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RESEARCH REPORT

See Before You Jump: Full Recognition of Parafoveal Words Precedes Skips During Reading

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Serial attention models of eye-movement control during reading were evaluated in an eye-tracking experiment that examined how lexical activation combines with visual information in the parafovea to affect word skipping (where a word is not fixated during first-pass reading). Lexical activation was manipulated by repetition priming created through prime–target pairs embedded within a sentence. The boundary technique (Rayner, 1975) was used to determine whether the target word was fully available during parafoveal preview or whether it was available with transposed letters (e.g., *Herman* changed to *Hreman*). With full parafoveal preview, the target word was skipped more frequently when it matched the earlier prime word (i.e., was repeated) than when it did not match the earlier prime word (i.e., was new). With transposed-letter (TL) preview, repetition had no effect on skipping rates despite the great similarity of the TL preview string to the target word and substantial evidence that TL strings activate the words from which they are derived (Perea & Lupker, 2003). These results show that lexically based skipping is based on full recognition of the letter string in parafoveal preview and does not involve using the contextual constraint to compensate for the reduced information available from the parafovea. These results are consistent with models of eye-movement control during reading in which successive words in a text are processed 1 at a time (serially) and in which word recognition strongly influences eye movements.

Keywords: eye movements, reading, word skipping, parafoveal preview

Advances in the understanding of eye-movement control during reading have led to a number of explicit models of how word recognition interacts with oculomotor control systems to determine detailed characteristics of eye movements during reading (Engbert, Nuthmann, Richter, & Kliegl, 2005; Pollatsek, Reichle, & Rayner, 2006; Reichle, Pollatsek, Fisher, & Rayner, 1998; Reilly & Radach, 2006). These models are among the most sophisticated and detailed accounts of the coordination of multiple processes in the study of human cognition. Uniformly these models characterize word recognition as a parallel process in the sense that a stimulus word is simultaneously evaluated against multiple lexical representations in memory (McClelland & Rumelhart, 1981). However, these models differ in their characterizations of how processing is distributed across successive words in a text: Serial attention models posit that one word is recognized before processing of the next word begins (Pollatsek et al., 2006; Reichle et al., 1998), while parallel models posit that a small number of successive words are processed simultaneously through a gradient of attention (Engbert et al., 2005; Reilly & Radach, 2006).

The phenomenon of *skipping* provides a particularly fruitful arena to test models of eye-movement control during reading. A word is said to be skipped when it is not fixated during a reader's first pass through the region of text in which it appears. Approximately 15% of content words are skipped during normal reading (Carpenter & Just, 1983; Rayner & Duffy, 1986), with higher rates of skipping for short words (Vitu, O'Regan, Inhoff, & Topolski, 1995), high-frequency words (Henderson & Ferreira, 1990), highly predictable words (Ehrlich & Rayner, 1981; Rayner & Well, 1996), and cases where the preceding fixation was close to the left edge of the word (Rayner, Sereno, & Raney, 1996). Thus, skipping rates are determined by a mixture of oculomotor processes (as indicated by the effects of word length) and word-recognition processes (as indicated by the effects of word frequency and predictability). Skipping is a rich source of evidence about how lexical processing is related to eye-movement control because it is the only phenomenon where the first-pass targeting of eye movements during reading is influenced not simply by the length of a word but by its identity (Drieghe, Rayner, & Pollatsek, 2005). For both serial and parallel models, skipping is a product of the normal process of targeting and initiating saccades.

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The EZ Reader model (Pollatsek et al., 2006; Reichle et al., 1998) is the best developed serial model of word recognition during reading; in general outline it works as follows. Attention is allocated to the word that the eyes are fixating until that word is recognized, at which point attention is shifted to the next word in the sequence (the word in *parafoveal preview*). Parafoveal preview allows lexical processing of the word to the right of fixation to begin in advance of the saccade to that word because the shift of attention occurs more rapidly than the processes responsible for initiating the saccade. Typically, the saccade to the next word is begun before the word to the right is completely recognized; in that case the head start provided by parafoveal processing facilitates recognition of the word once it is fixated. Alternatively, a skip occurs in the less typical instance where the complete recognition of the word to the right of fixation is imminent during parafoveal preview with sufficient time for the word-recognition system to cancel the planned saccade and retarget that saccade to skip over the just-recognized word in parafoveal preview and land on the following word. The likelihood of this event depends on lexical factors such as word frequency and predictability that have been amply demonstrated to influence the speed of word recognition. The EZ Reader model has been specified in considerably more detail than this, but for present purposes the critical idea is that lexically based skipping is based on complete recognition of a word in the parafovea using the same processes that are responsible for recognition of a fixated word.

The SWIFT model (Engbert et al., 2005) is the best developed parallel model of word recognition during reading. It incorporates an attentional gradient in which maximum lexical processing resources are devoted to the word being fixated but adjacent words to the right and left are also processed so that a total of about four successive words are processed simultaneously. The target of the next saccade is a stochastic function of the relative lexical activation of the not-yet-recognized words within the attentional gradient. This mechanism is developed to account for saccades progressing to the next word, refixations, and lexically based skips. In this model highly predictable words are skipped because their identity "can be guessed without (or with minimal) visual input" (Engbert et al., 2005, p. 784). In the parallel model lexically based skipping uses "coarse" word-recognition processes that depend heavily on contextual and low-spatial frequency information (Brysbaert, Drieghe, & Vitu, 2005) and in this way differs from the processes used for recognizing centrally fixated words in the fovea.

An Approach Based on Priming and the Boundary Technique

Research on the nature of lexical processing in the parafovea has been made possible by development of the *boundary technique* (Rayner, 1975), a gaze-contingent display technique where a preview letter string is displayed until the eyes progress past an invisible boundary triggering replacement by the target word, thereby allowing separation of parafoveal processing from foveal processing by presenting each with different information (see Angele, Slattery, Yang, Kliegl, & Rayner, 2008; Rayner, 1998). For lexically based skipping, word recognition is based on parafoveal processing of the preview string as it is influenced by context. The question of whether lexically based skips depend on full recognition or coarse recognition of words in the parafovea has been examined by comparing skipping rates for preview strings consisting of visually similar nonwords derived from words that are predicted to occur in a context and those that are not, for example the nonword *livor* from the word *liver* that is highly predicted in the sentence context *The doctor told Fred that his drinking would damage his* . . . . . very quickly, compared to the nonword *heant* derived from the contextually unpredicted word *heart* (Balota, Pollatsek, & Rayner, 1985; Drieghe et al., 2005). Skipping based on full word recognition should not occur when the string in parafoveal preview is a nonword, with the only skips observed depending on perceptual-motor factors that are not affected by context-based word prediction. Alternatively, skipping based on coarse word recognition using partial visual information should be increased for nonwords that are visually similar to words that are predicted to occur in context. Unfortunately, the results of studies taking this approach have not been clear cut (Balota et al., 1985; Drieghe et al., 2005), with discrepant results attributed to floor and ceiling effects and difficulty equating stimuli across conditions.

Lexical repetition priming, where processing of a target word is facilitated by recent exposure to that word as a prime, provides an alternative experimental method of using context to manipulate ease of word recognition. Prime–target relations can be varied so that the same word can be used in the repeated (primed) condition and in the new (control) condition. The different types of prime–target pairs can be embedded in sentences that are identical in a broad region surrounding the critical target word. Studies of eye movements during reading have provided clear evidence that lexical repetition priming facilitates word recognition as measured by first-pass reading times (e.g., Ledoux, Gordon, Camblin, & Swaab, 2007; Raney & Rayner, 1995; Traxler, Foss, Seely, Kaup, & Morris, 2000).

Priming techniques have also played an important role in determining how strings of letters are recognized as words. Research using the masked-priming technique, where the prime is briefly presented and then masked, has shown that the identity of letters in a word is at least partially represented independently of the positions in which they appear. This was demonstrated by showing that greater priming was found with transposed-letter (TL) primes, where the positions of two adjacent letters in the target word were switched, than for substituted letter (SL) primes, where two letters in the target word were replaced with visually similar letters (Perea & Lupker, 2003). When measured in terms of overlap of letters in position, the similarity of these two types of primes to the target word is identical. However, less priming is seen for the SL primes than the TL primes, which often show levels of priming that are indistinguishable from full repetition. Eye-tracking studies of reading have shown that first-pass reading-time measures of target words are shorter when TL preview is presented compared to when SL preview is presented, indicating that TL preview provided greater preview benefit than SL preview (Johnson, Perea, & Rayner, 2007). However, it is important to note that substantial slowing of reading is observed when TL letter strings are directly fixated as would be expected given that they are not English words (Johnson et al., 2007; Rayner, White, Johnson, & Liversedge, 2006; White, Johnson, Liversedge, & Rayner, 2008).

Current Experiment

This experiment uses repetition priming and the boundary technique to determine how lexical activation combines with visual information in the parafovea to affect skipping. Lexical repetition priming is manipulated through prime–target pairs embedded in a sentence, and the boundary technique is used to control whether the actual target word or the target word with transposed letters appears during parafoveal preview. For purposes of illustrating the conditions, the example below shows the possible primes in italics, the possible preview strings in brackets, and the target word in boldface.

> After lunch *Herman/Martin* and Sarah went shopping because [Herman/Hreman] **Herman** wanted . . .

The target word (*Herman* in this case) is seen with either full (Herman) or TL (Hreman) preview.

Figure 1 shows the possible paths for priming given these conditions. The effect of the prime on the preview string (Path A) is unambiguously indicated by variation in first-pass skipping rate, because skipping occurs before the target string is displayed. When the target word is not skipped, then its first-pass fixations include the effects of the preview string on the target (Path B)—perhaps as modulated by the effect of the prime on the preview string (Path A)—and of the prime on the target directly (Path C).

The critical question addressed by this study is whether repetition priming affects skipping when the preview string is a TL nonword generated from the target base word. As discussed above, briefly seen TL nonwords activate their base words (Perea & Lupker, 2003) and at a coarse level of visual perception (Brysbaert et al., 2005) should be very similar to those base words. If prior lexical activation combines with partial visual processing of the preview string to yield skipping, then within-sentence repetition should lead to increased skipping rates even when the preview string is a TL nonword. This possibility can be considered an extension of the SWIFT model's characterization that word predictability increases skipping through a combination of guessing and minimal visual information, though certainty about the predictions of detailed mathematical models can only be obtained through simulation, and Engbert et al. (2005) did not simulate results from boundary-technique experiments. In contrast, if skipping is based on full recognition of the parafoveal string as a word, of the sort that occurs when a word is directly fixated (Reichle et al., 1998), then repetition should not affect skipping rates for TL preview strings because they are not words. The only skipping observed should be due to oculomotor processes that are insensitive to lexical processing.

Method

Participants

Forty-eight undergraduates at the University of North Carolina at Chapel Hill participated for $10 or for course credit. All participants were native English speakers with normal or corrected-to-normal vision and were naïve about the research goals.

Stimuli and Design

Experimental stimuli consisted of single sentences following the pattern shown above (see Appendix for a complete list). Each sentence began with a locative phrase so that reading of the initial proper names was not influenced by strategies associated with the beginning of the sentence or the onset of the trial. The target word was a proper name placed at the beginning of the second clause of the sentence. It was either a *repeated* name, in which case it matched one of two names that were conjoined to make the subject of the first clause, or a *new* name in which case it did not match either of the preceding names. The target word was presented either with *full parafoveal preview* or with *transposed-letter* (TL) *preview* where the position of its second and third letters switched prior to the eyes crossing the invisible boundary. All names had either six or seven letters and were low-to-moderate in frequency with equal numbers of stereotypically female and male names. None was used in more than one sentence frame. Forty prime–target pairs of proper names were used in 40 sentence frames, each of which was followed by true–false comprehension questions. Assignment of prime–target pairs to the four experimental conditions (repetition vs. preview) was counterbalanced, as was the assignment of individual words within a pair to the prime or target roles; this resulted in eight lists of the 40 sentence frames. The experimental sentences were mixed in random order with 48 filler sentences, all of which were preceded by four warm-up trials.

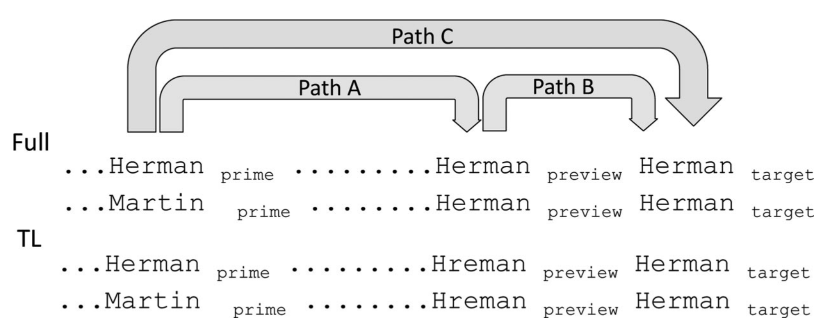

Figure 1. A schematic outline of the possible paths for priming within a sentence given the experimental conditions. Path A shows the effect of processing the prime word on processing of the preview string, which can only be seen in the parafovea; this path is the only way in which the language factors manipulated in the experiment can affect the rate of skipping the target word. Path B shows the effect of processing the preview string on processing of the target word, while Path C shows the direct effect of processing the prime word on the target word. The effects of these paths can be observed on first-pass reading measures of the target words on trials where they are not skipped.

Procedure

Eye movements were recorded from the participants' right eye using an SR EyeLink 1000. Stimuli were presented on a 20-in. ViewSonic G225f Monitor at a distance of 61 cm with a display resolution of 1024×768 pixels. At the beginning of each session the tracker was calibrated using a 9-point procedure; calibration was checked between trials, and the tracker was recalibrated when necessary. Participants were seated in a well-lit room with their head movements minimized by a chin rest and forehead rest. They were instructed to read the sentences silently in a natural way and to answer the subsequent true–false questions using a handheld console. The sentences and questions were presented from the left-center of the display screen. The experimenter monitored eye movements throughout the session. The gaze-contingent invisible boundary was placed immediately to the left of the target word. Display changes occurred an average of 11 ms after detecting the boundary trigger.

Analysis of Eye Movements

All trials in which the subject blinked during first-pass reading of the critical region consisting of the pretarget word, the target word, and the word after the target were excluded from the analysis, as were all trials in which the display change occurred prior to the first saccade that crossed the invisible boundary (this can occur when a fixation immediately to the left of the boundary includes samples that cross the boundary). Eight subjects who each lost more than 15% of data by these criteria were replaced. For the final analysis 7% of trials were excluded by these criteria.

First-pass skipping rates on the target word were calculated as the proportion of trials in which the target word was not fixated at all or was only fixated after a subsequent word had been fixated. Reading-time measures were calculated after setting outliers with durations less than 70 ms or greater than 900 ms to those boundaries. The measures of interest followed generally accepted definitions (Rayner, 1998). First-pass fixations were those after the eyes fixated on a word until they moved off the word, given that they had not progressed beyond that word before the first fixation. *Single-fixation duration* (SFD) was the average of the durations of the initial, first-pass fixation on a word given that the word received only one first-pass fixation. *First-fixation duration* (FFD) was the average of the duration of the initial, first-pass fixation on a word regardless of whether there were subsequent first-pass fixations on the word. *Gaze duration* (GZD) was the average of the sum of all first-pass fixation durations on a word.

Results and Discussion

Target-Word Skipping

Figure 2 shows first-pass skipping rates for the target word as a function of the experimental conditions. Skipping rates were higher when the target word was repeated compared to when it was new, $F_1(1, 47) = 4.30$, $p < .05$, and $F_2(1, 39) = 3.44$, $p = .071$, and when the preview stimulus was the full target string compared to when it was a TL string, $F_1(1, 47) = 5.46$, $p < .05$, and $F_2(1, 39) = 7.36$, $p < .05$. Critically, these two factors interacted such that the increase in skipping rates due to repetition was greater in the full preview condition than in the TL preview condition, $F_1(1, 47) = 6.73$, $p < .05$, and $F_2(1, 39) = 3.54$, $p = .068$.[1] This pattern shows the facilitative effect of the prime on processing of the parafoveal preview string (Path A in Figure 1) leads to increased skipping only when the preview string matches the prime word, not when it is a highly similar nonword created by transposing the positions of two word-internal letters. This pattern is consistent with serial-attention models of eye-movement control during reading where lexically based word skipping is based on the same word-recognition processes that are used for words that are fixated (Pollatsek et al., 2006; Reichle et al., 1998).

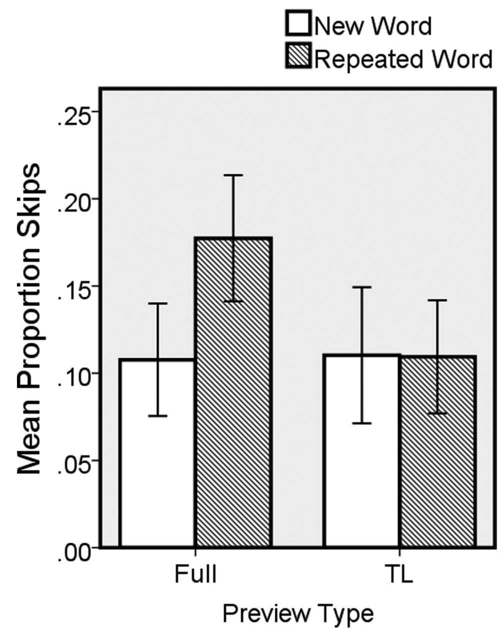

Figure 2. Proportion of trials on which the target word was skipped during first-pass reading, broken down by preview type and repetition. Error bars are 95% confidence intervals. TL = transposed letter.

Reading Times on Word Preceding Target

Table 1 shows first-pass single-fixation durations on the word preceding the target word. There were no main effects or interac-

[1] Analyses were also conducted on an additional measure, restricted skipping rate, in which first-pass skips of the target word were reclassified as nonskips if the skip was followed by an immediate regression back to the target word. This pattern of movement is thought to represent motor programming error in the targeting of the saccade rather than skipping based on lexical processing (Drieghe et al., 2005). Thus, this measure may reduce the contribution of oculomotor factors to skipping. Skip reclassification affected 1.7% of the valid trials. Restricted skipping rates were as follows: full-preview new (.088), full-preview repeated (.165), TL-preview new (.086), and TL-preview repeated (.097). Restricted skipping rates were significantly affected by repetition, $F_1(1, 47) = 9.99$, $p < .01$, and $F_2(1, 39) = 7.09$, $p < .05$; preview, $F_1(1, 47) = 4.95$, $p < .05$, and $F_2(1, 39) = 6.73$, $p < .05$; and the interaction of repetition and preview, $F_1(1, 47) = 6.81$, $p < .05$, and $F_2(1, 39) = 4.18$, $p < .05$. This is the same pattern of effects observed for raw skipping rates. Regardless of which measure is used, we believe that observed skipping rates reflect a mixture of skips based on word recognition and on oculomotor factors.

Table 1
Fixation Durations (Milliseconds) for the Word Immediately Preceding the Target for First-Pass, Single-Fixation Trials Only

Preview type	New	Repeated
Full	225	231
Transposed letter	224	225

tions of the experimental factors (repetition and preview) on this measure. The absence of such effects is consistent with the position that reading time on a fixated word is not influenced by the characteristics of the word in parafoveal preview (no parafoveal-on-foveal effects; Rayner & Juhasz, 2004; cf. Kennedy & Pynte, 2005). Single-fixation durations were slightly longer when the target word was subsequently skipped (236 ms) compared to when it was subsequently fixated (224 ms), though this difference was not close to significance ($p = .316$). This trend is consistent with the notion that skipping entails processing steps in addition to those used in planning and executing saccades to the next word (Pollatsek et al., 2006; Pollatsek, Rayner, & Balota, 1986; Rayner, Ashby, Pollatsek, & Reichle, 2004; cf. Kliegl & Engbert, 2005); the lack of statistical significance may be due to insufficient statistical power resulting from the small proportion of the trials that involve skips, or it may be because the characterization of skipping in the EZ Reader model is incorrect.

Reading Times on Target Word

Table 2 shows first-pass reading-time measures on the target word as a function of repetition and preview. For all three first-pass measures, times were shorter for repeated target words compared to new target words: SFD, $F_1(1, 47) = 5.19$, $p < .05$, and $F_2(1, 39) = 9.74$, $p < .01$; FFD, $F_1(1, 47) = 8.24$, $p < .01$, and $F_2(1, 39) = 11.31$, $p < .01$; and GZD, $F_1(1, 47) = 11.86$, $p < .01$, and $F_2(1, 39) = 15.23$, $p < .01$. Consistent with previous eye-tracking studies that embedded prime–target pairs in sentences (Ledoux et al., 2007; Traxler et al., 2000), this shows that processing the prime word facilitates processing of a matched target word, either directly or as mediated through processing of the preview string (Paths C and B in Figure 1). In addition, all three measures showed shorter times for target words seen with full preview compared to those seen with TL preview: SFD, $F_1(1, 47) = 8.81$, $p < .01$, and $F_2(1, 39) = 7.94$, $p < .01$; FFD, $F_1(1, 47) = 7.13$, $p = .010$, and $F_2(1, 39) = 7.64$, $p < .01$; and GZD, $F_1(1, 47) = 13.62$, $p < .01$, and $F_2(1, 39) = 13.44$, $p < .01$, indicating that processing of a previewed word, compared to a previewed TL nonword, facilitates processing of the target word (Path B in Figure 1). Finally, there was a numerical tendency across all three first-pass measures for the priming effect to be larger following TL preview than full preview, but the interaction between type of preview and repetition was not significant for any of these first-pass measures. This interaction potentially provides a way of assessing how the effect of the prime on processing of the preview string influences the joint effects of the prime and the preview string on first-pass processing of the target (i.e., how Path A moderates the effect of Path B in Figure 1). The absence of statistical significance prevents any strong conclusions, but taken together with the significant interaction on skipping rates (Figure 2), the trend toward an interaction suggests that reading times on targets following full preview and TL preview represent different mixtures of a priming process that varies stochastically across trials. For full preview, trials with high levels of priming lead to recognition-based skipping of the preview string and accordingly make no contribution to first-pass reading times on the target word. For TL preview, trials with high levels of priming do not lead to recognition-based skipping of the nonword preview string, and therefore they do contribute to first-pass reading times on the target word. More research will be needed to determine the value of this account.

Reading Times on Word After Target

Table 3 shows reading times on the word immediately after the target, selected for those trials where first-pass reading of the target was followed by a saccade to that word. This selection was done because such trials provide a way of examining whether there are *foveal-on-parafoveal* effects where ease of processing the target word affects ease of processing the next word (Henderson & Ferreira, 1990; Rayner & Duffy, 1986; Rayner, Sereno, Morris, Schmauder, & Clifton, 1989). All three first-pass measures showed faster times for words following repeated target words compared to new target words: SFD, $F_1(1, 47) = 5.65$, $p < .05$, and $F_2(1, 39) = 8.21$, $p < .01$; FFD, $F_1(1, 47) = 6.56$, $p = .014$, and $F_2(1, 39) = 6.63$, $p = .014$; and GZD, $F_1(1, 47) = 5.54$, $p < .05$, and $F_2(1, 39) = 7.00$, $p = .012$. These *spillover* effects are consistent with the idea that more time was available for processing the next word during fixation on repeated target words than was available during fixation on new target words. Preview type did not have a significant effect on any reading time measure ($p > .09$ for all comparisons), nor did it interact significantly with repetition ($p > .33$ for all comparisons). The absence of spillover effects attributable to the preview condition of the target word is consistent with the idea that preview affected only very early processing of that word.

Table 2
Reading Times (Milliseconds) for the Target Word Broken Down by Experimental Condition

Measure	New full	Repeated full	New TL	Repeated TL
SFD	214	204	234	216
FFD	215	205	230	214
GZD	248	229	274	246

Note. The measures of reading time are single-fixation duration (SFD), first-fixation duration (FFD), and gaze duration (GZD). TL = transposed letter.

Table 3
Reading Times (Milliseconds) for the Word After the Target Broken Down by Experimental Condition

Measure	New full	Repeated full	New TL	Repeated TL
SFD	226	213	232	207
FFD	231	210	227	212
GZD	258	234	268	239

Note. The measures of reading time are single-fixation duration (SFD), first-fixation duration (FFD), and gaze duration (GZD). TL = transposed letter.

Conclusion

Models of eye-movement control offer highly developed accounts of how processes of vision, oculomotor control, attention, and language are coordinated during skilled reading and of how different levels of information are combined during the recognition of words. The results reported here support the view that lexically based skipping occurs only when letter strings seen in parafoveal preview are recognized as words. They do so by showing that word-level context, in the form of repetition priming, causes increased skipping when the target word is fully available to parafoveal preview but not when the previewed string is a highly similar nonword created by transposing the positions of two word-internal letters. Though TL nonwords produce substantial priming in both masked-priming and eye-tracking studies (Johnson et al., 2007; Perea & Lupker, 2003), when fixated directly they are recognized as misspelled words (Rayner et al., 2006). The lack of evidence that repetition priming increases skipping when there is preview of a TL string, combined with clear evidence that repetition priming increases skipping with full preview, demonstrates that the use of top-down contextual information to generate skips by the eye-movement control system depends on the lexical status of the preview string. This pattern of results supports serial attention switching models of word processing during reading (Pollatsek et al., 2006; Reichle et al., 1998).

In general, serial models cannot be distinguished from parallel models on the basis of how word-level context and partial visual information are combined. Most likely it would be possible to modify a parallel attention-gradient model, such as SWIFT (Engbert et al., 2005), so that its word-recognition processes did not use word-level context to identify partial visual information in the parafovea as a word, just as it might be possible to modify a serial-attention model so that it did. For parallel models such a modification likely would retain the mechanism whereby context facilitates word recognition but would not allow it to override visual analysis of the lexical status of strings in the parafovea. For serial models such a modification would likely involve using very different word-recognition thresholds for parafoveal strings compared to foveal strings. In both cases it would be necessary to ensure that the modified models continued to account accurately for the broad range of phenomena to which they have already been applied. While such modifications are surely possible, current parallel and serial models of word recognition in relation to eye-movement control have been developed in alliance with principles of information combination that fit them most naturally. Spreading attention in parallel over several words in a text has the consequence that lexical processing must occur for letter strings that are poorly perceived because they are not directly fixated. Reliance on word level, as well as other types of language context, provides a natural way for a system to compensate for poor quality input. In contrast, the computational appeal of serial processing is that it provides a straightforward mechanism for separating streams of information that should not be mixed, as might occur if letters from adjacent words were assembled together to create a word not present in the text or if contextual constraint useful in identifying one word were used to misidentify a nearby word. Safeguards against such errors are created by a mechanism that attempts to recognize only one word at a time and that links the initiation of eye movements to perceptual evidence that the letter string being processed is a word.

References

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,* 697–707. doi:10.1080/13506280802009704

Balota, D. A., Pollatsek, A., & Rayner, K. (1985). The interaction of contextual constraints and parafoveal visual information in reading. *Cognitive Psychology, 17,* 364–390. doi:10.1016/0010-0285(85)90013-1

Brysbaert, M., Drieghe, D., & Vitu, F. (2005). Word skipping: Implications for theories of eye movement control in reading. In G. Underwood (Ed.), *Cognitive processes in eye guidance* (pp. 53–78). doi:10.1093/acprof:oso/9780198566816.003.0003

Carpenter, P. A., & Just, M. A. (1983). What your eyes do while your mind is reading. In K. Rayner (Ed.), *Eye movements in reading: Perceptual and language processes* (pp. 275–307). New York, NY: Academic Press.

Drieghe, D., Rayner, K., & Pollatsek, A. (2005). Eye movements and word skipping during reading revisited. *Journal of Experimental Psychology: Human Perception and Performance, 31,* 954–959. doi:10.1037/0096-1523.31.5.954

Ehrlich, S. F., & Rayner, K. (1981). Contextual effects on word perception and eye movements during reading. *Journal of Verbal Learning and Verbal Behavior, 20,* 641–655. doi:10.1016/S0022-5371(81)90220-6

Engbert, R., Nuthmann, A., Richter, E. M., & Kliegl, R. (2005). SWIFT: A dynamical model of saccade generation during reading. *Psychological Review, 112,* 777–813. doi:10.1037/0033-295X.112.4.777

Henderson, J. M., & Ferreira, F. (1990). Effects of foveal processing difficulty on the perceptual span in reading: Implications for attention and eye movement control. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 16,* 417–429. doi:10.1037/0278-7393.16.3.417

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

Kennedy, A., & Pynte, J. (2005). Parafoveal-on-foveal effects in normal reading. *Vision Research, 45,* 153–168.

Kliegl, R., & Engbert, R. (2005). Fixation durations before word skipping in reading. *Psychonomic Bulletin & Review, 12,* 132–138.

Ledoux, K., Gordon, P. C., Camblin, C. C., & Swaab, T. Y. (2007). Coreference and lexical repetition: Neural mechanisms of discourse integration. *Memory & Cognition, 35,* 801–815. doi:10.3758/BF03193316

McClelland, J. L., & Rumelhart, D. E. (1981). An interactive activation model of context effects in letter perception: I. An account of basic findings. *Psychological Review, 88,* 375–407. doi:10.1037/0033-295X.88.5.375

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

Pollatsek, A., Rayner, K., & Balota, D. A. (1986). Inferences about eye movement control from the perceptual span in reading. *Perception & Psychophysics, 40,* 123–130.

Pollatsek, A., Reichle, E. D., & Rayner, K. (2006). Tests of the E-Z reader model: Exploring the interface between cognition and eye-movement control. *Cognitive Psychology, 52,* 1–56. doi:10.1016/j.cogpsych.2005.06.001

Raney, G. E., & Rayner, K. (1995). Word frequency effects and eye movements during two readings of a text. *Canadian Journal of Experimental Psychology, 49,* 151–173. doi:10.1037/1196-1961.49.2.151

Rayner, K. (1975). The perceptual span and peripheral cues in reading. *Cognitive Psychology, 7,* 65–81. doi:10.1016/0010-0285(75)90005-5

Rayner, K. (1998). Eye movements in reading and information processing:

20 years of research. *Psychological Bulletin, 124,* 372–422. doi:10.1037/0033-2909.124.3.372

Rayner, K., Ashby, J., Pollatsek, A., & Reichle, E. D. (2004). The effects of frequency and predictability on eye fixations in reading: Implications for the E-Z reader model. *Journal of Experimental Psychology: Human Perception and Performance, 30,* 720–732. doi:10.1037/0096-1523.30.4.720

Rayner, K., & Duffy, S. A. (1986). Lexical complexity and fixation times in reading: Effects of word frequency, verb complexity, and lexical ambiguity. *Memory & Cognition, 14,* 191–201. doi:10.3758/BF03197692

Rayner, K., & Juhasz, B. J. (2004). Eye movements in reading: Old questions and new directions. *European Journal of Cognitive Psychology, 16,* 340–352. doi:10.1080/09541440340000385

Rayner, K., Sereno, S. C., Morris, R. K., Schmauder, A. R., & Clifton, C., Jr. (1989). Eye movements and on-line language comprehension processes. *Language and Cognitive Processes, 4,* SI21–SE49. doi:10.1080/01690968908406362

Rayner, K., Sereno, S. C., & Raney, G. E. (1996). Eye movement control in reading: A comparison of two types of models. *Journal of Experimental Psychology: Human Perception and Performance, 22,* 1188–1200. doi:10.1037/0096-1523.22.5.1188

Rayner, K., & Well, A. D. (1996). Effects of contextual constraint on eye movements in reading: A further examination. *Psychonomic Bulletin & Review, 3,* 504–509. doi:10.3758/BF03214555

Rayner, K., White, S. J., Johnson, R. L., & Liversedge, S. P. (2006). Raeding wrods with jubmled lettres: There is a cost. *Psychological Science, 17,* 192–193. doi:10.1111/j.1467-9280.2006.01684.x

Reichle, E. D., Pollatsek, A., Fisher, D. L., & Rayner, K. (1998). Toward a model of eye movement control in reading. *Psychological Review, 105,* 125–157. doi:10.1037/0033-295X.105.1.125

Reilly, R. G., & Radach, R. (2006). Some empirical tests of an interactive activation model of eye movement control in reading. *Cognitive Systems Research, 7,* 34–55. doi:10.1016/j.cogsys.2005.07.006

Traxler, M. J., Foss, D. J., Seely, R. E., Kaup, B., & Morris, R. K. (2000). Priming in sentence processing: Intralexical spreading activation, schemas, and situation models. *Journal of Psycholinguistic Research, 29,* 581–595. doi:10.1023/A:1026416225168

Vitu, F., O'Regan, J. K., Inhoff, A. W., & Topolski, R. (1995). Mindless reading: Eye-movement characteristics are similar in scanning letter strings and reading texts. *Perception & Psychophysics, 57,* 352–364. doi:10.3758/BF03213060

White, S. J., Johnson, R. L., Liversedge, S. P., & Rayner, K. (2008). Eye movements when reading transposed text: The importance of word-beginning letters. *Journal of Experimental Psychology: Human Perception and Performance, 34,* 1261–1276. doi:10.1037/0096-1523.34.5.1261

Appendix

Experimental Stimuli

The experimental stimuli are shown below with the alternate prime words separated by a slash and with the alternate preview strings enclosed in brackets and separated by a slash. Four counterbalanced lists were created so that a given subject saw only one version of each sentence.

Last week Cynthia and Lillian/Carroll joined protests because [Lillian/Llilian] Lillian could not afford the new rate.

Last week Cynthia and Carroll/Lillian joined protests because [Carroll/Craroll] Carroll could not afford the new rate.

Last spring Roxanne/Sabrina and Lynette went to the beach when [Roxanne/Rxoanne] Roxanne rented a house for a week.

Last spring Sabrina/Roxanne and Lynette went to the beach when [Sabrina/Sbarina] Sabrina rented a house for a week.

With loans Barbara and Cassidy/Roxanna started a business when [Cassidy/Csasidy] Cassidy finished college.

With loans Barbara and Roxanna/Cassidy started a business when [Roxanna/Rxoanna] Roxanna finished college.

Over the summer Colleen/Harriet and Jillian drove to the lake so that [Colleen/Cloleen] Colleen could go swimming.

Over the summer Harriet/Colleen and Jillian drove to the lake so that [Harriet/Hrariet] Harriet could go swimming.

Last night Melanie and Jocelyn/Suzanna went to see a movie after [Jocelyn/Jcoelyn] Jocelyn described the review from the newspaper.

Last night Melanie and Suzanna/Jocelyn went to see a movie after [Suzanna/Szuanna] Suzanna described the review from the newspaper.

In truth Raymond and Wallace/Carlton often talked online when [Wallace/Wlalace] Wallace visited other states.

In truth Raymond and Carlton/Wallace often talked online when [Carlton/Cralton] Carlton visited other states.

Each night Kenneth and Bernard/Stewart drove downtown because [Bernard/Brenard] Bernard was performing with the symphony orchestra.

(*Appendix continues*)

Each night Kenneth and Stewart/Bernard drove downtown because [Stewart/Setwart] Stewart was performing with the symphony orchestra.

Last week Derick/Cedric and Martin moved near campus after [Derick/Dreick] Derick was mugged downtown.

Last week Cedric/Derick and Martin moved near campus after [Cedric/Cderic] Cedric was mugged downtown.

Using a cage Howard and Arthur/Darren trapped the snake so that [Arthur/Atrhur] Arthur could transport it to a safe habitat.

Using a cage Howard and Darren/Arthur trapped the snake so that [Darren/Draren] Darren could transport it to a safe habitat.

Last July Deborah and Chasity/Allyson put on a yard sale because [Chasity/Cahsity] Chasity had made money with one the year before.

Last July Deborah and Allyson/Chasity put on a yard sale because [Allyson/Ayllson] Allyson had made money with one the year before.

At the meeting Graham and Jackson/Darrell outlined plans before [Jackson/Jcakson] Jackson wrote up the proposal.

At the meeting Graham and Darrell/Jackson outlined plans before [Darrell/Drarell] Darrell wrote up the proposal.

On Friday night Brandi/Felice and Claire left the party early after [Brandi/Barndi] Brandi made a rude comment at dinner.

On Friday night Felice/Brandi and Claire left the party early after [Felice/Fleice] Felice made a rude comment at dinner.

With great care Sharon/Aubrey and Joanna painted the living room while [Sharon/Sahron] Sharon was on vacation from work.

With great care Aubrey/Sharon and Joanna painted the living room while [Aubrey/Aburey] Aubrey was on vacation from work.

Quite spontaneously Martha and Selena/Louise got married when [Selena/Sleena] Selena lived in Washington.

Quite spontaneously Martha and Louise/Selena got married when [Louise/Luoise] Louise lived in Washington.

With patience Stacey and Latoya/Moriah waited for the landlord after [Latoya/Ltaoya] Latoya had a fight with him.

With patience Stacey and Moriah/Latoya waited for the landlord after [Moriah/Mroiah] Moriah had a fight with him.

For a long time Ronald and Vincent/Maurice worried about burglary after [Vincent/Vnicent] Vincent saw the report on property crime.

For a long time Ronald and Maurice/Vincent worried about burglary after [Maurice/Muarice] Maurice saw the report on property crime.

Perhaps because Bryant/Wesley and Morgan liked to play cards [Bryant/Byrant] Bryant offered to host a game each weekend.

Perhaps because Wesley/Bryant and Morgan liked to play cards [Wesley/Wseley] Wesley offered to host a game each weekend.

Last Friday Walter/Isaiah and George left work early after [Walter/Wlater] Walter completed the work on the project.

Last Friday Isaiah/Walter and George left work early after [Isaiah/Iasiah] Isaiah completed the work on the project.

A few days ago Austin and Duncan/Curtis went to the office once [Duncan/Dnucan] Duncan had finished the letters.

A few days ago Austin and Curtis/Duncan went to the office once [Curtis/Crutis] Curtis had finished the letters.

Every summer Dwight/Herman and Kelsey had a lovely garden because [Dwight/Diwght] Dwight gave good advice on what to grow.

Every summer Herman/Dwight and Kelsey had a lovely garden because [Herman/Hreman] Herman gave good advice on what to grow.

On record Bianca/Hayley and Tracey predicted a great season after [Bianca/Bainca] Bianca recruited the star player.

On record Hayley/Bianca and Tracey predicted a great season after [Hayley/Hyaley] Hayley recruited the star player.

At the mall Taylor/Bonnie and Monica shopped for tents before [Taylor/Tyalor] Taylor went camping.

At the mall Bonnie/Taylor and Monica shopped for tents before [Bonnie/Bnonie] Bonnie went camping.

In the field Chelsea and Bridget/Chandra set up the telescope before [Bridget/Birdget] Bridget started to look at the moon.

In the field Chelsea and Chandra/Bridget set up the telescope before [Chandra/Cahndra] Chandra started to look at the moon.

(*Appendix continues*)

At the station Celeste/Christa and Rebekah waited nervously after [Celeste/Cleeste] Celeste announced the train was late.

At the station Christa/Celeste and Rebekah waited nervously after [Christa/Crhista] Christa announced the train was late.

Each spring Donald and Weston/Carter planted the grass seed before [Weston/Wseton] Weston watered the new lawn.

Each spring Donald and Carter/Weston planted the grass seed before [Carter/Crater] Carter watered the new lawn.

At noon Michele/Belinda and Carolyn turned onto a side road because [Michele/Mcihele] Michele warned of the danger of the highway.

At noon Belinda/Michele and Carolyn turned onto a side road because [Belinda/Bleinda] Belinda warned of the danger of the highway.

Quite sadly Cameron and Maxwell/Brenton left the ski resort when [Maxwell/Mxawell] Maxwell caught the flu.

Quite sadly Cameron and Brenton/Maxwell left the ski resort when [Brenton/Bernton] Brenton caught the flu.

With practice Malcolm/Quinton and Brendan finished the course then [Malcolm/Mlacolm] Malcolm wanted to celebrate.

With practice Quinton/Malcolm and Brendan finished the course then [Quinton/Qiunton] Quinton wanted to celebrate.

Every week Candace and Dorothy/Marilyn went to the theater because [Dorothy/Droothy] Dorothy gave free acting lessons.

Every week Candace and Marilyn/Dorothy went to the theater because [Marilyn/Mrailyn] Marilyn gave free acting lessons.

For the album Willis/Melvin and Marcus wrote the song lyrics before [Willis/Wlilis] Willis composed the music.

For the album Melvin/Willis and Marcus wrote the song lyrics before [Melvin/Mlevin] Melvin composed the music.

By chance Caitlin and Addison/Tabitha were staying at the beach when [Addison/Aiddson] Addison won the surfing contest.

By chance Caitlin and Tabitha/Addison were staying at the beach when [Tabitha/Tbaitha] Tabitha won the surfing contest.

On the trip Marissa/Cecelia and Abigail brought repellent because [Marissa/Mraissa] Marissa was allergic to bug bites.

On the trip Cecelia/Marissa and Abigail brought repellent because [Cecelia/Cceelia] Cecelia was allergic to bug bites.

At the campground Brooke and Evelyn/Kendra cooked the hotdogs after [Evelyn/Eevlyn] Evelyn started the fire.

At the campground Brooke and Kendra/Evelyn cooked the hotdogs after [Kendra/Knedra] Kendra started the fire.

In spite of the rain Terence/Forrest and Douglas enjoyed the show where [Terence/Treence] Terence met the band.

In spite of the rain Forrest/Terence and Douglas enjoyed the show where [Forrest/Frorest] Forrest met the band.

On weekends Russell and Jarrett/Dominic liked to bird watch unless [Jarrett/Jrarett] Jarrett needed the binoculars for camping.

On weekends Russell and Dominic/Jarrett liked to bird watch unless [Dominic/Dmoinic] Dominic needed the binoculars for camping.

With reluctance Mariah/Pamela and Carrie washed the dishes while [Mariah/Mraiah] Mariah talked about the up-coming election.

With reluctance Pamela/Mariah and Carrie washed the dishes while [Pamela/Pmaela] Pamela talked about the up-coming election.

With much enthusiasm Gordon and Eugene/Dillon went to the play when [Eugene/Eguene] Eugene won the tickets in a contest.

With much enthusiasm Gordon and Dillon/Eugene went to the play when [Dillon/Dlilon] Dillon won the tickets in a contest.

After the trip Connor/Calvin and Dennis developed the film when [Connor/Cnonor] Connor finished the roll.

After the trip Calvin/Connor and Dennis developed the film when [Calvin/Clavin] Calvin finished the roll.

Last year Dustin and Damien/Philip bought books online until [Damien/Dmaien] Damien thought of borrowing from the library.

Last year Dustin and Philip/Damien bought books online until [Philip/Pihlip] Philip thought of borrowing from the library.

When asked Edward and Darryl/Carlos always sang at parties if [Darryl/Draryl] Darryl rolled out the piano.

When asked Edward and Carlos/Darryl always sang at parties if [Carlos/Cralos] Carlos rolled out the piano.

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