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Eye Movements When Reading Transposed Text: The Importance of Word-Beginning Letters

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Abstract

Participants' eye movements were recorded as they read sentences with words containing transposed adjacent letters. Transpositions were either external (e.g., *problme*, *rpoblem*) or internal (e.g., *porblem*, *probelm*) and at either the beginning (e.g., *rpoblem*, *porblem*) or end (e.g., *problme*, *probelm*) of words. The results showed disruption for words with transposed letters compared to the normal baseline condition, and the greatest disruption was observed for word-initial transpositions. In Experiment 1, transpositions within low frequency words led to longer reading times than when letters were transposed within high frequency words. Experiment 2 demonstrated that the position of word-initial letters is most critical even when parafoveal preview of words to the right of fixation is unavailable. The findings have important implications for the roles of different letter positions in word recognition and the effects of parafoveal preview on word recognition processes.

Keywords

reading; eye movements; word recognition; transposed letters; parafoveal processing

To establish a comprehensive account of word recognition, it is necessary to investigate the flexibility of letter encoding and in particular whether letters at certain positions within words are more easily encoded relative to letters at other positions. Much recent research has investigated these issues by employing experimental manipulations involving the systematic transposition of letters (TL) at different positions within words. In particular, there has been considerable interest in how text with TL nonwords is read (e.g., see Grainger & Whitney, 2004; Rayner, White, Johnson, & Liversedge, 2006[1]). In the present experiments, we recorded eye movements to precisely determine how disruptive TL nonwords are during reading. Specifically, we examined whether the position of transposed letters within a word influences how easily those words are processed. This was achieved by comparing the relative disruption

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[1] The short report by Rayner, White, et al. (2006) includes some preliminary analyses of the global data presented in much more detail in Experiment 1.

to eye movement behavior during reading caused by transposing adjacent letters at varying positions within words.

A number of studies using standard isolated word recognition tasks have shown that the coding of letter position is, in fact, quite flexible. For example, it has been clearly shown that nonwords involving a transposition of two letters (e.g., *jugde* for the base word *judge*) are more similar to their base words than substituted-letter nonwords in which two letters are replaced (e.g., *jupte*). This result has been found in a number of tasks including naming (Christianson, Johnson, & Rayner, 2005) and lexical decision (Chambers, 1979; Forster, Davis, Schoknecht, & Carter, 1987; O'Connor & Forster, 1981; Perea & Lupker, 2003a, 2003b, 2004). Thus, on the basis of these studies, it appears that TL nonwords can activate the lexical representation of their base words.

Evidence for the similarity between a TL nonword and its base word has also come from experiments in which participants are required to respond to the TL nonwords themselves (Andrews, 1996; Chambers, 1979; O'Connor & Forster, 1981) and from priming experiments in which TL nonwords are used as primes (e.g., Andrews, 1996; Christianson et al., 2005; Forster et al., 1987; Perea & Lupker, 2003a, 2003b, 2004). Recently, Johnson, Perea, and Rayner (2007; see also Johnson, 2007) conducted eye movement experiments in which they found that previews of words with transposed letters provided more benefit than previews with visually similar substituted letters. These experiments suggest that letter identity information plays a dominant role in lexical access (Perea & Lupker, 2003a, 2003b) relative to letter position information during word identification, at least for adjacent letters.

Davis and Bowers (2006) identified five different theoretical accounts that have been put forward to explain letter encoding during lexical processing. These are: (a) slot coding, (b) Wickel-coding, (c) continuous open bigram coding, (d) discrete open bigram coding, and (e) spatial coding. According to slot coding, a separate slot is assumed for each constituent letter of a word. This approach has been adopted in traditional models of lexical identification such as the interactive activation model (McClelland & Rumelhart, 1981), the dual route cascaded model (Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001), and the activation-verification model (Paap, Johansen, Chun, & Vonnahme, 2000; Paap, Newsome, McDonald, & Schvaneveldt, 1982). Note that more recently, "noisy" slot based coding has also been considered (Gómez, Perea, & Ratcliff, 2008; Perea & Lupker, 2004; Ratcliff, 1981). Wickelcoding is an explanation somewhat similar to slot-based coding that has been adopted in a number of connectionist models of lexical processing (see, e.g., Rumelhart & McClelland, 1986; Seidenberg & McClelland, 1989). According to Wickelcoding, letter positions are encoded in relation to their local letter context (e.g., the letter *O* in *DOG* would be coded as having a *D* to its left and a *G* to its right).

Continuous open bigram coding (Whitney, 2001; Whitney & Berndt, 1999; Whitney & Lavidor, 2005) as per the SERIOL model and discrete open bigram coding (e.g., Grainger & van Heuven, 2003) both involve encoding a word's constituent letters in terms of all the ordered bigram letter pairs that can be formed from the word (e.g., the word *DOG* would be encoded in terms of the bigrams *DO*, *OG*, and *DG*). The distinction between the two types of bigram coding, however, is that the activation levels associated with the bigrams under the discrete system are, as might be expected, discrete, having an activation of 0 or 1. In contrast, under the continuous bigram coding system, the bigrams have continuous activation values that lie between 0 and 1. For example, in the SERIOL model, letters nearer the word beginning are activated earlier and to a greater extent. Bigrams have higher activation levels if the letter inputs are more highly activated and if the component letters are closer together (less delay between their activations).

Finally, spatial coding is the method adopted in the SOLAR model of lexical identification (Davis, 1999; 2006; Davis & Bowers, 2004). According to the spatial coding approach, letter nodes within the lexical processing system are activated by a word's constituent letters, regardless of their position within the word. Thus, activation of a letter node occurs independent of letter position; the letter node for *D* would be activated by the word *DOG*, the word *ADO*, and the word *BUD*, regardless of the fact that the *D* appears in a different position in each of the words. Activation for each letter node reduces as a function of left to right position within the word. In this system, differential identification of words is achieved as a consequence of different words producing different spatial patterns of activation across the array of letter nodes, hence, spatial coding.

Davis and Bowers (2006) conducted one experiment using an illusory word paradigm and two masked form priming experiments to evaluate each of these competing accounts. Their results were consistent with the predictions of the spatial coding account, but not with any of the alternative explanations. Nevertheless, it is clear that further experimental work is required before the alternative theories of letter encoding can be categorically ruled out. However, what should be clear from the substantial body of research investigating isolated word processing is that any letter encoding system that attempts to account for these and related experimental findings requires a degree of flexibility that goes beyond the earliest and simplest of accounts.

An important point to note from the discussion above is that almost all of the studies discussed so far have examined lexical processing using isolated word paradigms. In the present experiments, we wished to examine the influence of TL nonwords under otherwise normal sentence reading conditions. During reading, words are processed as constituents of sentences or paragraphs and eye movements are made while processing the text. Thus, monitoring eye movements during reading, unlike responses to isolated words, involves the measurement of an aspect of human behavior that is a natural component of the reading process. Furthermore, there is a substantial body of evidence to indicate that eye movement behavior is highly sensitive to lexical variables (see Rayner, 1998, for a review). In this way, eye movement methodology permits the experimenter to investigate aspects of lexical processing as they occur during normal reading. Also, as sentences are spatially extended (in English) from left to right, letter information from foveal words, as well as from words in the parafovea, may be processed on any particular fixation. Additionally, because readers make a sequence of fixations when reading, any letter encoding effects that do occur may appear in one or more fixations (associated with both foveal and parafoveal processing). To this extent, effects may be both temporally distributed (over fixations across time) and spatially distributed (across different words within the sentence). It is for this reason that we considered a variety of reading time measures in our experiments to establish exactly when and how letter transpositions at different positions within words first disrupt reading.

Our research is similar in some respects to work reported by Rayner and Kaiser (1975) and by Jordan, Thomas, Patching, and Scott-Brown (2003). Rayner and Kaiser asked participants to read short passages of text in which beginning, middle, or end letters of words were replaced by either visually similar or dissimilar letters. While replacements with dissimilar letters made reading harder than replacements with similar letters, changes to beginning letters were far more disruptive than changes to middle and end letters. Jordan, Thomas, et al. recorded reading times for sentences that included words with visually degraded letters. They demonstrated that degradation of external letters made reading more difficult than degradation of internal letters.

The present experiments investigated the relative importance of different letter positions for normal reading. Different types of TL nonwords were presented within sentences such that two aspects of letter position processing were investigated. Based on the experiments reported by Rayner and Kaiser (1975) and those of Jordan, Thomas, et al. (2003; see also isolated word studies showing similar effects, e.g., Carr, Lehmkuhle, Kottas, Astor-Stetson, & Arnold, 1976; Forster, 1976; Humphreys, Evett, & Quinlan, 1990; Jordan, Patching, & Milner, 2000; Jordan, Patching, & Thomas, 2003), we manipulated whether external letter or internal letter pairs were transposed (externality). We also manipulated whether adjacent transposed letter pairs were toward the beginning of words, or toward the ends of words (location). Experiment 1 examined an additional question, namely, whether lexical processing difficulty (as manipulated by word frequency) influences the ease with which incorrect letter position information can be dealt with. We will discuss this manipulation in more detail below. Experiment 2 investigated whether the TL effects shown in Experiment 1 hold when the preview of words to the right of fixation was prevented such that words had to be processed exclusively in foveal vision.

In contrast to Rayner and Kaiser (1975) and Jordan, Thomas, et al. (2003), we recorded participants' eye movements and manipulated beginning and ending letters independently such that they could be directly compared. The eye movement data were taken as an online measure of disruption to reading caused by letter transpositions. We assumed that if some types of transpositions cause more disruption to reading than others, then letter encoding for those positions must be more critical for word recognition. We analyzed global sentence reading measures to determine how our transposition manipulations affected eye movement behavior generally. However, of particular interest were local measures, that is, specific analyses of eye fixations on the critical high- and low-frequency words that might reflect the time course of disruption to early and later processing (see *Results* section for the specific eye movement measures used in the experiments). For example, early processes may reflect initial letter coding or competition between lexical candidates, whereas late effects may reflect a verification stage in which words are fully identified and integrated into the sentence context.

We expected that word-initial transpositions would be more disruptive than word-final transpositions (Rayner & Kaiser, 1975) and that word-external transpositions would be more disruptive than word-internal transpositions (Jordan, Thomas, et al., 2003). On the assumption that both these variables might affect the ease of letter encoding, we also predicted that we might observe interactive effects such that word-external letters at word beginnings might cause more disruption than words in the other transposed conditions. Since letter encoding is a process required early in lexical identification, we expected that these effects would appear with some immediacy after an initial fixation on a TL word. However, increased reading times may persist throughout subsequent stages of word identification and integration into the sentence context, and therefore we also expected that we might observe disruption in later measures of processing.

Experiment 1

There is some evidence from isolated word experiments to suggest that TL effects can be modulated by word frequency. For example, O'Connor and Forster (1981) showed that when transpositions were made in high- and low-frequency words (e.g., *mohter* and *bohter*, respectively), participants produced more errors (i.e., they responded that the TL nonwords were words) on high-frequency items than low-frequency items. These results indicate that high-frequency TL nonwords are more effective in activating the lexical representation of their base word than low-frequency TL nonwords (see also Perea, Rosa, & Gomez, 2005). Andrews (1996) reported similar findings for transposed-letter neighbors (e.g., *silver* and *sliver*). Other evidence using priming methodology with the lexical decision task, in contrast, has shown no modulation of the TL effect by word frequency (Forster et al., 1987). On balance, it does appear that it may be easier to identify a high-frequency word than a low-frequency word on the basis of nonwords with transpositions in the same position.

In relation to eye movement research, to date there has been no work to investigate the modulatory influence of word frequency on transposed letter effects. However, it is very well established that word frequency has a strong influence on eye movements during reading such that readers look longer at low-frequency words than high-frequency words (Rayner & Duffy, 1986). The frequency effect is very robust and has been replicated on numerous occasions (e.g., Altarriba, Kroll, Sholl, & Rayner, 1996; Henderson & Ferreira, 1990; Hyönä & Olson, 1995; Inhoff & Rayner, 1986; Just & Carpenter, 1980; Kennison & Clifton, 1995; Liversedge et al., 2004; Rayner, Liversedge, White, & Vergilino-Perez, 2003; White, 2008). The question of whether lexical frequency modulates processing difficulty associated with TL nonwords during normal reading remains open. On the basis of isolated word experiments, however, it does appear that we might expect frequency to exert an influence such that greater disruption to processing occurs for low-frequency words, which are less effective in activating a word's base form, than for high frequency words. Thus, we included the manipulation of the frequency of a critical word in our experimental sentences to investigate its influence on transposition effects for that word. We predicted that TL nonwords (with letter transpositions in the same position) would be more effective in activating the base form of a high- than a low-frequency word, indicating that accurate letter position information is less critical for successful lexical identification of words that are easier to identify than for words that are more difficult to identify.

Method

Participants—Thirty students from the University of Durham, Durham, England, with normal or corrected-to-normal vision were paid to participate in the experiment. All were naïve in relation to the purpose of the experiment.

Apparatus—The sentences were presented on a ViewSonic 17GS monitor with the characters presented in Courier font. The monitor was interfaced with a computer through a VGA board. The sentences were displayed at a viewing distance of 80 cm and 3.7 characters subtended one degree of visual angle. The room was dimly illuminated. The letters were presented in light cyan on a black background. Eye movements were monitored using a dual-Purkinje-image eye tracker that was interfaced with the computer. The resolution of the eye tracker is less than 10 min of arc and the sampling rate was every millisecond. Monocular eye movements were recorded although viewing was binocular.

Materials and design—Participants read 80 experimental sentences with 10 experimental conditions. The experimental conditions derived from a 2 (target word frequency: high vs. low) × 5 (type of transposition: none, internal transposition–beginning letters, internal transposition–ending letters, external transposition–beginning letters, external transposition–ending letters) design. A sample sentence is shown in Table 1 with the 10 different manipulations. In the control condition, the items were spelled correctly (e.g., *problem*). Two TL variables, externality and location, were manipulated within participants and items. Transpositions were always adjacent and were either internal (e.g., *porblem, probelm*) or external (e.g., *rpoblem*, *problme*) and either at the word beginning (e.g., *porblem*, *rpoblem*) or ending (e.g., *probelm, problme*). For each transposition condition, all words five or more letters long were transposed within each sentence. None of the transpositions produced real words, and all of the transpositions produced a change in spelling. Within each sentence there was one critical word for which the variable of word frequency was manipulated within participants and items. The critical word was either frequent (e.g., *problem*) or infrequent (e.g., *anagram*). There were two sentence frames into which each of these critical words could fit, thereby ensuring that every participant saw all of the critical words. Each of the sentences was up to 71 characters long.

To ensure that the TL nonwords could be correctly identified, we conducted a norming experiment in which participants (who did not participate in the eye movement experiment) read the sentences and circled words that they could not understand. For each item, six participants completed each of the 10 different conditions. Ten lists of sentences were created in which the 10 conditions were counterbalanced according to a Latin-square design. The lists also included 20 filler sentences that contained nonwords. Only one of the control words (which were not transposed) was circled as not understood. In contrast, 87% of the nonwords from the filler sentences were circled as not understood. The fact that the vast majority of the control words were not circled and the majority of nonwords were circled shows that participants were doing the task appropriately. Overall, 1.2% of the TL nonwords were circled as not understood. For the 80 experimental items used here, one third or fewer of the participants circled any of the component TL nonwords in any one condition.[2]

The sentences contained 10.7 words on average (*SD* = 1.5), but an average of only 4 words (*SD* = 1.2) were transposed (none of the transpositions produced other words). The critical high-/low-frequency words were 7 to 10 letters long ($M = 7.9$, $SD = 0.9$), and they were embedded approximately in the center of the same sentential frame for each item. Word frequencies in counts per million were calculated using the CELEX English written word form corpus (Baayen, Piepenbrock, & Gulikers, 1995). The frequent words had significantly higher word frequency ($M = 142$, $SD = 96$) than the infrequent words ($M = 1.6$, $SD = 1$), $t(39) = 9.23$, $p < .001$. There was no difference in the number of orthographic neighbors between the high-frequency ($M = 0.5$, $SD = 0.8$) and low-frequency ($M = 0.5$, $SD = 1.1$) words ($t < 1$), based on the complete English Lexicon Project database (Balota et al., 2002). To ensure that the frequent and infrequent words were equally predictable, a sentence completion pretest was undertaken. Ten participants were given the beginning portions of a sentence up to the critical word and asked to provide a single word that they felt would fit as the next word in the sentence (there were no transpositions). For the 80 experimental sentences, the 10 participants responded with a critical word only twice: once for the frequent condition and once for the infrequent condition. Therefore, there was no difference in the predictability of the critical words between the frequent and infrequent word conditions.[3]

Each participant saw all of the frequent and infrequent critical words as they were presented in different sentence frames. The items were counterbalanced so no participant saw any critical word more than once. The sentences were presented in a fixed pseudo-random order with 5 filler sentences presented at the beginning. Ten lists of 85 sentences were constructed. The conditions were rotated following a Latin-square design so that each participant read 8 sentences in each condition. Thirty of the sentences were followed by a comprehension question to ensure that participants concentrated on understanding the sentences.

Procedure—Participants were told that

> Some of the letters in some of the words may be mixed up. However you will probably be able to guess what most of these words mean. Therefore please concentrate on understanding the sentences to the best of your ability.

A bite bar was used to minimize head movements. Before the presentation of a sentence, the accuracy of the eye tracker was checked and recalibrated if necessary. After reading each

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[2] There were differences in the percentage of TL nonwords circled as not understood across the four transposition conditions (internal beginning: $M = 0.91$; internal ending: $M = 0.64$; external beginning: $M = 2.22$; external ending: $M = 1.06$). There were significant effects of externality, $F_2(1,79) = 15.78$, $MSE = 3.8$, $p < 0.001$, location, $F_2(1,79) = 6.55$, $MSE = 6.3$, $p < 0.05$, and an interaction between these two variables, $F_2(1,79) = 5.64$, $MSE = 2.8$, $p < 0.05$. Fewer words with external beginning transpositions were understood than any of the other three types of transposition (*t*s > 3, *p*s < 0.01). The differences in the proportion of TL nonwords not understood reflects similar patterns in the disruption caused to reading by these same TL nonwords in Experiments 1 and 2.

[3] A list of experimental sentences and critical words is available from the first author on request.

sentence, participants pressed a button to continue and used a button box to respond *yes*/*no* to comprehension questions. The experiment lasted about 30 min.

Analyses—Fixations under 80 ms that were within one letter of the next or previous fixation were incorporated into that fixation. Any remaining fixations under 80 ms and over 1,200 ms were discarded. Four percent of trials were excluded due to tracker loss or blinks on first-pass reading of the critical word and zero reading times on the first part of the sentence.

Results

The results were analyzed in terms of global and local measures. Global measures were based on all of the fixations within the sentence. Local measures were based only on the high or low frequency critical word. Repeated measures analyses of variance (ANOVAs) based on participant (F_1) and item (F_2) variability were undertaken. The mean error rate on the comprehension questions was 4%, indicating that participants properly read and understood the sentences. After the experiment, participants were asked if there were any words that they did not understand in any of the sentences. Thirty-three percent of participants said they understood everything, 17% said they did not understand just one of the words, and 50% said that there were a couple or a few words that they did not understand. Thus, despite the inclusion of the transpositions, participants were able to identify the words in the sentences.

Global measures—Global measures include total sentence reading time, average forward and regressive fixation duration, and total number of forward and regressive fixations per sentence. Fixations preceded by rightward (progressive) moving saccades are referred to as forward fixations, and fixations preceded by leftward moving saccades are referred to as regressive fixations. The global measures provide an index of the overall difficulty that readers experienced throughout the entire sentence when the words contained transpositions in different positions. Note that the number and duration of forward fixations is more likely to reflect effects of early processing, whereas the number and duration of regressive fixations and total sentence reading time is more likely to reflect effects of later processing.

When collapsed across the four different types of transposition, all of the global measures showed a significant difference between the control text and text including TL nonwords (ts > 3.7, ps $< .01$). Table 2 shows that reading times were longer and there were more fixations for the text with TL nonwords compared to the control condition. Total sentence reading times ranged from 36% longer in the external beginning transposed condition to 11% longer in the internal ending transposed condition, compared to the control condition.

In order to investigate the effect of transposition more carefully, 2 (externality: internal, external) × 2 (location: beginning, ending) ANOVAs were carried out for the four transposed conditions, and the results of these statistical analyses are shown in Table 3.

There was a main effect of externality such that there were longer total sentence reading times, longer forward and regressive fixation durations, and more forward and regressive fixations when transpositions were external compared to when they were internal (Fs > 10, ps $< .01$). Therefore, external letters are clearly more critical for word recognition than internal letters. There was also an effect of location for forward fixation durations such that fixations were longer for sentences in which there were transpositions at word beginnings, compared to word endings. There was no interaction between location and externality for forward fixation durations, and even for internal transpositions, the word-beginning transpositions were more disruptive than the word-ending transpositions, $t_1(29) = 2.93$, $p < .01$, $t_2(79) = 2.33$, $p < .05$. In contrast to average forward fixation duration, there was no main effect of location and no interaction between externality and location for the number of forward fixations (Fs < 1.2).

There were also significant or marginal effects of transposition location for the later measures of regressive fixation durations, number of regressive fixations, and total sentence reading time, with increased reading times and regressions for word-beginning than word-ending transpositions (*F*s > 1.7, *p*s < .2). These effects were qualified by significant or marginal interactions between externality and location, such that there were significant effects of location for external (*t*s > 2.1, *p*s < .05) but not internal (*t*s < 1.5, *p*s > .15) transpositions. External-beginning transpositions were more disruptive than any of the other three types of transposition for all these three measures (*t*s > 2.1, *p*s < .05). Clearly the first letters of a word are very important for word recognition during reading. In addition, note that for total sentence reading time, transposition of the external-ending letters caused more disruption than both internal-beginning transpositions, $t_1(29) = 4.55$, $p < .001$; $t_2(79) = 3.7$, $p < .001$, and internal-ending transpositions, $t_1(29) = 4.52$, $p < .001$; $t_2(79) = 4.66$, $p < .001$. These results suggest that, overall, the position of word-final letters may be more critical than the position of word-internal letters.

In summary, for all of the measures transposition of the external-beginning letters caused numerically the most disruption, indicating that the position of the word-initial letters are most critical for word recognition. Furthermore, at least for later global measures of processing, the position of word-initial letters is much more critical than any of the other letters, whereas the position of word-final letters is more critical than the position of word-internal letters.

Local measures—We calculated the duration of the first fixation, the gaze duration (the sum of fixations on a word before leaving it), and total time (the sum of all fixations within a word) on the critical high-/low-frequency word. The first fixation and gaze duration measures usually reflect quite immediate influences on eye movements that are associated with the fixated word. In contrast, the total time on a word is generally taken to reflect less immediate linguistic influences that take longer to manifest within the eye movement record. For example, first fixation and gaze durations may reflect initial letter coding or competition between lexical candidates, whereas the measure of total time may reflect processes related to full word identification and integration into the sentence context.

Similar to the global analyses, Table 4 shows that there were longer reading times and more fixations on the TL nonwords compared to the control words. A series of 2 (frequency: frequent, infrequent word) × 2 (text: control, TL nonword) ANOVAs were undertaken collapsing across the four different types of transposition. There were main effects of both frequency (*F*s > 52, *p*s < .001) and text (*F*s > 17, *p*s < .001) for all of the measures, indicating that low-frequency words with and without transpositions were more difficult to read than similar high-frequency words, and that words with a transposition were more difficult to read than words without a transposition, regardless of their frequency. There were no significant interactions between these two variables for first fixation duration or gaze duration (*F*s < 2.5). However, there was a significant interaction for total time, $F_1(1, 29) = 10.44$, $MSE = 5{,}680$, $p < .01$; $F_2(1, 79) = 12.05$, $MSE = 16{,}143$, $p < .01$.

The difference in total time between TL nonwords and control words was greater for low-frequency (224 ms) than for high- frequency (131 ms) critical words $t_1(29) = 3.23$, $p < .01$; $t_2(79) = 3.47$, $p < .01$. This finding is in line with isolated word studies (e.g., O’Connor & Forster, 1981) and supports our prediction that high-frequency words with transpositions would be more effective in activating a word’s base form than low-frequency words with transpositions. The larger TL effect for low-frequency than high-frequency words indicates that accurate letter position information is less critical for successful identification of words that are easier to identify than words that are more difficult to identify. It is important to note that the interactive effect occurred for total time, but not for earlier measures such as first fixation and gaze duration, indicating that the effect is being driven by fixations made during reinspection of the word. Thus, frequency appears to modulate TL effects at later stages of processing, perhaps at a verification stage (to establish unequivocally that the word has been identified correctly given the full sentential context), rather than during earlier stages of processing such as initial letter encoding during lexical identification.

To explore the local data in more detail, we carried out some further analyses to investigate the effect of word frequency on TL effects. We conducted 2 (frequency: frequent, infrequent word) × 2 (externality: internal, external) × 2 (location: beginning, ending) ANOVAs. The results of these analyses (main effects and the Location × Externality interaction) are shown in Table 5.

All of the reading time measures showed a main effect of word frequency (Fs > 24, ps < .001), with longer reading times for infrequent compared to frequent words. Similar to the global analyses, the local analyses showed that external transpositions produced more disruption to reading than internal transpositions (Fs > 5.6, ps < .05). There were also main effects of transposition location for first fixation, gaze duration, and total time (Fs > 4.8, ps < .05), with more disruption for word-beginning than word-ending transpositions. In addition to the main effects, the interaction between externality and location was marginal for first fixation duration and gaze duration, with slightly weaker effects for total reading time (see Table 5). For all three measures, reading times were longer for words with beginning compared to ending transpositions, but this effect was far more pronounced for external transpositions (first fixation, 26 ms; gaze duration, 60 ms; total time, 81 ms) than for internal transpositions (first fixation, 10 ms; gaze duration, 21 ms; total time, 18 ms). Thus, the local analyses are consistent with the global analyses in that they demonstrate that external word-initial letters are most critical for word recognition.

First fixation duration showed no difference between the external ending and internal transpositions (ts < 1). However, although gaze durations showed no significant difference between external ending and internal beginning transpositions, $t_1(29) = 1.29$, $p > .20$; $t_2(79) = 1.22$, $p > .22$, external ending transpositions were more disruptive than internal ending transpositions, $t_1(29) = 2.68$, $p < .05$, $t_2(79) = 3.21$, $p < .01$. The results suggest that for very early processing of the critical word, the position of the word-final letter was equally important to the position of the internal letters. However, subsequent processing begins to follow the same trends as for the global measure of total sentence reading time, such that for later word processing the position of word-final letters becomes more important than the position of internal letters.

Finally, for total time there was an interaction between word frequency and externality that was marginal by items, but not reliable by participants, $F_1(1, 29) = 2.65$, $MSE = 18{,}672$, $p = .114$; $F_2(1, 79) = 3.64$, $MSE = 59{,}205$, $p = .06$. The numerical interaction indicates that there was a bigger effect of externality for the low- compared to high-frequency words. Similar to the interaction between text and word frequency for total time described above, the interaction indicates that accurate letter position information for external letters is more critical for words that are more difficult to identify.

Overall, the local and global measures for Experiment 1 both consistently show that the positions of the word-initial letters are more critical for word processing than any of the other letter positions. In addition, the local measures indicate that the frequency of words modulates processing of TL nonwords at least in the later stages of word processing.

Discussion

Text including TL nonwords is clearly more difficult to read than text that does not include transposed letters. However, participants reported understanding most or all of the words in the experiment. Therefore, the longer reading times for transposed text are likely to arise largely due to difficulty with attaining understanding of individual words, rather than simply a failure to identify words at all. The fact that sentences including TL nonwords can be understood with increases in sentence reading times as low as 11% suggests that word recognition processes must be quite flexible in the way letter position information is encoded. Both global and local analyses revealed main effects of externality and location, with external transpositions leading to more disruption than internal transpositions and beginning transpositions leading to more disruption than ending transpositions. Transposing the first letters of a word (external beginning transpositions) caused the most disruption for all the global and local measures. The positions of the first letters of the word are therefore more critical than the ending letters of the word for letter position encoding during reading. Additionally, external ending transpositions were more important than internal transpositions (especially so in later measures), suggesting that external letters have a privileged role relative to internal letters during word identification. Finally, in line with the two main effects, the interactive pattern indicates that, at least numerically, the position of external, word initial letters are much more vital than other letters to word identification during reading.

Experiment 2

The results of Experiment 1 suggest that the word-initial letters are especially important in word recognition. There are at least two reasons why this might be the case. First, it may be that a word's initial letters are simply intrinsically important during lexical identification. For example, readers may process a word's constituent letters from left to right during lexical identification. Therefore, word initial letters would have critical status during identification. Alternatively, word initial letters may be particularly critical for lexical identification due to the way in which words are visually processed during reading. Clearly, when people read English sentences they make a series of fixations and saccades usually in a left to right direction. Thus, a word is initially available to be processed visually in the parafovea prior to direct fixation, and then after a saccade onto the word it is available for direct inspection in foveal vision. Given that words in English are horizontally spatially extended left to right, and that visual acuity falls off from the fovea to the periphery, then the letters at the beginning of a word will be more clearly visible in parafoveal vision than the letters at the end of a word. This may be why word-initial external letters are particularly important during English reading. This suggestion is consistent with a substantial body of previous research (e.g., Briihl & Inhoff, 1995; Inhoff, 1989, 1990; Rayner, Well, Pollatsek, & Bertera, 1982) that has shown that word-beginning letters especially facilitate parafoveal processing. Thus, the larger effects obtained for external word-initial letters in Experiment 1 may have occurred either due to their parafoveal availability, or alternatively as a consequence of these letters having intrinsic importance in lexical identification.

In Experiment 2 we investigated whether the letter position effects shown in Experiment 1 occurred solely due to the parafoveal availability of word initial letters. To do this we used a presentation methodology such that words to the right of fixation were only made available once the eye moved to them. Such a manipulation prevents participants from obtaining a parafoveal preview of words before they are directly fixated. Thus, in using this method in Experiment 2 we ensured that all words were processed exclusively in foveal vision.[4] Additionally, similar to Experiment 1, we included a comparison condition in which text was

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[4] Letter information for words to the left of fixation was retained in the unavailable preview condition in Experiment 2 in order to enable accurate targeting of regressions to words earlier in the sentence, and therefore minimizing disruption to reading. We recognize that, theoretically, words to the left of the fixated word could therefore be parafoveally processed. However, previous research suggests that in reading left-to-right languages the majority of parafoveal processing occurs for words to the right of fixation in comparison to the left (McConkie & Rayner, 1976). Therefore, for simplicity, throughout the paper we refer to words in the unavailable preview condition in Experiment 2 as being processed exclusively in foveal vision.

presented normally, thereby permitting direct comparison of the transposition effects obtained in the two experiments. We predicted that if the word initial letter effects observed in Experiment 1 arose exclusively due to parafoveal processing, then while we might still obtain disruption due to transpositions, there should be no modulatory influence of whether the transposition occurred at the beginning or end of the word. Alternatively, if word initial letters are intrinsically important during lexical identification and the effects are not driven by parafoveal processing that occurs prior to direct fixation, then similar effects to those observed in Experiment 1 should also occur in Experiment 2.

Method

Participants—Thirty students from the University of Durham with normal or corrected-to-normal vision were paid to participate in the experiment. All were naïve in relation to the purpose of the experiment.

Apparatus—The sentences were presented on a Philips 21B582BH, 24-in monitor with the characters presented in Courier font in white on a black background. The monitor had a P22 phosphor with decay rate to 0 in less than 1 ms. The sentences were displayed at a viewing distance of 90 cm and 4.4 characters subtended one degree of visual angle. The room was dimly illuminated. Eye movements were again monitored by a dual-Purkinje-image eye tracker that was interfaced with the computer.

Materials and design—Participants read 80 experimental sentences with 10 experimental conditions. The experimental conditions derived from a 2 (preview: available vs. unavailable) × 5 (type of transposition: correct, internal transposition-beginning letters, internal transposition-ending letters, external transposition-beginning letters, external transposition-ending letters). In the unavailable preview condition, a saccade-contingent change technique was used (McConkie & Rayner, 1975; Rayner, 1975) such that all words to the right of the fixated word (including following regressions) had letters replaced with *X*s. Table 6 shows examples of stimuli presentation during the unavailable preview conditions. The transposition manipulations were the same as in Experiment 1. The stimuli were largely the same as in Experiment 1 except that, to reduce the number of experimental conditions, word frequency was not manipulated. Each critical word from Experiment 1 was presented in one sentence per item; hence, all participants saw the same sentences that were simply transposed in different ways. Consequently, local analyses of a critical 7- to 10-letter-long word for each of the items could be undertaken. In addition, one sentence was shortened slightly to reduce the maximum number of characters per sentence to 66.

The sentences were presented in a fixed pseudorandom order across two blocks of equal length. In one block, the text was presented normally (available preview). In the other block, all words to the right of the fixated word appeared only when the eye moved to them (unavailable preview). Five filler sentences were presented at the beginning of each block. The order of the blocks was fixed such that there were 10 lists of 90 sentences, of which 80 were experimental sentences. Whether the preview in each of the blocks was available or unavailable was counterbalanced across the other five conditions following a Latin-square design, so each participant read 8 sentences in each condition. Twenty-eight of the sentences were followed by a comprehension question to ensure that participants concentrated on understanding the sentences.

Procedure—The procedure was the same as in Experiment 1.

Analyses—Five percent of trials were excluded due to tracker loss.

Results

The same global and local measures are presented as in Experiment 1, and statistical analyses were undertaken in a similar manner to Experiment 1. The mean error rate on the comprehension questions was 6%, indicating that participants properly read and understood the sentences.

Global measures—For the global measures of number of fixations and fixation durations, fixations were excluded if they were less than 80 ms or longer than 1,200 ms. Table 7 shows the mean global measures for each condition. Collapsing across the four types of transposition, 2 (preview: available, unavailable) × 2 (text: control, transposed) ANOVAs were undertaken. For total sentence reading time, number of forward fixations, and duration of forward and regressive fixation durations, there were significantly longer reading times or more fixations for text with unavailable previews, compared to available previews (Fs > 30, ps < .001). Although there was no significant effect of preview for the number of regressive fixations, $F_1 < 1$, $F_2(1, 79) = 1.72$, $MSE = 0.76$, $p = .193$, availability of parafoveal preview to the right of fixation clearly facilitated text processing.

Similar to Experiment 1 for all of the measures, there were longer reading times and more fixations on the text including TL nonwords compared to the control conditions (Fs > 15, ps < .001). For the available preview conditions, total sentence reading times ranged from 42% longer in the external-beginning transposition to 9% longer in the internal-ending transposition condition compared to the control condition (these were 28% and 7% longer, respectively, for the unavailable preview conditions). There was no interaction between preview and text for total sentence reading time (Fs < 1), number of forward fixations (Fs < 1.2), number of regressive fixations, $F_1(1, 29) = 1.29$, $MSE = 0.27$, $p = .266$; $F_2(1, 79) = 2.43$, $MSE = 0.51$, $p = .123$, or the duration of regressive fixations, $F_1 < 1$, $F_2(1, 77) = 2.22$, $MSE = 1{,}341$, $p = .14$. However, there was an interaction between preview and text for forward fixation durations, $F_1(1, 29) = 5.54$, $MSE = 113$, $p < .05$; $F_2(1, 79) = 5.85$, $MSE = 262$, $p < .05$, such that there was disruption for transposed compared to control text when preview was available, $t_1(29) = 5.89$, $p < .05$; $t_2(79) = 5.51$, $p < .05$, but not when preview was unavailable, $t_1(29) = 1.41$, $p = .168$; $t_2(79) = 1.61$, $p = .112$. Note that in the unavailable preview conditions, the forward fixations are those fixations that cause words with transpositions to be made visible to the reader, often for the first time. Thus it is important that the lack of transposition effects for unavailable previews (but not available previews) suggests that the transpositions were processed parafoveally, at least to some degree.

To investigate the effects of preview and transposition more carefully, 2 (preview: available, unavailable) × 2 (externality: internal, external) × 2 (location: beginning, ending) ANOVAs were undertaken across the eight TL nonword conditions. The statistical details of the main effects and the externality × location interactions are shown in Table 8. There were significantly longer total sentence reading times, longer forward and regressive fixation durations, and more forward fixations in the unavailable compared to the available preview conditions (Fs > 47, ps < .001). The number of regressive fixations showed a similar pattern of effects, but this was significant only across items and not participants. Similar to the effect of preview reported above, these findings support many previous studies showing that text to the right of fixation is preprocessed during reading and this facilitates normal reading (see Rayner, 1998).

For all of the global measures, there was a significant main effect of externality such that reading times were longer and there were more fixations on words with external than internal transpositions (Fs > 4.2, ps < .05). As in Experiment 1, there was no effect of location and no interaction between externality and location for the number of forward fixations (Fs < 1). However, there were main effects of location for the other global measures such that reading times were longer and there were more fixations on words with transpositions at their beginnings, compared to their endings (Fs > 9.9, ps < .01). Also similar to Experiment 1, the numerical effect of location was larger for external than internal transpositions, though the interaction between location and externality was only significant for the number of regressive fixations. Collapsing across the variable of preview, there were significantly more regressive fixations for external-beginning compared to external-ending transpositions, $t_1(29) = 6.64$, $p < .001$; $t_2(79) = 4.08$, $p <.001$, but no such significant effect for internal transpositions, $t_1(29) = 1.75$, $p < .091$; $t_2 < 1.1$. Furthermore, there were no three-way interactions between preview, location, and externality for any of the measures (Fs < 1.6, ps > .22).

Given the main effects of location, the interactive patterns for location and externality, and the absence of a three-way interaction with preview, it is clear that regardless of whether the text was presented with or without an available preview, the external-beginning transpositions were most disruptive to reading. That is, even when there is no parafoveal preview of the word to the right of fixation, word-initial letters are still most critical for word recognition. In addition, as in Experiment 1, the external-ending transpositions were numerically more disruptive than the internal transpositions for total sentence reading time both when the preview was available and when it was unavailable. Therefore, even when words are processed exclusively in foveal vision, the results suggest that, at least for later measures of processing, the position of the word-final letter is more critical than the position of the word-internal letters.

There was no interaction between preview and externality for any of the global measures (Fs < 2.99). There was no reliable interaction between preview and location for total sentence reading time, number of regressive fixations, number of forward fixations (Fs < 2.52), or regressive fixation durations, $F_1(1, 29) = 2.04$, $MSE = 781$, $p < .164$, $F_2(1, 77) = 7.56$, $MSE = 2{,}443$, $p < .01$. However, for forward fixation durations, there was a significant interaction between preview and location, $F_1(1, 29) = 4.99$, $MSE = 142$, $p < .05$, $F_2(1, 79) = 6.3$, $MSE = 529$, $p < .05$, with longer fixation durations for word-beginning than word-ending transpositions for the unavailable preview conditions (11 ms difference), $t_1(29) = 3.29$, $p < .01$, $t_2(79) = 3.95$, $p < .001$, but no reliable difference for the available preview conditions (3 ms difference), $t_1(29) = 1.68$, $p < .104$, $t_2(79) = 1.41$, $p =.162$. Once again, this result indicates that word-beginning letters are extremely important for word recognition during reading. Furthermore, it appears that word-beginning letters have intrinsic importance in lexical identification such that word-initial transpositions still produce disruption even when parafoveal processing is not possible.

Local measures—Table 9 shows the mean local measures for each condition. Note that, as in Experiment 1, first fixation and gaze durations are likely to reflect earlier effects of processing than total time. Furthermore, the manipulation of parafoveal preview in the present study is likely to have more critical implications for early measures of word processing; hence, first fixation and gaze duration may be especially influenced by this manipulation. It is important to note that the detailed time course of processing shown by these measures not only tests whether the same effects hold with and without preview, but also tests whether the same effects may occur but within different time frames. For example, an effect that may occur in first fixation as a result of parafoveal processing of the available preview may be delayed when preview is prevented—for example, occurring in gaze duration.

Note that first fixation durations shorter than 80 ms and longer than 1,200 ms were excluded, and gaze durations shorter than 80 ms were also excluded. We first collapsed across different types of transposition and, similar to the global analyses, found longer reading times in the unavailable preview conditions, compared to the available preview conditions (Fs > 174, ps < .001). In addition, there were longer reading times on the TL nonwords compared to the control words (Fs > 10, ps < .001). Again, consistent with earlier analyses, preventing preview and transposing words' constituent letters had a disruptive effect on reading.

For first fixation durations there was no interaction between preview and whether the words were transposed (Fs < 1). However, there was a significant interaction for gaze duration, $F_1(1, 29) = 10.16$, $MSE = 3{,}339$, $p < .01$; $F_2(1, 78) = 10.81$, $MSE = 8{,}498$, $p < .01$, and a similar trend for total time, $F_1(1, 29) = 3.24$, $MSE = 5{,}043$, $p = .082$; $F_2(1, 79) = 3.48$, $MSE = 10{,}604$, $p = .066$, such that transpositions were much more disruptive for unavailable previews, where parafoveal processing was not possible (mean gaze duration difference = 147 ms; mean total time difference = 234 ms), than was the case for available previews, where text was presented normally (mean gaze duration difference = 77 ms; mean total time difference = 190 ms). These results suggest that disruption to processing due to transpositions was distributed across those fixations made prior to the critical word (parafoveal processing) as well as on the critical word (foveal processing) when the text was presented normally. However, under unavailable preview conditions, since parafoveal processing was not possible, disruption as a result of the transpositions could only commence once the critical word was fixated. Thus, the effects for gaze duration and total time on the word were larger under unavailable preview conditions than under available preview conditions.

As with the global analyses, in order to investigate the effects of transposition more carefully, 2 (preview: available, unavailable) × 2 (externality: internal, external) × 2 (location: beginning, ending) ANOVAs were undertaken across the eight transposition conditions. The statistical details of the main effects and the Externality × Location interactions are shown in Table 10. As in the analyses above, there were longer reading times on the words with unavailable, compared to available, previews (Fs > 102, ps < .001).

First fixation duration and total time produced significant effects of location (Fs > 5, ps < .05) with longer times for word-beginning than word-ending transpositions. Also, words with external transpositions produced longer gaze durations and total times than internal transpositions (Fs > 35, ps < .01), though there was no such effect for first fixation durations (Fs > 1). See the interactions described below for further clarification.

There were trends toward an interaction between externality and location for first fixation duration and gaze duration. The numerical pattern was again consistent with previous results, with a larger difference between beginning and ending transpositions when they were external (first fixation = 25 ms; gaze duration = 56 ms) than when they were internal (first fixation = 9 ms; gaze duration = 2 ms). Once again, the data clearly show that external word-initial letters are extremely important for lexical identification during reading. External ending transpositions were also numerically more disruptive than internal transpositions for gaze durations and total time.

There were significant interactions between preview and externality for first fixation duration, $F_1(1, 29) = 6.54$, $MSE = 1{,}746$, $p < .05$; $F_2(1, 78) = 5.6$, $MSE = 4{,}921$, $p < .05$, and gaze duration, $F_1(1, 29) = 4.59$, $MSE = 19{,}959$, $p < .05$; $F_2(1, 78) = 4.35$, $MSE = 33{,}662$, $p < .05$. For first fixation duration, collapsing across the variable of location, external transpositions produced significantly more disruption than internal transpositions for available preview conditions, $t_1(29) = 2.6$, $p < .05$; $t_2(79) = 2.43$, $p < .05$, but not for unavailable preview conditions, $t_1(29) = 1.22$, $p = .234$; $t_2(79) = 1.26$, $p = .211$. In contrast, for gaze duration there were significant effects of externality for both available previews, $t_1(29) = 5.94$, $p < .001$; $t_2(79) = 4.53$, $p < .001$, and unavailable previews, $t_1(29) = 4.75$, $p < .001$; $t_2(79) = 5.19$, $p < .001$, but the effect of externality was almost twice as large for unavailable compared to available previews. The results suggest that when parafoveal preprocessing to the right of fixation is prevented, the effects of the position of external letters are delayed such that there is no effect of externality for measures of initial word processing (first fixation duration). However the externality of transpositions does subsequently influence word processing, as shown by the effects in gaze duration. Note that any disruption to externality processing caused by unavailable previews was resolved during first pass, such that there was subsequently no interaction between preview and externality for total time (*F*s < 1). Hence, overall, external transpositions are more disruptive than internal transpositions regardless of whether there is preview to the right of fixation, but preview does influence the time course of these effects.

There were no significant interactions between preview and location for first fixation duration, $F_1(1, 29) = 1.02$, $MSE = 2{,}990$, $p = .320$; $F_2(1, 78) = 2.41$, $MSE = 5{,}476$, $p = .125$, gaze duration (*F*s < 1), or total time (*F*s < 1). Finally, there were no reliable three-way interactions for first fixation duration (*F*s < 4.3) or for gaze duration or total time (*F*s < 1).

Discussion

Overall, the effects of transposed letters in Experiment 2 are similar to the results of Experiment 1. Transposition of the word-initial letters caused most disruption to reading and transposition of beginning letters was more disruptive than transposition of ending letters, with a bigger effect of location for external than internal transpositions. Preventing parafoveal processing to the right of fixation in Experiment 2 had two effects on processing of the transpositions. First, effects of the externality of transposed letters occurred in later local measures for the unavailable previews compared to when previews were available. In other words, disruption occurred with less immediacy when parafoveal preprocessing could not take place. Thus, when words are processed exclusively in foveal vision, word recognition processes are delayed compared to reading normally presented text in which words are first processed parafoveally. Second, the effects of location were larger when preview was not available compared to the normally presented text (global forward fixation duration). These results not only suggest that word-beginning letters have intrinsic importance to lexical identification (i.e., they are not entirely driven by parafoveal preprocessing), but also that processing of word-beginning letters is a vital aspect of parafoveal preprocessing during normal reading.

General Discussion

The present article, along with that of Rayner, White, et al. (2006), provides the first objective measures of the ease with which TL nonwords can be read within sentences. Text including TL nonwords increases reading times by as little as 9% for normally presented text. Given that these sentences effectively include nonwords, it is noteworthy that the language processing system is able to comprehend such sentences in such a relatively short time.

Although we did not use letter substitutions in the present experiments, it is instructive that when letters are substituted rather than transposed, readers take much longer to read sentences (Rayner & Kaiser, 1975). In the Rayner and Kaiser experiment, when the letter substitutions were visually similar internal letters (so *problem* was printed as *pncblem*) reading time doubled; when ending letters were substituted (*problnc*), reading time also doubled; and when beginning letters were substituted (*qroblem*), reading time was 2.5 times longer than normal. When dissimilar letters were substituted for internal letters (*prkylem*) or final letters (*problky*), reading time tripled; when dissimilar letters were substituted for beginning letters (*fyoblem*), reading time quadrupled. In all cases (except for visually similar internal letter substitutions), comprehension also suffered. The fact that letter transpositions are so much easier than letter substitutions demonstrates that the specific letters of a word are critical for identifying what the word is and that readers cannot rely exclusively on context for word recognition. In comparison to letter substitutions, letter transposition makes it much easier for readers to recover what the actual form of the word should be. Obviously, the availability of all of the letters provides veridical information; in addition, it may be easier to identify exactly which letters are incorrect in TL nonwords than in letter substitutions.[5]

Experiment 1 examined whether lexical difficulty impacted on the ease with which TL nonwords could be read. There were larger effects of transpositions on total reading time for infrequent compared to frequent words. In line with some previous studies (Andrews, 1996; O’Connor & Forster, 1981; Perea et al., 2005), these findings suggest that lexical difficulty does impact on the ability of the word recognition system to process incorrect letter position information. To be clear, letter position encoding is a constituent process of lexical identification. Words that are difficult to process may have an increased dependence on correct letter position information, or else longer reading times for such words may provide more opportunity for processing of precise letter position information. Note that the effect of word frequency on processing of transposed letters reported here only reached significance for the measure of total time, which indicates that word frequency may impact on processing of TL nonwords largely in the later stages of word processing.

The present experiments also indicate that the position of some letters within words is more important than others. The results suggest that the positions of external letters are generally more important for word recognition than the position of internal letters. These findings support previous studies that suggest that external letters are more critical than internal letters for word recognition (Chambers, 1979; Estes, Allmeyer, & Reder, 1976). However, it is critical that of the external letters, the position of the word-initial letter is more important than the word-final letter. Furthermore, in the early stages of word processing, word-final letters may be equal in importance to word-internal letters, whereas in the later stages of processing the final letters of words are more critical for word recognition than the internal letters of words. Note that previous studies (e.g., Jordan, Thomas, et al., 2003) that manipulated both external letters concurrently and recorded only overall reading times could not have identified these differences.

The position of the external letters of words could be more critical for word recognition for either visual or linguistic reasons. The external letters of words have less lateral masking (Bouma, 1973) and therefore may be more easily identified such that they become very important in identifying letter strings (see account of the SERIOL model below). Alternatively, the external letters of words, perhaps along with word length information, may together be sufficient to allow fast recognition of some words (Clark & O’Regan, 1999). Note that Johnson et al. (2007) demonstrated that the position of the word-final letter is important in parafoveal word processing, whereas the results presented here suggest that the word-final letters are more important in the later stages of word processing. Perhaps when processing visually degraded words in the parafovea, lateral masking may have a greater influence on the clarity of letter information such that word-final letters may be easier to process than internal letters in the parafovea.

In addition to the effect of externality on letter position processing, the results of both Experiments 1 and 2 also show an effect of location such that word-beginning letters are more critical for word recognition than word-ending letters. As noted above, for later measures, the word-final letters may be more critical than internal-beginning letters, perhaps because word-final letters may be important in lexical identification. However, at least within the categories of internal and external letters, letter location is clearly important. Previous research has suggested that the beginning portions of words are more important than the final portions (Lima & Pollatsek, 1983; Mewhort & Beal, 1977). However, such effects might be explained by differences in processing only the external letters, whereas the results of Experiment 1 suggest that the position of internal letters is also more critical when these are toward the

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[5] Note that in both Rayner and Kaiser’s (1975) study and the present study, the position of the transpositions or substitutions was consistent throughout the sentence. Consequently, the possibility cannot be ruled out that participants adopted a strategy—for example, retransposing letters in particular positions throughout the remainder of the sentence. However, no participants reported having used any such strategy.

beginning, compared to the end, of words (though the effects are smaller than those for external letters). The results of Experiment 2 suggest that not only are word-beginning letters intrinsically important to lexical identification, but that parafoveal preprocessing is especially critical to processing of word-beginning letters during normal reading.[6]

One possible explanation for why beginning letters are more critical for word recognition than ending letters is because letters within words are processed serially rather than in parallel, at least for early word processing. The orthographic uniqueness point effects shown by Kwantes and Mewhort (1999a) would support such a hypothesis. Kwantes and Mewhort (1999b) proposed a model (LEX) that is based on the notion that in order to identify words, readers search their lexicon one letter at a time until the word can be uniquely identified. Letters at the beginning of a word, then, are especially important for narrowing down the possible set of lexical items. However, it is possible that the serial processing identified in these experiments was specific to the naming task, and the same effects may not occur during sentence reading. For example, Miller, Juhasz, and Rayner (2006) were unable to replicate Kwantes and Mewhort’s (1999a) orthographic uniqueness point effect when participants read words embedded in sentences. Alternatively, word-initial letters may highly constrain the number of lexical candidates such that these are more important for word recognition than word-ending letters.

Word recognition models that demand that letters be processed in relation to specific positions simply can not explain why TL nonwords can be processed so easily (Grainger & Jacobs, 1996; McClelland & Rumelhart, 1981; Paap et al., 1982). In contrast, more recent models that enable more flexible letter position coding may be able to account for the ease with which TL nonwords can be identified (Davis, 1999, 2006; Davis & Bowers, 2004; Gómez et al., 2008; Whitney, 2001; Whitney & Berndt, 1999; Whitney & Lavidor, 2005). It is important to note that all of these models are based on the assumption that words are processed only foveally. Some accounts have included the variable of which letter is fixated, which has implications for the visual degradation of other letters in the word (Clark & O’Regan, 1999). However, models of word recognition still have not attempted to explain how initial parafoveal processing prior to fixation is subsequently integrated with foveal processing once the word is fixated. The differences in the effects of transposition between the available and unavailable preview conditions in Experiment 2 highlight how critical such factors are in word recognition processes (see also Rayner, Liversedge, & White, 2006). Ultimately, a truly comprehensive model of reading would integrate models of word recognition with models of eye movement control (Grainger, 2003; see also Liversedge & Blythe, 2007).

Critically, the present experiments show that in natural reading, whereas some effects have an early influence on behavior (e.g., parafoveal processing of external letter positions), others tend to influence later measures of behavior (e.g., modulation of transposition effects by word frequency). However, current models of word recognition and letter coding simply do not predict such a detailed time course of effects. Furthermore, although TL nonwords provide an opportunity to investigate letter position coding, ultimately the process of recognizing them as words may also entail reevaluation of word identity in relation to sentential context. Clearly, such processes are not necessarily captured by models of word recognition or letter coding. Nevertheless, in the final part of this article we consider whether models that allow flexible letter coding can account for the effects of externality and location on letter position processing reported here. (See Davis and Bowers, 2006, for further evaluation of these models.)

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[6] An alternative explanation for the larger effect of location when preview is unavailable prior to fixation is that initial fixations land nearer to the beginning of words with unavailable, compared to available, previews. Perhaps fixations nearer the beginning of words are more likely to show a greater effect of processing of the word-beginning, compared to the word-ending, characteristics.

In the overlap model (Gómez et al., 2008; Perea & Lupker, 2004; Ratcliff, 1981), each letter is activated to the greatest degree within its correct letter position, but activation also spills over into neighboring letter positions as a Gaussian function. However, while the model does give special status to word-initial letters, it treats word-final letters the same as word-internal letters. As the current results indicate, although word-initial letters are most important in visual word recognition, word-final letters are more crucial for word recognition processes than word-internal letters, especially for later measures of processing. In addition, it is not clear whether the overlap model discriminates between the levels of importance of different internal letter positions. Again, the current results indicate that in reading sentences, these letter positions have different levels of importance and should not be treated equally.

The SOLAR model (Davis, 1999, 2006; Davis & Bowers, 2004) relies on the spatial coding of letter nodes in visual word recognition. According to this model, words with transpositions are similar to their base words because they contain the same letter nodes. The SOLAR model also has difficulty accounting for some of the current findings. In the model, the strength of the activation differs as a function of letter position, with activation levels decreasing systematically from left to right. Thus, the model can account for both the privileged role of word-initial letters and the overall difference between beginning and ending letters. However, the SOLAR model predicts that word-internal letters are more important in visual word recognition than word-final letters, which was not supported by findings for the later measures reported here.[7]

The SERIOL model (Whitney, 2001; Whitney & Berndt, 1999; Whitney & Lavidor, 2005) codes letter nodes with varying activation levels based on their position within the letter string. Furthermore, ordinal letter pairs are activated as bigrams (e.g., the word *judge* activates 10 bigrams: *JU, JD, JG, JE, UD, UG, UE, DG, DE, GE*). However, as explained in the introduction, bigrams with less separation are more highly activated. Thus, encoding of letter identity is based on relative letter position rather than absolute letter position. Transposed-letter words are similar to their base words because they differ in only one bigram (e.g., the TL nonword *jugde* has all of the bigrams of its base word *judge* except for *DG*). In contrast to the overlap model and the SOLAR model, the SERIOL model may be able to account for more of the findings presented here. Moving from left to right through the letter string, letters receive progressively less excitatory input, creating a positional gradient across the word. This feature of the model, then, accurately predicts that word-initial letters will receive the most activation. It also accounts for the stronger activation of word-initial letters found near the beginning of the word than near the end of the word. However, the model also specifies that lateral inhibition of adjacent letters can reduce the excitatory input of a letter node. Thus, word-final letters (which do not experience as much lateral inhibition as word-internal letters due to the following space) would have a stronger advantage than word-internal letters.

To summarize, we report two experiments that investigated reading of sentences including TL nonwords. The results of Experiment 1 indicate that letter position processing is more critical for words that are lexically difficult to process. Furthermore, the position of letters within words influences their importance for word recognition and also the time (or stage) at which letters

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[7] Davis (2008) has made available a program called Match Calculator that calculates a value corresponding to the match between two letter strings for different types of letter encoding methods. It must be emphasized that such matches do not represent model simulations, and to this extent cannot be considered to represent model predictions, as they do not take account of processing beyond the level of letter encoding. The match scores range from 0 to 1 where 0 indicates no match and 1 indicates a perfect match. Using this calculator for the transposed vs. control critical words in the experiments here, the current letter encoding mechanism in Davis's SOLAR model produces the following match scores: external beginning transposition 0.77; external ending transposition 0.86; internal beginning transposition 0.95; internal ending transposition 0.95. The poorer matches for external compared to internal transpositions are consistent with our finding that processing difficulty was greater for external compared to internal transpositions. Furthermore, the poorer match for external beginning compared to external ending transpositions is also consistent with effects shown in the present paper. It is important to emphasize again, however, that these match scores do not represent predictions derived from the SOLAR (or any other) model.

at particular positions become critical for word processing. Both Experiments 1 and 2 show that the position of word-initial letters is especially critical for word processing. In addition, the results of Experiment 2 suggest that processing of words parafoveally prior to fixation not only plays a critical role in processing of word-beginning letters, but also has important implications for the time course and nature of the word recognition process.

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Table 1

Experiment 1: Sample Experimental Sentence

Word frequency	**Transposition**	**Example**
Frequent	Control	The boy could not solve the *problem* so he asked for help.
	Internal, beginning	The boy cuold not slove the *porblem* so he aksed for help.
	Internal, ending	The boy colud not sovle the *probelm* so he asekd for help.
	External, beginning	The boy oculd not oslve the *rpoblem* so he saked for help.
	External, ending	The boy coudl not solev the *problme* so he askde for help.
Infrequent	Control	The boy could not solve the *anagram* so he asked for help.
	Internal, beginning	The boy cuold not slove the *aangram* so he aksed for help.
	Internal, ending	The boy colud not sovle the *anagarm* so he asekd for help.
	External, beginning	The boy oculd not oslve the *naagram* so he saked for help.
	External, ending	The boy coudl not solev the *anagrma* so he askde for help.

Note. The critical word is shown in italics.

Table 2

Global Measures for Each of the Conditions in Experiment 1

			Fixation duration (ms)				**Number of fixations**			
	Total sentence reading time (ms)		**Forward**		**Regressive**		**Forward**		**Regressive**	
Condition	***M***	***SD***	***M***	***SD***	***M***	***SD***	***M***	***SD***	***M***	***SD***
Control	2,967	786	239	34	221	89	8.8	1.7	1.6	1.6
Internal transposition										
Beginning	3,336	1,051	248	38	236	86	9.3	1.9	2.1	1.9
Ending	3,289	1,142	243	36	237	87	9.4	2.2	1.9	2.1
External transposition										
Beginning	4,046	1,643	256	36	263	97	10.2	2.8	3.0	2.7
Ending	3,635	1,330	248	36	244	84	10.1	2.5	2.2	2.1

Table 3

Global Measures in Experiment 1: 2 (Externality: Internal, External) × 2 (Location: Beginning, Ending) ANOVAs: Main Effects and Externality × Location Interaction

				Fixation duration						**Number of fixations**					
	Total sentence reading time			**Forward**			**Regressive**			**Forward**			**Regressive**		
Factor	***F***	***MSE***	***p***	***F***	***MSE***	***p***	***F***	***MSE***	***p***	***F***	***MSE***	***p***	***F***	***MSE***	***p***
Externality															
F_1	77.32	110,219	***	10.14	107	**	13.09	823	**	73.95	0.3	***	33.31	0.37	***
F_2	81.09	280,521	***	12.55	269	**	11.21	2,263	**	73.85	0.78	***	55.45	0.57	***
Location															
F_1	26.6	57,161	***	23.68	58	***	5.09	490	*	< 1	0.25	—	42.75	0.15	***
F_2	9.62	483,249	**	17.94	206	***	1.74	1,653	.191	< 1	1.42	—	21.46	0.94	***
Externality × Location															
F_1	15.48	61,312	***	1.34	47	.257	6.96	332	*	1.13	0.32	.296	14	0.21	**
F_2	7.84	332,504	**	< 1	176	—	3.50	2,074	.065	<1	1.14	—	11.63	0.71	**

Note. Analyses are shown across participants (F_1) and items (F_2). For all global measures in Experiment 1, the degrees of freedom were (1, 29) for the F_1 analyses and (1, 79) for the F_2 analyses.

* $p < .05$.

** $p < .01$.

*** $p <$ 001.

Table 4

Local Measures for the Critical Word for Each of the Conditions in Experiment 1

		First fixation duration (ms)		Gaze duration (ms)		Total time (ms)	
Transposition	**Frequency**	***M***	***SD***	***M***	***SD***	***M***	***SD***
Control	High	232	56	270	83	318	140
	Low	266	79	337	135	406	220
Internal							
Beginning	High	255	93	312	158	397	253
	Low	278	104	394	209	537	355
Ending	High	247	86	294	141	371	244
	Low	267	90	369	162	527	475
External							
Beginning	High	274	100	387	198	555	378
	Low	300	121	473	323	769	664
Ending	High	248	78	336	180	474	339
	Low	274	112	404	250	688	589

Table 5

Local Measures in Experiment 1: 2 (Frequency: Frequent, Infrequent) × 2 (Externality: Internal, External) × 2 (Location: Beginning, Ending) ANOVAs: Main Effects and Externality × Location Interaction

	First fixation duration			Gaze duration			Total time		
Factor	***F***	***MSE***	***p***	***F***	***MSE***	***p***	***F***	***MSE***	***p***
Frequency									
F_1	24.10	1,424	***	49.41	7,197	***	50.97	37,253	***
F_2	24.65	3,764	***	45.82	21,152	***	57.76	92,614	***
Externality									
F_1	5.63	1,573	*	15.26	12,679	**	45.95	35,098	***
F_2	6.99	3,541	*	31.50	17,080	***	59.53	74,041	***
Location									
F_1	15.43	1,295	***	12.57	7,166	**	4.87	29,555	*
F_2	12.27	4,089	**	11.87	22,169	**	5.29	83,259	*
Externality × Location									
F_1	3.40	1,396	.075	3.99	5,527	.055	2.24	24,974	.146
F_2	3.57	3,051	.062	4.02	14,271	*	2.80	64,936	.098

Note. Analyses are shown across participants ($F1$) and items ($F2$). For the local measures in Experiment 1, the degrees of freedom were (1, 29) for the F_1 analyses and (1, 79) for the F_2 analyses.

[*] $p < .05$.

[**] $p < .01$.

[***] $p < 001$.

Table 6

Examples of Stimuli Presentation for the Unavailable Preview Condition in Experiment 2

Fixated word	**Example sentence**
The	`The XXX XXXXX XXX XXXXX XXX XXXXXXX XX XX XXXXX XXX XXXX.`
could	`The boy could XXX XXXXX XXX XXXXXXX XX XX XXXXX XXX XXXX.`
boy	`The boy XXXXX XXX XXXXX XXX XXXXXXX XX XX XXXXX XXX XXXX.`
help.	`The boy could not solve the problem so he asked for help.`

Note. Note that following regressions, previously presented words to the right of the fixated word are replaced by *X*s again.

Table 7

Global Measures for Each of the Conditions in Experiment 2

Transposition condition	Total sentence reading time (ms)		Fixation duration (ms)				Number of fixations			
			Forward		Regressive		Forward		Regressive	
	M	***SD***	***M***	***SD***	***M***	***SD***	***M***	***SD***	***M***	***SD***
Preview available										
Control	3,146	982	215	92	197	83	8.4	2.1	2.0	1.7
Internal										
Beginning	3,688	1,308	226	101	220	111	8.9	2.3	2.6	2.1
Ending	3,435	958	225	92	212	108	8.9	2.0	2.2	1.8
External										
Beginning	4,482	1,632	236	111	245	135	10	2.6	3.4	2.4
Ending	4,048	1,548	231	101	225	112	9.6	2.6	2.6	2.1
Preview unavailable										
Control	5,639	2,424	323	142	222	108	11.8	2.6	2.0	1.8
Internal										
Beginning	6,287	2,007	330	145	264	163	12.4	3.0	2.8	2.2
Ending	6,035	1,975	324	143	235	121	12.6	2.9	2.6	2.3
External										
Beginning	7,213	2,533	338	156	284	163	13.3	3.0	3.7	2.8
Ending	6,606	2,573	322	145	248	130	13.6	3.4	2.7	2.4

Table 8

Global Measures in Experiment 2: 2 (Preview: Available, Unavailable) × 2 (Externality: Internal, External) × 2 (Location: Beginning, Ending) ANOVAs: Main Effects and Externality × Location Interaction

				Fixation duration						**Number of fixations**					
	Total sentence reading time			**Forward**			**Regressive**			**Forward**			**Regressive**		
Factor	***F***	***MSE***	***p***	***F***	***MSE***	***p***	***F***	***MSE***	***p***	***F***	***MSE***	***p***	***F***	***MSE***	***p***
Preview															
F_1	229.76	1,791,830	***	310.94	1,984	***	47.84	1,414	***	257.22	3.16	***	2.21	2.08	.148
F_2	603.27	1,657,831	***	1,756.48	886	***	55.98	2,717	***	573.23	3.62	***	5.89	1.46	*
Externality															
F_1	37.16	728,957	***	6.03	280	*	6.16	1,982	*	74.28	0.74	***	32.81	0.64	***
F_2	66.29	993,245	***	4.27	959	*	21.78	3,083	***	51.45	2.5	***	28.35	1.56	***
Location															
F_1	24.44	274,345	***	9.91	278	**	41.01	741	***	< 1	0.53	—	41.22	0.48	***
F_2	15.76	1,257,217	***	14.28	541	***	23.28	3,276	***	< 1	2.38	—	23.01	2.69	***
Externality × Location															
F_1	2.27	259,566	.143	3.97	224	.056	1.65	833	.210	< 1	0.64	—	13.51	0.31	**
F_2	1.89	1,686,920	.174	2.05	990	.156	1.35	3,611	.249	< 1	2.97	—	7.91	1.97	**

Note. Analyses are shown across participants (F_1) and items (F_2). For average regressive fixation duration the degrees of freedom for the items analysed were (1, 77) because regressive fixations were not made in all of the conditions for all of the items. For all other global measures in Experiment 2, the degrees of freedom were (1, 29) for the F_1 analyses and (1, 79) for the F_2 analyses.

* $p < .05$.

** $p < .01$.

*** $p < 001$.

Table 9

Local Measures for the Critical Word for Each of the Conditions in Experiment 2

Transposition condition	First fixation duration(ms)		Gaze duration (ms)		Total time (ms)	
	M	***SD***	***M***	***SD***	***M***	***SD***
Preview available						
Correct	231	82	300	134	336	169
Internal						
Beginning	239	88	345	211	456	390
Ending	246	85	332	164	423	280
External						
Beginning	271	116	439	240	667	553
Ending	245	86	391	253	556	455
Preview unavailable						
Correct	353	112	509	164	553	179
Internal						
Beginning	390	121	576	256	712	478
Ending	366	137	594	254	681	362
External						
Beginning	377	140	758	508	916	700
Ending	352	136	694	468	837	613

Table 10

Local Measures in Experiment 2: 2 (Preview: Available, Unavailable) × 2 (Externality: Internal, External) × 2 (Location: Beginning, Ending) ANOVAs: Main Effects and Externality × Location Interaction

	First fixation duration			Gaze duration			Total time		
Factor	***F***	***MSE***	***p***	***F***	***MSE***	***p***	***F***	***MSE***	***p***
Preview									
F_1	132.90	6,794	***	132.62	37,358	***	102.84	42,007	***
F_2	329.15	7,016	***	262.82	46,529	***	196.65	55,255	***
Externality									
F_1	< 1	1,813	—	45.94	16,959	***	35.50	56,147	***
F_2	< 1	7,249	—	38.37	44,794	***	50.74	93,703	***
Location									
F_1	5.10	2,935	*	1.16	16,278	.291	9.33	19,288	**
F_2	11.63	4,705	**	4.23	41,505	*	6.34	104,251	*
Externality × Location									
F_1	3.08	2,018	.09	3.23	12,325	.083	1.06	33,026	.312
F_2	1.75	4,604	.19	3.86	27,710	.053	2.36	73,501	.129

Note. Analyses are shown across participants (F_1) and items (F_2). For first fixation duration and gaze duration the degrees of freedom for the items analyses were (1, 78) because the critical word was not fixated on first pass for all of the conditions for one item. For all other analyses shown in the table, the degrees of freedom were (1, 29) for the F_1 analyses and (1, 79) for the F_2 analyses.

* $p < .05$.

** $p < .01$.

*** $p <$ 001.