mean bigram frequency (word *n*+1 t (44) = 0.20, p = .84, word *n*+2 (t (44) = -0.48, p = .63) or number or orthographic neighbors (word *n*+1 t (44) = 1.27, p = .21, word *n*+2 t (44) = -1.40, p = .17).

Furthermore, Schotter and Jia (2016) recently demonstrated that the plausibility of a parafoveal preview influences the size of the preview benefit. Therefore, it is important to ensure that there were no significant differences in how plausible each preview type was. We checked this by having 54 participants rate our sentences up to and including either word n+1 or word n+2. Participants were instructed to “read the beginning of 78 sentences one by one and rate how plausible each sentence sounds on a scale of 1 to 5, with 1 being very plausible and 5 being completely implausible. It is important to remember that these are not complete sentences, and so your task is to judge how plausible they sound up to a certain point, and how plausibly you think the sentence could be completed.” A paired t-test conducted on the average rating for each item showed that there was no plausibility difference between the substitution and transposition preview for either word *n*+1 (t (44) = -0.92, p = .36; transposition mean = 3.10, substitution mean = 3.00) or word *n*+2 (t (44) = -0.40, p = .69; transposition mean = 3.30, substitution mean = 3.25). Also, 64 participants completed a cloze task. Twenty-five of these participants predicted word *n*+1 given the sentence up to and including word *n*. The cloze probability of word *n*+1 was negligible, with participants predicting the identity preview 5.3% of the time, the transposition preview 1.2% of the time, and the substitution preview 0% of the time. We also had 39 participants predict word *n*+2 given one of the three possible *n*+1 previews. The cloze probabilities were again very low, with 7.4%, 0%, and 0% of completions being the identity, transposition, and substitution *n*+2 given the identity *n*+1, 2.6%, 0%, and 0% of completions being the identity, transposition, and substitution *n*+2 given the substitution preview of word *n*+1, and 3.9%, 0%, and 0.2% of completions being the identity, transposition, and substitution *n*+2 given the transposition preview of word *n*+1. Altogether, our stimuli were well-matched, with no significant differences between the two incorrect preview conditions.

Procedure. Participants were presented with an information sheet and consent form upon arrival. A head rest was used to stabilize the reader in front of the eye tracker. A three-point horizontal calibration grid was used, with an acceptance criterion of an average error below 0.33 degrees.

Each trial began with a central drift check followed by a gaze-contingent fixation cross in the position of the first character. The participant was re-calibrated if the cross did not trigger or the drift correct returned a value greater than 0.33 degrees. The participant was also re-calibrated at regular intervals. When the cross triggered a sentence appeared. Participants read for comprehension, and pressed a button once they had read each item. There were eight practice trials. The forty-five experimental items were mixed in with 64 filler items, 40 of which were part of another gaze-contingent study. On one third of the trials participants were shown a yes/no comprehension question, and answered using a game controller. Across all participants 94% of the questions were answered correctly. The experiment took approximately 30 minutes. At the end of the session participants were asked if they had noticed anything unusual. Regardless of whether participants initially responded with an affirmative answer their response was followed up by more specific questions about whether they had noticed any flashes on the screen or words seeming to change as they read. If a participant had noticed any display changes they were asked to estimate how many trials this had occurred on. In general, participants did not detect the display changes, although as mentioned above some participants reported noticing more than five; we excluded the data from these participants.

Results

Prior to analyzing our data we removed any fixations above 800ms, and merged any fixations below 80ms with any fixation less than 0.5 degrees of visual angle away, or any fixations below 40ms with any fixation within 1.25 degrees of visual angle. Trials in which the participant blinked while fixated on a critical region were excluded, as well as trials in which the display change executed early or more than 10ms after fixation onset on a post-boundary word (see Slattery, Angele, and Rayner, 2011). Altogether these exclusions accounted for 28% of the data. Finally, for each measure we removed any observations that were more than 3 standard deviations from the grand mean; while the amount of data removed due to this criterion varied across measures, it accounted for 1.14% of the total data at most. Data loss was approximately equal across conditions.

We examined several measures across several regions of interest in order to assess the effect of our manipulation. The measures we examined were first fixation duration (FFD; the duration of the first fixation on a word), gaze duration (GD; the sum of all fixations on a word from the first fixation until a saccade to another word), single fixation duration (SFD; the duration of a fixation when it is the only first pass fixation made on a word), go-past time (GP; the sum of all fixations from the first fixation in a region until a saccade was made to the right of the region), and skipping probability (SP; the probability that readers will skip a word in first pass reading). We examined these measures on word *n*, word *n*+1, and word *n*+2. In addition we also examined reading time measures on a composite region, consisting of both word *n*+1 and word *n*+2. Given that our preview manipulation extended across both of these words it does not seem unreasonable to assume that any effect of our manipulation may be more likely to appear in a complex manner across both of these words in a way that may not be detected through the analysis of the individual words. More generally, recent research has shown that preview manipulations on word *n*+2 may appear more clearly in composite, but not separate, regions especially when skipping rates of one of the regions is high (see Yu, Cutter, Yan, Bai, Fu, Drieghe, & Liversedge, 2016). The means and standard deviations of these measures are displayed in Table 1.

To analyze the data we constructed Linear Mixed Models (LMMs) using the lme4 package (Bates, Maechler, & Bolker, 2012) in R (2013). LMMs retain greater statistical power than ANOVAs in unbalanced designs (see Baayen, 2008) and so are well-suited to analyzing boundary studies, in which trials are often excluded due to technical errors. The preview condition was treated as a fixed factor. Helmert contrasts were used in order to compare 1) the identity preview condition to both the transposition and substitution preview conditions simultaneously and 2) to compare the transposition preview to the substitution preview. Subjects and items were treated as random factors, with both random intercepts and slopes in accordance with Barr, Levy, Scheepers, and Tily (2013). In some cases the slopes were removed due to either a failure to converge or when the correlations in the random structure were equal to 1 or -1 which indicates overparametrization of the model. The final specified structure of the models can be found in the attached R Scripts. The beta values, standard errors, and t-values of the contrasts are displayed in Table 2.

Word *n*. There were no significant effects of our manipulation on word *n*.

Word *n* + 1. There were significant identity preview effects across all fixation time measures on word *n*+1, such that participants would fixate this word for less time given an identity preview, relative to the two incorrect preview types. However, there were no significant differences between the transposition and substitution preview in any measure. Furthermore, the direction of any numerical differences between these two conditions varied from measure to measure. Finally, there were no effects of our manipulation upon the skipping of word *n*+1.

Word *n*+2. There were significant identity preview effects on word *n*+2 in gaze duration, go-past time, and skipping probabilities, but not in first or single fixation durations. In the fixation time measures this effect was facilitative, such that participants fixated word *n*+2 for less time following an identity preview. Furthermore, in the skipping probabilities participants were more likely to skip word *n*+2 given an identity preview as opposed to either false preview. There was a significant difference between the transposition and substitution preview in single fixation durations, such that participants would fixate word *n*+2 for less time following a transposition relative to substitution preview.

Composite region. In our composite region we observed significant identity preview effects across all fixation time measures. There were no significant differences between the transposition and substitution previews, and the direction of any numerical differences between these conditions varied across measures.

Discussion

In Experiment 1 we presented readers with an identity preview of word *n*+1 and *n*+2, a preview in which the final letter of word *n*+1 and the initial letter of word *n*+2 had been transposed, or a preview in which the final and initial letter of word *n*+1 and *n*+2 had been substituted for alternative letters. We hypothesized that if word *n*+1 and *n*+2 were processed in parallel we may observe a preview benefit of the transposition condition relative to the substitution condition. Furthermore, we hypothesized that we would observe a preview benefit of the identity preview relative to the other two preview types, regardless of whether words are processed in serial or parallel. While we observed significant benefits of our identity preview condition relative to the two alternative preview types, we found very little evidence that word *n*+1 and *n*+2 were processed in parallel.

Across the three regions and five measures that we analyzed there was a significant difference between our transposition and substitution condition in just one measure, in one region. This effect was in single fixation durations, with word *n*+2 being fixated for 18 milliseconds less following a transposition preview as opposed to a substitution preview. It is briefly worth discussing this effect in the context of the rest of our data in order to assess whether it was part of a larger, more meaningful trend, rather than simply being a spurious effect. We consider it to be the latter. Across all of our other measures and regions there was no consistent trend towards this effect, with there being many instances of the opposite trend being present. Had there been a genuine effect of the manipulation we would at least have expected some sort of consistent trend across measures, even if this generally failed to reach significance. As such, we will not make further efforts to interpret this anomaly.[4]

The results of Experiment 1 are in line with those of a recent investigation of Chinese reading (Gu & Li, 2015). In this study readers were presented with parafoveal previews of a four-character target region. These four characters would either form a single four-character word, or two two-character words. The parafoveal preview of this region would either be an identity preview, a preview in which the second and third character had been transposed, or a preview in which the second and third character were substituted; in the case of the two incorrect preview types the target region neither formed a single four-character word nor any two-character words. Depending upon whether the target region formed a single word or two words the transposition would either be within a word, or between two words. When the target region formed a single word the transposition preview led to significantly faster reading times than the substitution preview, similarly to the effects that occurred in Johnson's (2007) study in English. When the target region formed two separate words, however, there were no differences between the transposition and substitution previews, a finding similar to the results in the current experiment. Our interest in the current study was primarily in whether orthographic information from one word in the parafovea can influence the processing of an adjacent parafoveal word. Given this, it is interesting to note that inter-word transposition effects do not seem to occur either in a language where parafoveal-on-foveal effects tend to be quite rare (i.e. English), or in Chinese where such effects are far more common (e.g. Yan, Kliegl, Shu, Pan, & Zhou, 2010; Yan, Richter, Shu, & Kliegl, 2009; Yan & Sommer, 2015). It is also interesting to note that such effects failed to occur regardless of whether word spacing was or was not present.

Future research should focus upon establishing how exactly the parafoveal processing of transposed letter previews are influenced by factors such as morpheme and lexeme boundaries, as well as typographical spaces between words. One question that still needs to be addressed is whether a preview in which a transposition is made between two morphemes (i.e. across a lexical boundary but not across a space) leads to a greater preview benefit than a preview in which these letters are substituted. As outlined above transposed letter effects do not occur between morphemes in masked priming studies (Christianson et al., 2005) but do in direct fixation times during natural reading; future research should examine whether between morpheme transposition effects occur in the parafovea. Conversely, it could also be the case that a transposed letter effect may occur between two words when these words form a larger unit. Cutter, Drieghe, and Liversedge (2014) demonstrated that readers process spaced compounds (e.g. *teddy bear*) as single lexical units; it could be the case that if a letter transposition was made between the constituent words of these spaced compounds in the parafovea, then this would provide a preview benefit relative to a substituted letter preview. Clearly, this issue requires further investigation in the future.

Experiment 2

Experiment 1 was primarily based upon prior research demonstrating transposed letter effects in parafoveal previews. However, there is a second phenomenon from isolated word recognition research which our preview manipulation can be viewed in relation to, referred to as letter migration errors (Davis & Bowers, 2004; Mozer, 1983; Treisman & Souther, 1986). This is an effect whereby presenting two or more words concurrently for a limited duration leads to the perception of an illusory word, which was a combination of the two presented words. For example, having seen *line* and *love* participants report the word *lone* as being present. This is referred to as a letter migration error since the misperception involves a letter from one word (e.g. the *o* in *love*) migrating to the other word to form the illusory word.

These effects have been reported across a number of tasks. Mozer (1983) briefly presented participants with a target word (e.g. *line*) paired with a context word (e.g. *love*). Once the words had disappeared a probe appeared where one of these words had been, and participants were required to name this word. When participants made an error it was more likely to involve reporting a conjunction of the two presented words (e.g. *lone, live,* or *love*) than a word that was not a conjunction (e.g. *lane, lice,* or *lace*). Davis and Bowers (2004) extended this finding by demonstrating that the effect can also occur across letter positions (e.g. *step* and *soap* resulting in the response *stop*). Treisman and Souther (1986) observed letter migration effects in a search task. They instructed participants to search an array of four words for a pre-specified target word, which could either be present or absent. The array was only briefly presented, in order to necessitate the distribution of attention across all words. On trials in which the target was absent, its constituent letters could either be distributed across the words in the array (e.g. *dab, dam, say, hay* for the target *day*) or were not present (e.g. *bud, bug, bun, bus* for the target *but*). Participants falsely responded that the target word was present more often in the former than the latter condition. This suggests that orthographic information extracted from multiple words in the array was fed into the lexicon simultaneously, in order to activate the lexical representation of the target word.

One interpretation of these findings is that they occur due to the distribution of attention across the multiple presented word forms. Presumably, the presented words must be orthographically encoded simultaneously due to the short exposure durations used in these studies. These multiple word forms may then proceed to feed activation into the lexicon in parallel, and as a result both sets of orthographic information activate lexical representations at the same time. Indeed, Davis and Bowers (2004) convincingly argued that the locus of these effects is most likely at the level of the lexicon. Consequently, a word which shares the orthography of all of the displayed words sometimes receives enough activation to lead to the false identification of an illusory word. In light of this, these letter migration errors may have interesting implications for the debate between serial and parallel approaches to lexical processing during reading. These effects suggest that when two words are lexically processed in parallel we should indeed expect orthographic information from one word to influence the processing of the other, in the way that Reichle et al. (2009) proposed.

Contrary to this suggestion, we observed no such effects in Experiment 1. This null effect could be due to one of at least two reasons. It could be that unlike in somewhat artificial, time-limited, isolated word recognition tasks, words are not typically processed in parallel during normal reading. However, there is an alternative possibility. In Experiment 1 our transposition was always made between the final letter of one word, and the initial letter of another. While Davis and Bowers (2004) showed that letter migration effects occur between letters from different positions within a word, this did not include the initial letter of a word. As such, we may have failed to observe an effect in Experiment 1 due to the within-word location of our manipulation, rather than our target words being lexically processed in serial order. We explored this possibility in Experiment 2 by making our transpositions between equivalent letter positions in the two words (e.g. *pit hop* rather than *hip top* as a transposition preview of *hit pop*). Our hypotheses here were very similar to those of Experiment 1, in that we predicted that if word *n*+1 and word *n*+2 are typically processed in parallel then we may observe a preview benefit in the transposition condition relative to the substitution condition.[5] On the other hand, if word *n*+1 and word *n*+2 are processed in serial order then we would only expect an identity preview benefit, with no difference between the transposition and substitution condition.

Method

Participants. 66 native English speakers with normal or corrected to normal vision participated. An additional 6 participants were tested but removed from the analysis due to noticing more than five display changes. Participants were rewarded with research credits.

Apparatus. The same apparatus was used as in Experiment 1, with the only change being that the monitor was running at a refresh rate of 120 hertz.

Materials and Design. Thirty-three pairs of words from which two new words could be created by transposing or substituting two letters between the words were embedded in sentences. While the transposition could be made for any letter position in the word, it would always maintain the letters within word position. Both words were always three letters long. The transposition was made between the initial, middle, and final letters in 11, 12, and 10 items, respectively. The two target words were embedded beyond an invisible boundary, as word *n*+1 and word *n+2*, and had their parafoveal preview manipulated. Participants received either a correct preview (e.g. *hit pop*), a transposed letter preview (e.g. *pit hop*), or a substituted letter preview (e.g. *fit cop*). All items are listed in Appendix B. Once again, we obtained norms from the SUBTLEX corpus (Brysbaert & New, 2009) which is part of the English Lexicon Project (Balota et al., 2007). No significant differences were present between the transposition (*n*+1 mean = 3.26, *n*+2 mean = 3.14) and substitution condition (*n*+1 mean = 3.19, *n*+2 mean = 4.01) in terms of the log frequency per million of word *n*+1 (t (32) = -0.29, p = .77) or word *n*+2 (t (31) = -1.42, p = .16). We also assessed whether our transposed letter previews differed from our substituted letter previews in terms of bigram frequency (*n*+1 transposition mean = 3512, substitution mean = 3112; *n*+2 transposition mean = 2911, substitution mean = 3251) and number of orthographic neighbors (*n*+1 transposition mean = 20.76, substitution mean = 20.76; *n*+2 transposition mean = 21.63, substitution mean = 21.73). There were no significant differences between the transposed letter and substituted letter previews in mean bigram frequency (word *n*+1 t (32) = 0.99, p

= .33, word *n*+2 (t (31) = -0.91, p = .37) or number of orthographic neighbors (word *n*+1 t (32) = 0, p = 1, word *n*+2 t (31) = -0.17, p = .86). Once again, there were no significant differences in the plausibility of the substitution and transposition preview for either word *n*+1 (*t* (32) = -1.04, p = .31; transposition mean = 3.00, substitution mean = 2.92) or word *n*+2 (*t* (32) = 0.33, p = .74; transposition mean = 3.25, substitution mean = 3.29). Furthermore, the cloze probability of word *n*+1 was negligible, with participants predicting the identity preview 4% of the time, the transposition preview 0% of the time, and the substitution preview 0% of the time. Word *n*+2 was also mostly unpredictable, with 3.5%, 0%, and 0% of completions being the identity, transposition, and substitution *n*+2 given the identity *n*+1, 2.3%, 0%, and 0.2% completions being the identity, transposition, and substitution *n*+2 given the substitution preview of word *n*+1, and 1.6%, 0%, and 0% completions being the identity, transposition, and substitution *n*+2 given the transposition preview of word *n*+1. Altogether, our stimuli were well-matched, with no significant differences between the two incorrect preview conditions.

Procedure. For the most part the experimental procedure was identical to Experiment 1. The only changes were that the acceptance criterion for the calibration and drift check was lowered to 0.25 degrees and the gaze-contingent fixation cross was replaced with a second drift check. The thirty-three experimental items were mixed in with 43 filler items. Across all participants 95% of the comprehension questions were answered correctly. The experiment took approximately 20 minutes.

Results

We used the same data exclusion criteria in Experiment 2 as in Experiment 1, accounting for a removal of 16% of the data gathered across all measures, with a maximum of an additional 1.2% of the data being lost due to measure specific outlier cleaning. Data loss was approximately equal across conditions. We computed the same measures across the same regions of interest as in Experiment 1, and constructed LMMs to perform the same contrasts. Means and standard deviations of the computed measures are presented in Table 3 and the output from our LMMs are shown in Table 4.

Word *n*. No significant effects of our preview manipulation were observed during fixations on word *n*, or in skipping probabilities on this word.

Word *n*+1. Participants' first fixation durations, gaze durations, go-past times, and single fixation durations were significantly shorter when given an identity preview of word *n*+1 and word *n*+2 than a preview including either a letter transposition or substitution. However, we observed no significant differences between the transposition and substitution condition. Furthermore, any numerical differences were in the opposite direction to what was hypothesized. There was no effect of our manipulation on skipping this word.

Word *n*+2. There was a significant identity preview benefit during fixations on word *n*+2 in both go-past times and single fixation durations. Once again, there were no significant differences between the transposition and substitution condition, and the direction of any numerical differences was inconsistent between measures. There was no effect of our manipulation on the skipping of this word.

Composite region. We observed significant identity preview benefit in first fixation durations, gaze durations, and go-past times. However, no significant differences were observed between the transposition and substitution condition.

Bayesian analysis. While the analysis presented above provides no evidence that there was a significance difference between reading behaviour when participants were presented with a transposition preview rather than a substitution preview, it does not necessarily supply evidence that there was not an effect of this manipulation. This is due to the fact that null hypothesis significance testing only allows us to reject the null hypothesis, but not to state positive evidence in favor of it. In order to ensure that our data genuinely represent evidence that orthographic information from one word does not influence the processing of another word, we conducted a Bayesian analysis on the data for selected measures from both Experiment 1 and Experiment 2, by calculating Bayes factors (Jeffreys, 1961; Kass & Raftery, 1995; Rouder, Morey, Speckman, & Province, 2012). Bayes factors allow us to assess the extent to which a data set supports one of two competing hypotheses (e.g. Theory A and Theory B), by providing a ratio of the data's marginal likelihood under two differing statistical models. When there is no evidence for either hypothesis this ratio is 1:1, whereas this ratio increases as evidence for Theory A increases, and decreases as evidence for Theory B increases. A Bayes Factor between 3:1 and 1:3 is considered to be merely anecdotal evidence, and not conclusive enough to support either Theory A or Theory B. Bayes factors above 3:1 are considered to be substantial evidence in favor of Theory A, while Bayes factors below 1:3 (i.e. 0.33) are considered to be substantial evidence in favor of Theory B.[6] By calculating Bayes factors for a model which either does or does not include a certain variable it is possible to assess whether we have support in favor of an effect of that variable, or in favor of a null effect of that variable. Thus, this type of analysis may allow us to actively state that the processing of the transposition preview did not differ from the processing of a substitution preview, rather than that we simply lack evidence in favor of an effect.

A further aspect of Bayesian LMMs that is advantageous in comparison to non-Bayesian LMMs is that it is possible to determine and assess the contribution of random effects to the model. Singmann, Klauer, and Kellen (2014) argued that while there is not a data driven approach for obtaining an optimal random effects structure for non-Bayesian

LMMs, this is not the case for Bayesian LMMs. Rather, it is possible to assess whether the inclusion of, for example, a random slope for items improves the fit of the model. Thus, it is possible to first determine the optimal random structure for a data set, and then assess the fixed effect of a variable on the basis of this model.

In order to conduct our Bayesian analysis we used the BayesFactor package (Morey, Rouder, & Jamil, 2015) in R. We used the default prior setting alongside Laplace sampling. Due to it not being possible to code individual contrasts in Bayesian LMMs, we constructed several models to assess our effects. In order to assess whether we obtained identity preview effects we recoded our condition variable such that the identity preview was considered to be one level of a factor, while the transposition and substitution previews were considered to be the second level of this factor, and compared models with and without this factor in order to determine whether we had evidence for or against an identity preview effect. In order to assess whether there was an effect of our transposition preview relative to our substitution preview we constructed models in which all three preview types were coded as different levels of a single factor; these models were compared to the model in which the transposition and substitution preview were treated as identical. If the Bayes factor provided evidence in favor of the model in which all three preview types were different it would suggest an effect of our transposition preview relative to our substitution preview, whereas if it provided evidence in favor of the model in which these two incorrect previews were considered to be the same it would suggest no effect of our manipulation. In addition to varying the way in which we specified the fixed effects in our Bayesian LMMs, we also constructed models with four different random structures; intercepts only for both subjects and item; slopes and intercepts for items but intercepts only for subject and vice versa; and a full random structure. This analysis was conducted upon first fixation duration, gaze duration, and go-past time on the composite region. We selected these measures since we possessed far more data than for our individual regions, and thus more power to obtain substantial evidence in favor of either hypothesis.

The outcome of our Bayesian analysis is displayed in Table 5. We report the Bayes factors for the fixed effect in the most likely random structure; this was the intercept only model for all measures with the exception of first fixation duration in Experiment 1, where there was evidence for the model including random slopes for items.

As can be seen from Table 5, there was substantial evidence in favor of an identity preview effect in all but one measure across both Experiment 1 and Experiment 2. The one measure in which we did not observe substantial evidence in favor of an effect was first fixation duration in Experiment 1, in which we observed anecdotal evidence in favor of an effect. More importantly, we observed substantial evidence against an effect of our transposition preview relative to our substitution preview in all measures. Overall, it seems fair to conclude that our Bayesian analysis supports our assertion that while there was an effect of whether or not participants received identity previews, there was no effect of whether participants received a transposition or substitution preview.

Discussion

Experiment 2 was conducted in order to ensure that the null effect observed in Experiment 1 was due to parafoveal orthographic information extracted from word *n*+1 not influencing the lexical processing of word *n*+2 (and vice versa), rather than being a consequence of the transposition being made between the final and first letter of the two words. Our data suggest that it is indeed the case that orthographic information from one word in the parafovea does not influence the processing of another parafoveal word. Once again we observed significant identity preview benefits across the majority of measures, but nothing that suggested the transposition preview facilitated target word processing to a greater extent than the substitution preview. Thus, it seems fair to conclude that, unlike in isolated word recognition tasks, letter migration effects do not occur between two parafoveal words during natural reading.

Before proceeding it is important to consider the possibility that while a letter migration effect did not appear in our overall data, there may have been a sub-set of trials in which such effects were present. Specifically, it could be the case that these effects are sensitive to the amount of time participants spent fixated on the pre-boundary word. As mentioned above, letter migration effects tend to be observed in isolated word recognition tasks as a result of short exposure durations to the words. Furthermore, the number of errors made tends to increase with shorter exposure durations. There is a large level of variation between studies observing these effects in the exposure durations used. For example, Treisman and Souther (1986) used exposure durations of 150–250ms, Davis and Bowers (2004) an average of 96ms or 71ms, and Mozer (1983) an average of 348ms, with a range of 262–425ms. It is difficult to determine an exact range of exposure durations at which migration effects may be observed during reading, with some of the times in the studies listed above being quite long (e.g. 348ms) relative to the average fixation (i.e. 250ms) and others relatively short (e.g. 96ms). Indeed, this range could be seen to suggest that the amount of time spent fixating prior to the boundary should have had very little influence on letter migration effects. Nonetheless, we conducted further analyses to investigate this possibility. In order to test this hypothesis, we examined whether including the last fixation duration prior to crossing the invisible boundary significantly improved the fit of our LMMs. We tested this as both a main effect in the model, and an interactive term with our preview contrasts. While including this measure as a main effect did significantly improve the fit of our model for several measures (all measures on word n+1, first fixation duration on the composite region),[7] allowing it to interact with the preview contrast did not lead to a significant improvement in the fit of the model for any measures. For completeness, we note that the improvement for the model for single fixation durations on word *n*+2 was marginal (p=.059), but the crucial interaction between pre-target fixation and the contrast between substituted and transposed preview was not close to being significant, (*b*=-0.03, SE=0.11, t=-0.31).

Likewise, a re-analysis of Experiment 1 showed a similar pattern in that including pre-fixation duration in the LMMs did not improve the fit of any of the measures with the exception of single fixation duration on word *n*+2, where there was a marginal improvement (p=.06). We still examined the model, which did show a significant interaction between the final pre-target fixation and the contrast between the transposed and substituted preview (*b*=0.25, SE=0.11, t=2.17). To further investigate this interaction we performed a median split of our data on the basis of final pre-target fixation duration. Our effects appeared to be driven by the fact that in the case of the identity and substitution preview, the single fixation duration on word *n*+2 increased alongside pre-target fixation duration, increasing from 229ms to 253ms and from 247ms to 274ms respectively, while in the transposition condition single fixation durations remained constant, staying at 240ms for short and long final pre-target fixation durations. Thus, not only was the improvement in our model merely marginal, it was driven by a trend in which the identity preview was less facilitative than a transposition preview with increased exposure durations. Considering that the improvement in the fit of our model was only marginal, and that the pattern of effects made little sense, it seems fair to consider the effects in this measure as not representing a meaningful finding.

One criticism we foresee of Experiment 2 that we wish to address before moving on is that word *n*+1 and word *n*+2 were not orthographically similar. This could be considered a problem, since prior work on letter migration effects has found that the effects tend to be observed when the presented words are similar (e.g. *step* and *soap* leading to the perception of *stop*; *dab, dam, say* and *hay* leading to the perception of *day*) but not when the presented words are dissimilar (e.g. *step* and *frog* do not lead to the perception of *stop*). However, consideration of the theoretical explanation for this effect suggests that this should not have been an issue in our experiment. In typical studies of letter migration effects the participant's task is to name a single target word. As such, observing a letter migration effect in these studies not only depends upon the orthographic information from the two presented words causing activation in the lexicon in parallel, but also that the illusory word becomes lexically activated enough to lead to the identification of that word, rather than either of the two presented words. In the *step/soap* example above where the illusory word shares 75% of orthographic information with both presented words this level of activation is likely to be reached; three letters from each presented word would activate the illusory word's lexical representation. In contrast, in the *step/frog* example above, the two presented words are more dissimilar, and the illusory word shares 75% of orthographic information with one of the presented words, but only 25% of such information with the other. Under these circumstances it is unlikely that the illusory word would become sufficiently activated to be a serious candidate. Consequently, in a winner-takes-all task such as naming this word is unlikely to be identified. However, we do not consider this to be an issue in a natural reading study implemented using the boundary paradigm. Unlike in studies using a naming paradigm, preview benefit effects are not dependent upon the identification of a single lexical item so much as the activation of multiple lexical items which overlap with the previewed text on one of several abstract characteristics (i.e. orthography, phonology, or semantics). Any lexical item that is activated on the basis of this parafoveal information will be identified faster upon fixation. As such, in the current study any cases in which orthographic information from both parafoveal words was fed into the lexicon in parallel should have been enough to lead to a benefit of the migration preview relative to the substitution preview. However, in a naming task the activation of the target words from the migration preview would not need to exceed the activation of the words in the parafovea.

General Discussion

In the current study we investigated a prediction which should arguably be made by parallel accounts of lexical processing (Reichle et al., 2009). We investigated this by examining whether orthographic information from one parafoveal word influences the processing of another parafoveal word. We presented readers with parafoveal previews of words *n*+1 and *n*+2 in which a letter of each word had either been transposed to the other word, or been substituted with an alternative letter. We hypothesized that if orthographic information from both words was fed into the lexicon at the same time then we would observe significantly shorter fixation times given a transposition—rather than substitution—preview. However, while we observed significant identity preview benefits there was no notable effect of our transposition preview relative to our substitution preview. This was the case both when the preview manipulation affected the final character of word *n*+1 and the first character of word *n*+2 (Experiment 1) and when our manipulation affected the letter at the same letter position in both word *n*+1 and word *n*+2 (Experiment 2). We confirmed the null effect of the transposition manipulation in an additional Bayesian analysis, whereby we found substantial evidence against this effect.

Our findings offer no support for the notion that word *n*+1 and word *n*+2 are processed simultaneously while still in the parafovea. Had we observed such an effect, it would have been highly compelling evidence that multiple words within the perceptual span are processed in parallel during natural reading. While a parallel model of eye movement control such as SWIFT (Engbert et al., 2005; Schad & Engbert, 2012) does not explicitly predict an effect of our transposition manipulation, we consider this to be due to the model not defining how the parallel lexical processing of multiple words should occur. As will be seen below, the only attempt to design a model of parallel word identification is unable to account for our findings.

Attempts have recently been made to design a model of multiple-word reading, albeit outside of the context of eye movement control (Grainger, Mathôt, & Vitu, 2014; see also Grainger, Dufau, & Ziegler, 2016). While our findings do not necessarily pose a problem for the general concept of parallel lexical processing, they do have implications for this model. In their model Grainger et al. use an open-bigram coding scheme, whereby both contiguous (e.g. *ro* in *rock*) and non-contiguous (e.g. *rc* in *rock)* pairs of letters within a word activate bigrams, which in turn feed activation up to whole word representations. Crucially, in addition to the letters within a word being able to form bigrams with each other, they are also able to form bigrams with the space preceding and following the word. While letters are not able to form bigrams with letters from spatially adjacent words, the bigrams that are activated from several words within the perceptual span all feed activation up to a single whole word representation, and it is through this mechanism that orthographic information from one word is able to influence the processing of another word. As such, if the bigrams produced by one word overlap with the bigrams of a spatially adjacent word, then word identification should be facilitated relative to when the words do not share bigrams. Our results contradict this position. In both of our experiments the letters available in the transposition preview should have led to the parafoveal activation of a greater number of bigrams from the target words than the letters available in the substitution preview. Take, for example, the case of the transposition preview *hop tan* for the target words *hot pan.* Here, the *t* in *tan* and the space at the beginning and end of this word would have activated the bigrams *#-t* (in which # represents a space) and *t-#*, which are part of the target word *hot*. Furthermore, the *p* in *hop* and the spaces at the beginning and end of this word would have activated the bigrams *#-p* and *p-#* from *pan*. Upon these bigrams feeding activation to the whole word representations they would increase the activation of our target words, due to no longer being specifically linked to a particular word in the perceptual span at this level of the model. In contrast, the *b* and *f* in the substitution preview *hob fan* would not activate any of these four bigrams by joining with the spaces on either side of each word. A difference of two bigrams per word does not seem trivial for three letter target words, which, in the coding system used by Grainger et al., would only contain nine bigrams in total. As such, our results pose a challenge for this approach, and may need to be taken into consideration in any future iteration of this model. It should be noted that while this model does not explicitly state that information is extracted from word *n*+2, it presumably should if attempting to account for both word *n*+1 and word *n*+2 orthographic preview effects using a single mechanism.

Although we do not consider our results to necessarily be evidence against the general idea of parallel processing, they do raise a number of interesting questions. Specifically, our findings have relevance for phenomena that are sometimes interpreted as evidence of parallel lexical processing. As discussed in depth earlier, it could be assumed that orthographic parafoveal-on-foveal effects are due to orthographic information from the parafoveal word either facilitating (e.g. Angele et al., 2013) or inhibiting (e.g. Inhoff et al., 2000) the processing of a spatially adjacent word. However, our findings call this explanation into question, with very little evidence of orthographic information from one word influencing the processing of an adjacent word. It could be argued that the main difference here is that in our study orthographic information from word *n*+2 would have had to influence the processing of word *n*+1 (and vice versa), as opposed to orthographic information from word *n*+1 affecting the processing of word *n*, as in prior studies. However, for this to be a plausible explanation for the difference, a parallel processing account would have to make a clear distinction between the way in which word *n* and word *n*+1 are processed in parallel relative to the way in which word *n*+1 and word *n*+2 are processed in parallel. No such distinction is currently made. It could be that the decrease in visual acuity further into the parafovea could go some way to explaining our lack of effect from the perspective of a parallel model, with information from word *n*+2 not being extracted quickly enough to influence the processing of word *n*+1; however, presumably by this same logic the model would predict no *n*+2 preview effects. Once again, it is difficult to see exactly how a parallel model could approach lexical processing in such a way as to account for existing patterns of effects in a plausible manner. We consider our findings to be more in line with the explanation of orthographic parafoveal-on-foveal effects that was proposed by Reichle, Pollatsek, and Rayner (2006), whereby unusual visual configurations pop-out from the page, and interfere with typical processing. In studies showing an effect of word *n*+1's orthographic characteristics on the processing of word *n* such unusual visual configurations are typically present, with either illegal letter strings being present in word *n*+1, or word *n*+1 being a repetition of word *n*. In the current study there was nothing visually unusual about our parafoveal preview, hence leading to the null effect. Indeed, the fact that there were no effects of our preview manipulation on word *n* further supports the idea that our manipulation was not visually salient; presumably, if it had been we would have observed similar effects to presenting participants with orthographically illegal letter strings in word *n*+1.

In summary, the current study aimed to assess whether word *n*+1 and word *n*+2 are lexically processed in parallel during reading. This was tested by examining whether orthographic information from two words in the parafoveal preview affected the processing of each other. Our findings suggested this was not the case, with participants not gaining a benefit from a preview in which the correct letter identity information was present in the parafovea but as part of the wrong words, relative to a preview in which the identities of two letters were incorrect. While this result is not necessarily evidence against parallel lexical processing, it certainly needs to be taken into account in any future attempts to model the parallel processing of multiple words and in the interpretation of phenomena such as parafoveal-on-foveal effects.

References

Angele, B., & Rayner, K. (2011). Parafoveal processing of word n + 2 during reading: Do the preceding words matter? *Journal of Experimental Psychology: Human Perception and Performance, 37,* 1210-1220. doi:10.1037/a0023096

Angele, B., Slattery, T. J., Yang, J., Kliegl, R. & Rayner, K. (2008). Parafoveal processing in reading: Manipulating n+1 and n+2 previews simultaneously. *Visual Cognition, 16:6,* 697-707. doi:10.1080/13506280802009704

Angele, B., Tran, R., & Rayner, K. (2013). Parafoveal-on-foveal overlap can facilitate ongoing word identification during reading: Evidence from eye movements. *Journal of Experimental Psychology: Human Perception and Performance, 39,* 526-538. doi: 10.1037/a0029492

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

Balota, D.A., Yap, M.J., Cortese, M.J., Hutchison, K.A., Kessler, B., Loftis, B., Neely, J.H., Nelson, D.L., Simpson, G.B., & Treiman, R. (2007). The English Lexicon Project. *Behavior Research Methods, 39*, 445-459.

Barr, D. J., Levy, R., Scheepers, C., & Tily, H. J. (2013). Random effects structure for confirmatory hypothesis testing: Keep it maximal. *Journal of Memory and Language, 68*(3), 255-278. doi: 10.1016/j.jml.2012.11.001

Bates, D., Maechler, M., & Bolker, B. (2012). lme4: Linear mixed-effects models using S4 classes. (R Package Version 0.999999–0). Retrieved from http://CRAN.R-project.org/package=lme4

Brysbaert, M., & New, B. (2009). Moving beyond Kučera and Francis: A critical evaluation of current word frequency norms and the introduction of a new and improved word frequency measure for American English. *Behavior Research Methods, 41*, 977-990. doi:10.3758/BRM.41.4.977

Christianson, K., Johnson, R. L., & Rayner, K. (2005). Letter transpositions within and across morphemes. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 31*, 1327-1339. doi:10.1037/0278-7393.31.6.1327

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. doi:10.1037/xlm0000013

Cutter, M. G., Drieghe, D., & Liversedge, S. P. (2015). How is information integrated across fixations in reading? In A. Pollatsek & R. Treiman (Eds.), *The Oxford handbook of reading* (pp. 245-260). New York, NY: Oxford University Press.

Dare, N., & Shillcock, R. (2013). Serial and parallel processing in reading: Investigating the effects of parafoveal orthographic information on nonisolated word recognition. *Quarterly Journal of Experimental Psychology, 66*, 487-504. doi: 10.1080/17470218.2012.703212

Davis, C. J., & Bowers, J. S. (2004). What do letter migration errors reveal about letter position coding in visual word recognition? *Journal of Experimental Psychology: Human Perception and Performance, 30*, 923-941. doi: 10.1037/0096-1523.30.5.923

Drieghe, D. (2011). Parafoveal-on-foveal effects on eye movements during reading. In S. Liversedge, I. Gilchrist, & S. Everling (eds.) *Oxford Handbook on Eye Movements* (pp. 839-855). Oxford, UK: Oxford University Press.

Drieghe, D., Rayner, K., & Pollatsek, A. (2008). Mislocated fixations can account for parafoveal-on-foveal effects during reading. *Quarterly Journal of Experimental Psychology, 61*, 1239-1249. doi: 10.1080/17470210701467953

Engbert, R., Nuthmann, A., Richter, E. M., & Kliegl, R. (2005). SWIFT: a dynamical model of saccade generation during reading. *Psychological review*, *112*, 777. doi: 10.1037/0033-295X.112.4.777

Frost, R. (2015). Cross-linguistic perspective on letter-order processing: Empirical findings and theoretical considerations. In A. Pollatsek & R. Treiman (Eds.), *The Oxford handbook of reading* (pp. 88-98). New York, NY: Oxford University Press.

Grainger, J., Dufau, S., & Ziegler, J. C. (2016). A vision of reading. *Trends in Cognitive Sciences.* Advance online publication. doi: 10.1016/j.tics.2015.12.008

Grainger, J., Mathôt, S., & Vitu, F. (2014). Tests of a model of multi-word reading: Effects of parafoveal flanking letters on foveal word recognition. *Acta Psychologica, 146,* 35-40. doi: 10.1016/j.actpsy.2013.11.014

Gu, J., & Li, X. (2015). The effect of character transposition within and across words in Chinese reading. *Attention, Perception, & Psychophysics, 77,* 272-281. doi: 10.3758/s13414-014-0749-5

Inhoff, A. W., Radach, R., Starr, M., & Greenberg, S. (2000). Allocation of visuo-spatial attention and saccade programming during reading. In A. Kennedy, R. Radach, D. Heller, & J. Pynte (Eds.). *Reading as a perceptual process* (pp. 221-246). Amsterdam, Netherlands: North-Holland/Elseiver Science Publisher. doi: 10.1016/B978-008043642-5/50012-7

Inhoff, A. W., Starr, M., & Shidler, K. L. (2000). Is the processing of words during eye fixations in reading strictly serial? *Perception & Psychophysics, 62*, 1474-1484. doi: 10.3758/BF03212147

Jeffreys, H. (1961). *Theory of Probability*. New York: Oxford University Press.

Johnson, R. L. (2007). The flexibility of letter coding: Nonadjacent letter transposition effects in the parafovea. In R. P. G. van Gompel, M. H. Fisher, W. S. Murray, & R. L. Hill (Eds.). *Eye movements: A window on mind and brain* (pp. 425-440). Oxford, United Kingdom: Elsevier.

Johnson, R. L., & Dunne, M. D. (2012). Parafoveal processing of transposed-letter words and nonwords : Evidence against parafoveal lexical activation. *Journal of Experimental Psychology: Human Perception and Performance, 38,* 191-212. doi: 10.1037/a0025983

Johnson, R. L., Perea, M., & Rayner, K. (2007). Transposed-letter effects in reading: Evidence from eye movements and parafoveal preview. *Journal of Experimental Psychology: Human Perception and Performance, 33,* 209-229. doi: 10.1037/0096-1523.33.1.209

Kass, R. E., & Raftery, A. E. (1995). Bayes factors. *Journal of the American Statistical Association, 90*, 773-795.

Kliegl, R., Risse, S., & Laubrock, J. (2007). Preview benefit and parafoveal-on-foveal effects from word n+2. *Journal of Experimental Psychology: Human Perception and Performance, 33*, 1250-1255. doi:10.1037/0096-1523.33.5.1250

Morey, R. D., Rouder, J. N., & Jamil, X. (2015). BayesFactor: Computation of Bayes factors for common designs. Version 0.9.12. Retrieved from http://bayesfactorpcl.r-forge.r-project.org.

Mozer, M. C. (1983). Letter migration in word perception. *Journal of Experimental Psychology: Human perception and performance, 9*, 531. doi: 10.1037/0096-1523.9.4.531

Pagán, A., Blythe, H. I., & Liversedge, S. P. (2016). Parafoveal preprocessing of word initial trigrams during reading in adults and children. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 42,* 411-432. doi: 10.1037/xlm0000175

Perea, M., & Carreiras, M. (2012). Perceptual uncertainty is a property of the cognitive system. *Behavioral and Brain Sciences, 35,* 298-299. doi:10.1017/S0140525X12000118

Perea, M., & Lupker, S. J. (2003). Does judge activate court? Transposed-letter similarity effects in masked associative priming. *Memory & Cognition*, *31,* 829-841. doi:10.3758/BF03196438

Radach, R., Inhoff, A. W., Glover, L., & Vorstius, C. (2013). Contextual constraint and N+ 2 preview effects in reading. *The Quarterly Journal of Experimental Psychology*, *66,* 619-633. doi:10.1080/17470218.2012.761256

Rayner, K. (1975). The perceptual span and peripheral cues during reading. *Cognitive Psychology, 7,* 65-81.

Rayner, K., Juhasz, B. J., & Brown, S. J. (2007). Do readers obtain preview benefit from word N+2? A test of serial attention shift versus distributed lexical processing models of eye movement control in reading. *Journal of Experimental Psychology: Human Perception and Performance, 33,* 230-245. doi:10.1037/0096-1523.33.1.230

Reichle, E. D., & Drieghe, D. (2014). Using E-Z Reader to examine the consequences of fixation-location measurement error. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 41,* 262-270. doi: 10.1037/a0037090

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. doi:10.1016/j.tics.2008.12.002

Reichle, E. D., Pollatsek, A., Rayner, K. (2006). E-Z Reader: A cognitive-control, serial-attention model of eye-movement behavior during reading. *Cognitive Systems Research, 7,* 4-22. doi: 10.1016/j.cogsys.2005.07.002

Reichle, E. D., Rayner, K., & Pollatsek, A. (2003). The EZ Reader model of eye-movement control in reading: Comparisons to other models. *Behavioral and brain sciences*, *26*(04), 445-476. doi: 10.1017/S0140525X03000104

Reichle, E. D., Warren, T., & McConnell, K. (2009). Using EZ Reader to model the effects of higher level language processing on eye movements during reading. *Psychonomic Bulletin & Review*, *16*, 1-21. doi:10.3758/PBR.16.1.1

Risse, S., & Kliegl, R. (2012). Evidence for delayed parafoveal-on-foveal effects from word *n*+2 in reading. *Journal of Experimental Psychology: Human Perception and Performance, 38*, 1026-1042. doi: 10.1037/a0027735

Risse, S., & Kliegl, R. (2014). Dissociating preview validity and preview difficulty in parafoveal processing of word *n*+1 during reading. *Journal of Experimental Psychology: Human Perception and Performance, 40,* 653-668. doi: 10.1037/a0034997

Rouder, J. N., Morey, R. D., Speckman, P. L., & Province, J. M. (2012). Default Bayes factors for ANOVA designs. *Journal of Mathematical Psychology, 56*, 356-374. doi: 10.1016/j.jmp.2012.08.001

Schad, D. J., & Engbert, R. (2012). The zoom lens of attention: Simulating shuffled versus normal text reading using the SWIFT model. *Visual Cognition*, *20*, 391-421. doi:10.1080/13506285.2012.670143

Schotter, E. R., & Jia, A. (2016). Semantic and Plausibility Preview Benefit Effects in English: Evidence from Eye Movements. *Journal of Experimental Psychology: Learning, Memory, and Cognition,42,* 1839-1836. doi: 10.1037/xlm0000281

Schotter, E. R., Reichle, E. D., & Rayner, K. (2014). Rethinking parafoveal processing in reading: Serial-attention models can explain semantic preview benefit and N+2 preview effects. Visual Cognition, 22, 309-333. doi: 10.1080/13506285.2013.873508

Singmann, H., Klauer, K. C., & Kellen, D. (2014). Intuitive logic revistited: New data and a Bayesian mixed model meta-analysis. *PLOS One, 9.* doi:10.1371/journal.pone.0094223

Slattery, T. J., Angele, B., & Rayner, K. (2011). Eye movements and display change detection during reading. *Journal of Experimental Psychology: Human Perception and Performance, 37*, 1924-1938. doi: 10.1037/a0024322

Stites, M. C., Federmeier, K. D., & Christianson, K. (2016). Do morphemes matter when reading compound words with transposed letters? Evidence from eye-tracking and event-related potentials. *Language, Cognition and Neuroscience*, *31*, 1299-1319. doi: 10.1080/23273798.2016.1212082

Treisman, A., & Souther, J. (1986). Illusory words: The roles of attention and of top-down constraints in conjoining letters to form words. *Journal of Experimental Psychology: Human Perception and Performance, 12,* 3-17. doi: 10.1037/0096-1523.12.1.3

White, S. J. (2008). Eye movement control during reading: Effects of word frequency and orthographic familiarity. *Journal of Experimental Psychology: Human Perception and Performance, 34,* 205-223. doi: 10.1037/0096-1523.34.1.205

White, S. J., & Liversedge, S. P. (2006). Foveal processing difficulty does not modulate non-foveal orthographic influences on fixation positions. *Vision Research, 46,* 426-437. doi:10.1016/j.visres.2005.07.006

Yan, M., Kliegl, R., Shu, H., Pan, J., & Zhou, X. (2010). Parafoveal load of word n + 1 modulates preprocessing effectiveness of word n + 2 in Chinese reading. Journal of Experimental Psychology: Human Perception and Performance, 36, 1669-1676.

Yan, M., Richter, E. M., Shu, H., & Kliegl, R. (2009). Readers of Chinese extract semantic information from parafoveal words. *Psychonomic Bulletin & Review, 16,* 561-566. doi: :10.3758/PBR.16.3.561

Yan, M., Sommer, W. (2015). Parafoveal-on-foveal effects of emotional word semantics in reading Chinese sentences: Evidence from eye movements. *Journal of Experimental Psychology: Learning, Memory, and Cognition.* Advance online publication. doi: 10.1037/xlm0000095

Yu, L., Cutter, M. G., Yan, G., Bai, X., Fu, Y., Drieghe, D., & Liversedge, S. P. (2016). *Word n+2 preview effects in three-character Chinese idioms and phrases*. Manuscript submitted for publication.

Footnotes

[1] It should also be noted that there are various other explanations for parafoveal-on-foveal effects in a serial model. These explanations typically view the effects as being artefacts of other phenomena such as mislocated fixations (Drieghe et al., 2008) and eye-tracker error (Reichle & Drieghe, 2014). While these explanations are able to explain the inhibitory effects discussed above—and may even explain some of the inconsistencies in the observation of these effects—they cannot account for the facilitative effects.

[2] There is an extensive literature examining the locus of this effect in terms of visual word identification. We do not explore this literature in the current article due to our primary concern being the way in which the orthographic information from one word influences the processing of an adjacent word.

[3] Typically boundary change studies are run at a refresh rate of either 120 or 150 hertz. Unfortunately Experiment 1 of the current study was run at 75 hertz due to an oversight. This led to a higher number of late display changes than is usual for this kind of study. However, we are confident that our data exclusion criteria ensured that the late changes did not contribute to the effects we report. Furthermore, this oversight was addressed in Experiment 2.

[4] Subsequent exploratory data analysis of this transposition effect also indicated that it depended on the specific criterion used for data cleaning. For example, in a preliminary analysis in which outliers were removed on the basis of an observation being 2.5 standard deviations away from the mean for a participant per condition as opposed to the grand mean, this effect was only marginally significant. The dependence of this effect on precise data cleaning parameters, combined with the absence of this effect in first fixation duration, gaze duration, and go-past time, leads us to believe that it is most likely spurious in nature.

[5] While our manipulation in Experiment 2 could be more accurately described as a migration preview than a transposition preview we continue to use the latter terminology for the sake of consistency with Experiment 1.

[6] Technically as the ratios become greater they represent various different classes of evidence for each theory. However, for simplicity's sake we refer to either anecdotal evidence or substantial evidence.

[7] It could be argued that we should report these additive models in place of our basic models, due to the improved fit. However, the only reason we constructed these models was to use them as a baseline to compare our interactive model to, rather than there being a theoretically interesting reason to examine a main effect of pre-target fixation duration. As such, we see little point in reporting these models in addition to our main analyses.

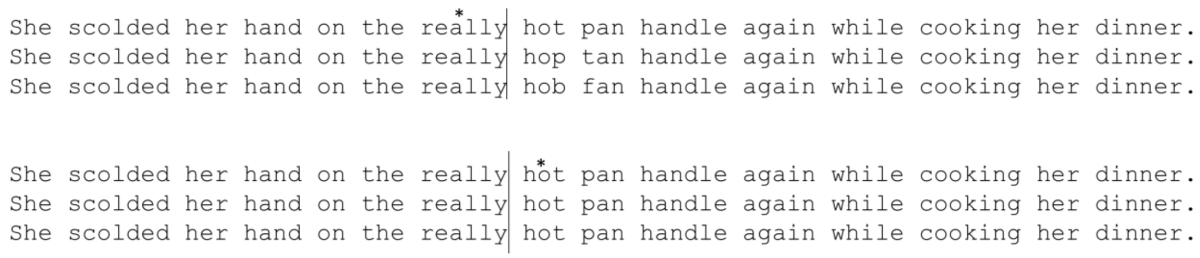

Figure 1. An illustration of the stimuli and the boundary paradigm. The vertical black line represents the invisible boundary, and the asterisk the point of fixation. Prior to the eye crossing the boundary participants are presented with either an identity preview (*hot pan*), a preview in which two letters have been transposed (*hop tan*), or a preview in which the same two letters have been substituted (*hob fan*). After the eye crosses the boundary, the previews become the target words in all conditions.

Table 1

Mean Fixation Time Measures (in Milliseconds) and Skipping Probability for all Target Regions in Experiment 1. Standard Deviations are Presented in Parentheses.

Preview	Word *n*	Word *n*+1	Word *n*+2	Composite region
		First fixation duration		
Identity	220(64)	247(82)	237(84)	247(82)
Transposition	216(60)	261(87)	245(92)	264(91)
Substitution	214(60)	261(86)	249(92)	264(92)
		Gaze duration		
Identity	230(74)	259(93)	252(99)	383(183)
Transposition	227(72)	278(97)	276(123)	451(204)
Substitution	225(74)	280(98)	275(117)	446(200)
		Go-past time		
Identity	236(81)	272(104)	266(112)	411(189)
Transposition	235(79)	297(109)	301(139)	485(198)
Substitution	232(81)	293(107)	299(132)	486(205)
		Single fixation duration		
Identity	222(66)	251(84)	243(90)	-
Transposition	214(55)	275(89)	241(93)	-
Substitution	215(60)	277(90)	259(95)	-
		Skipping probability		
Identity	.17(.38)	.30(.46)	.28(.45)	-
Transposition	.18(.39)	.30(.46)	.22(.42)	-
Substitution	.15(.36)	.30(.46)	.23(.42)	-

Note. Single fixation duration on the composite region is not included due to there being very few instances in which participants made only a single fixation on this region.

Table 2

Fixed Effect Estimates, Standard Errors, and t-values from the LMM contrasts for all Measures across All Regions in Experiment 1.

	First fixation duration			Gaze duration			Go-past time			Single fixation duration			Skipping probability		
Effect	*b*	SE	T	*b*	SE	t	*b*	SE	t	*b*	SE	t	*b*	SE	z
Word *n*															
Identity effect	0.01	0.02	0.72	0.01	0.02	0.59	0.01	0.02	0.28	0.02	0.02	1.02	0.02	0.15	0.12
Transposition effect	-0.01	0.02	-0.45	-0.01	0.02	-0.37	-0.01	0.02	-0.28	-0.01	0.02	0.43	-0.28	0.18	-1.59
Word *n*+1															
Identity effect	**-0.06**	**0.02**	**-2.90**	**-0.08**	**0.03**	**-3.27**	**-0.10**	**0.03**	**-3.51**	**-0.10**	**0.03**	**-3.27**	0.01	0.13	0.06
Transposition effect	0.00	0.02	0.10	0.01	0.02	0.24	-0.01	0.03	-0.55	0.02	0.03	0.62	-0.00	0.15	-0.03
Word *n*+2															
Identity effect	-0.05	0.03	-1.67	**-0.08**	**0.03**	**-3.21**	**-0.12**	**0.03**	**-4.11**	-0.03	0.03	-1.29	**0.31**	**0.13**	**2.47**
Transposition effect	0.02	0.03	0.73	0.01	0.03	0.28	0.01	0.03	0.31	**0.07**	**0.03**	**2.23**	0.04	0.15	0.25
Composite region															
Identity effect	**-0.07**	**0.02**	**-3.88**	**-0.17**	**0.03**	**-5.51**	**-0.19**	**0.03**	**-6.52**	-	-	-	-	-	-
Transposition effect	0.00	0.02	0.03	-0.01	0.03	-0.20	-0.00	0.03	-0.15	-	-	-	-	-	-

Significant terms are presented in bold.

Table 3

Mean Fixation Time Measures (in Milliseconds) and Skipping Probability for all Target Regions in Experiment 2. Standard Deviations are Presented in Parentheses.

Preview	Word *n*	Word *n*+1	Word *n*+2	Composite region
		First fixation duration		
Identity	223 (59)	257 (89)	245 (83)	253 (87)
Transposition	219 (58)	274 (101)	260 (95)	272 (101)
Substitution	224 (65)	270 (92)	256 (91)	266 (94)
		Gaze duration		
Identity	257 (88)	272 (101)	279 (119)	426 (216)
Transposition	251 (92)	297 (116)	296 (129)	470 (224)
Substitution	253 (96)	291 (109)	292 (127)	472 (232)
		Go-past time		
Identity	269 (97)	285 (108)	297 (137)	464 (229)
Transposition	267 (102)	314 (119)	326 (147)	517 (229)
Substitution	267 (104)	304 (113)	327 (148)	520 (241)
		Single fixation duration		
Identity	229 (57)	262 (91)	250 (84)	-
Transposition	222 (51)	291 (97)	267 (95)	-
Substitution	225 (62)	280 (92)	271 (93)	-
		Skipping probability		
Identity	0.10 (0.30)	0.26 (0.44)	0.26 (0.44)	-
Transposition	0.09 (0.29)	0.28 (0.45)	0.24 (0.43)	-
Substitution	0.07 (0.26)	0.29 (0.45)	0.27 (0.44)	-

Note. Single fixation duration on the composite region is not included due to there being very few instances in which participants made only a single fixation on this region.

Table 4

Fixed Effect Estimates, Standard Errors, and t-values from the LMM contrasts for all Measures across All Regions in Experiment 2.

	First fixation duration			Gaze duration			Go-past time			Single fixation duration			Skipping probability		
Effect	*b*	SE	t	*b*	SE	t	*b*	SE	t	*b*	SE	T	*b*	SE	z
Word *n*															
Identity effect	0.01	0.01	0.63	0.03	0.02	1.47	0.02	0.02	0.89	0.02	0.02	1.43	0.21	0.18	1.17
Transposition effect	0.01	0.02	0.75	0.00	0.03	0.06	-0.00	0.02	-0.14	0.00	0.02	0.08	-0.21	0.22	-0.95
Word *n*+1															
Identity effect	**-0.05**	**0.02**	**-2.51**	**-0.08**	**0.02**	**-3.41**	**-0.08**	**0.02**	**-3.52**	**-0.08**	**0.02**	**-3.46**	-0.14	0.12	-1.22
Transposition effect	-0.01	0.03	-0.32	-0.01	0.03	-0.36	-0.02	0.03	-0.82	-0.05	0.03	-1.46	0.02	0.14	0.89
Word *n*+2															
Identity effect	-0.04	0.02	-1.58	-0.04	0.03	-1.54	**-0.09**	**0.03**	**-3.20**	**-0.06**	**0.03**	**-2.22**	0.05	0.12	0.47
Transposition effect	-0.01	0.02	-0.54	-0.01	0.03	-0.38	0.00	0.03	0.02	0.01	0.03	0.36	0.15	0.14	1.11
Composite region															
Identity effect	**-0.05**	**0.02**	**-2.54**	**-0.10**	**0.03**	**-3.32**	**-0.13**	**0.03**	**-5.08**	**-**	**-**	**-**	**-**	-	-
Transposition effect	-0.01	0.02	-0.68	0.00	0.03	0.11	0.00	0.03	0.00	-	-	-	-	-	-

Significant terms are presented in bold.

Table 5

Bayes Factors for an Identity Effect and Transposition Effect in both Experiment 1 and Experiment 2.

	FFD	GD	GP
		Experiment 1	
Identity effect	2.14	**3.03 X 10^{9}**	**8.32 X 10^{14}**
Transposition effect	*0.01*	*0.01*	*0.10*
		Experiment 2	
Identity effect	**5.07**	**879.35**	**6.44 X 10^{6}**
Transposition effect	*0.15*	*0.11*	*0.10*

Bayes factors indicating at least substantial evidence against an effect are italicised, while Bayes factors indicating at least substantial evidence in favor of an effects are presented in bold. Bayes factors which are underlined were based on a model with random slopes for items, while Bayes factors which are not underlined are based upon a model with random intercepts only.

Appendix A

A list of the stimuli used in Experiment 1. The target words are presented in italics, with the first pair being the correct words, the second pair the transposition preview, and the final pair the substitution preview.

1. She happily watched the drowsy *owl nap/own lap/owe cap* during the daytime at the nature reserve.
2. It was well over an hour past the child's normal *bed time/bet dime/bee mime* once dinner was finished.
3. The detective knew that the local *mob put/mop but/moo hut* lots of time and effort into hiding evidence.
4. The president had claimed that it was really *not war/now tar/nor far* but humanitarian intervention.
5. He vowed that he would never *let duck/led tuck/leg suck* hunting occur on any of the land of his estate.
6. It was unsurprising that the rusty *pen tip/pet nip/peg dip* did not write particularly smoothly on paper.
7. She found the recent *hit pop/hip top/him hop* song that they kept playing on the radio very irritating.
8. The woman at the local *bar took/bat rook/ban book* her time finishing her drink before heading home.
9. He said that he would start wearing his furry *hat more/ham tore/hag core* once winter began to set in.
10. The ancient bread recipe said to gently *rub gin/rug bin/rum kin* into the dough in order to flavour it.

11. She scolded her hand on the really *hot pan/hop tan/hob fan* handle again while cooking her dinner.
12. He was instructed to write the answer to the maths *sum nice/sun mice/sub vice* and neatly in the booklet.
13. No matter how hard he tried he could only manage to get the stiff *lid part/lip dart/lit cart* way open.
14. She gently put her warm coffee *mug down/mud gown/mum town* upon the wooden desk and began to speak.
15. She saw the girl who was actually rather *sad try/sat dry/sag pry* and summon a smile for her mother.
16. She found the large *rat nest/ran test/raw best* hidden behind a large cardboard box inside the garage.
17. She was upset to find the entire *lot gone/log tone/low cone* with only a couple of crumbs left in the tray.
18. He would recall the really *mad trip/mat drip/map grip* that he had been on during summer for years to come.
19. The smelly *bog was/bow gas/box has* full of unpleasant chemicals that had leaked from the power plant.
20. He felt the wooden *oar tug/oat rug/oak jug* against something that was stuck under the river's water.
21. He liked to slowly *sip tea/sit pea/sin sea* as opposed to drinking it quickly like his brother did.
22. The customer saw the local butcher with the bloody *arm kill/ark mill/are bill* the last of the chickens.

23. The scout leader watched the smart *kid tie/kit die/kin lie* the complicated knot to secure the rope.
24. She saw the woman carrying the orange *bag dash/bad gash/ban rash* across the road to get to the shop.
25. The fizzy drink came in a silver *tin can/tic nan/tit fan* with a ring pull lid and cost eighty pence.
26. The angry *cop gave/cog pave/con cave* the suspect ten seconds to leave the vehicle full of stolen goods.
27. She thought that the man wearing the dirty fabric *rag must/ram gust/raw lust* definitely be homeless.
28. She was unable to believe that he would meanly *rip dear/rid pear/rig tear* old Sally off like that.
29. She was aware of the fact that her new sales *job grew/jog brew/joy crew* in duties as time went on.
30. He was the kind of man who would *pat your/pay tour/par sour* dog without permission if he felt like it.
31. He heard his fragile *rib make/rim bake/rig sake* a loud cracking sound as he stood up from his chair.
32. She saw the black *car tap/cat rap/cab gap* the other car on its rear bumper at the traffic lights.
33. He greatly enjoyed eating a moist *fig bun/fib gun/fin sun* as part of his lunch, with a pear and nuts.
34. Since he liked to keep his quiet *pub neat/pun beat/pup heat* he employed a cleaner to take care of it.

35. She heard a really noisy *big bang/bib gang/bit fang* when the factory on the edge of town exploded.
36. Sadly the lovely *bed got/beg dot/bee cot* soaked and damaged by the damp in the roof of the house.
37. The lost shoe that had been left behind would *fit none/fin tone/fix zone* of the people who tried it on.
38. The child watched his clever *dad mark/dam dark/day bark* the examination papers carefully last night.
39. The farmer could have sworn that he saw the female *pig nod/pin god/pie cod* at her mate in the next sty.
40. As the sailor viewed *his dock/hid sock/him lock* and boats he felt a great sense of pride and achievement.
41. The man was worried that the polio *jab may/jam bay/jar ray* cause swelling, but he had to have it.
42. He knows that tree trunks *rot well/row tell/rod hell* when they are kept in both warm and damp conditions.
43. The bad employee was known to often *rob dye/rod bye/row eye* from out of the textiles store cupboard.
44. The reporter with the paper *pad wove/paw dove/pal love* his way through the crowd at the press conference.
45. She held the brown *wig near/win gear/wit fear* the light to compare the colour of it to her own hair.

Appendix B

A list of the stimuli used in Experiment 2. The target words are presented in italics, with the first pair being the correct words, the second pair the transposition preview, and the final pair the substitution preview.

1. The girl found the recent *hit pop/pit hop/fit cop* song very irritating.
2. She knows that the yellow *fog can/cog fan/dog* man make navigating difficult.
3. He could see a hint of bright *red lip/led rip/fed dip* under the bride’s veil.
4. The pirate with the stained *map ran/man rap/mad rat* towards the treasure.
5. The man swung the wooden *bat far/fat bar/cat car* too late to hit the ball.
6. She hoped that the smelly *wet bed/bet wed/set fed* would dry out over the weekend.
7. The reporter with the paper *pad saw/sad paw/dad law* the grand opening ceremony.
8. The landlord at the trendy *bar can/car ban/tar man* pour drinks very quickly.
9. The bishop said that people who often *sin pay/pin say/win day* for it eventually.
10. She liked to gently *sip tea/tip sea/zip pea* while she sat and read her book.
11. She saw a single *sun ray/run say/gun lay* break through the grey clouds.
12. The man had a sticky *fig for/fog fir/fag fur* his afternoon snack yesterday.
13. The weather made the ginger *cat hot/cot hat/cut hit* and sweaty during the day.
14. Last night the crazed *fan hit/fin hat/fun hut* the security guard out of his way.
15. At lunch the tomato *pip got/pop git/pup gut* stuck in the poor girl’s throat.
16. The child hid the broken *pot far/pat for/pet fur* away from his mother’s house.
17. She wanted to play on the sandy *bay but/buy bat/boy bet* the weather was too cold.
18. She flinched as the thick *mud hit/mid hut/mad hot* her right in the face.
19. The man wearing the fabric *rag did/rig dad/rug dud* not look very healthy.
20. As the wind blew the falling *nut hit/nit hut/net hot* Daniel on the head.
21. She tried to get into the yellow *cab but/cub bat/cob bet* was beaten to it.

22. The food was stored in a pretty *tin pot/ton pit/tan pat* next to the fridge.

23. The policeman watched as the mafia *don lit/din lot/den let* his Cuban cigar.

24. She had counted *six fat/sit fax/sin far* men crowded around the shop counter.

25. The athlete who fell during the eighth *lap hid/lad hip/lag his* from the reporters.

26. The local shop started selling their *big hat/bit hag/bin had* for half price.

27. He knew that the massive *war tax/wax tar/wag tap* had bankrupted many businesses.

28. She saw how well the sticky *web fit/wet fib/wed fin* over the top of the burrow.

29. She was concerned that the flimsy *top may/toy map/too mad* not be warm enough.

30. The farmer watched as the sweaty *hog bit/hot big/hop bib* the poor sheep.

31. She tried to quickly *jam her/jar hem/jaw hen* new purse into her suitcase.

32. She saw the happy *hag hum/ham hug/hay hut* as she walked down the street.

33. The baker handed him the plastic *bun bag/bug ban /bud bat* after he paid her.