Parafoveal Processing and Word Skipping During Reading

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ABSTRACT

WONIL CHOI: Parafoveal Processing and Word Skipping During Reading
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In this study, two questions related to eye movements during reading and word recognition were addressed: 1) Does the process of word recognition influence eye movements during reading? 2) If so, to what extent does lexical processing influence word skipping? Experiment 1 showed a greater rate of skipping for high-frequency target words than low-frequency target words when full-parafoveal preview of those target words was available but not when parafoveal preview consisted of nonwords created by transposing two word-internal letters of the target. Experiment 2 investigated further how lexical status influences eye movements during reading by manipulating word repetition and parafoveal preview. The results showed that lexicality of letter string in parafoveal preview is a crucial determinant of word skipping. These results support models of reading in which control of eye movements is strongly influenced by word recognition and where lexical processing occurs for one input word at a time.

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Introduction

Language comprehension is a useful vehicle to understand how the cognitive system works because a variety of cognitive functions, such as attention, perception, memory, motor control, and even executive control, must be coordinated in order for language processing to be successful. In particular, an interest in the relation between word recognition and the eye-movement control system during reading is one of the central topics in psycholinguistics (Rayner, 1998). Word skipping during reading has been a crucial dependent measure with which to study this relation because it reflects natural reading processes and because it allows insight into how both the targeting and timing of eye movements are influenced by the process of word recognition. This paper reports two experiments that use word skipping as a measure of the extent to which the word to the right of the one being fixated is recognized during reading. These experiments test hypotheses about how higher-level and lower-level information are combined during word recognition, and about how word recognition interacts with the attentional, perceptual and motor processes that play important roles in eye movements during reading. Before the current experiments are described, the relevant background on eye-movement control and on word recognition, focusing on studies of word skipping, is reviewed.

Word Skipping in Reading

Eye movements during reading are characterized as a combination of fixations (where the eyes are stationary) and saccades (where the eyes move rapidly). When reading English, eye fixations stay on a given word for around 200-250ms and the average saccadic length is seven-to-nine letter spaces (Rayner, 1998). Whereas most words in a text are fixated during reading, some words are skipped for various reasons. For example, proficient readers skip about one third of words (Brysbaert, Drieghe, & Vitu, 2005). Moreover, around 65-75 % of short words (2-3 letter words) or function words are skipped during reading of English text (Carpenter & Just, 1983; Rayner & McConkie, 1976).

Why do skilled readers skip a substantial proportion of words? It is crucial to answer this question in order to understand how eye-movement control works during reading comprehension. There are two kinds of factors that affect whether readers skip the word next to the currently fixated word: oculomotor factors and language-related factors. The major oculomotor factor influencing skipping is word length (Brysbaert et al, 2005). Many studies have shown that short words are skipped more frequently than long words (Brysbaert et al. 2005 for a review). For example, Vitu, O'Regan, Inhoff, and Topolski (1995) found that readers skipped 80 % of one-letter strings, 60 % of three-letter strings, 30 % of five-letter strings, and 10 % of seven or more letter strings irrespective of the lexical status of a given letter string. The major language-related variables that influence skipping are word frequency and contextual predictability. Drieghe, Rayner, and Pollatsek (2005) examined skipping rates for words seen in the parafovea by manipulating contextual predictability of target words. They used a boundary paradigm which was designed to detect what kind of information can be integrated across eye movements during reading, systematically varying parafoveal preview (Rayner, 1975). The authors compared the skipping rates for six different conditions: (1) predictable word, (2) unpredictable word, (3) semantically anomalous word, (4) visually similar nonword, (5) visually dissimilar nonword, and (6) orthographically illegal nonword. They found that skipping rates were higher in the predictable condition as compared to the other 5 conditions (including the unpredictable condition) and that there was no difference of skipping rates among the other 5 conditions. The results indicate that contextual predictability is one of the factors affecting skipping rates.

Along with contextual predictability, word frequency is an important language-based variable that influences whether or not word skipping occurs (Brysbaert et al., 2005). White (2008) recorded readers' eye-movements to investigate whether skipping was affected by word frequency when orthographic familiarity was controlled. Fixation times and probability of word skipping were measured for high-frequency words (e.g. town) and low-frequency words (e.g. cove) that were matched on orthographic familiarity. The author compared sentences like 'He loved to visit the local *town* near to where his grandparents lived' with sentences like 'He loved to visit the local *cove* near to where he learnt to swim'. More skipping occurred in the high-frequency condition than in the low frequency condition.

Rayner, Ashby, Pollatsek, and Reichle (2004) manipulated both linguistic variables simultaneously: word frequency and contextual predictability. They found a clear interaction between word frequency and contextual predictability, meaning that higher skipping rates were observed in the high-frequency condition than in the low-frequency condition when the target word was predictable. The findings of Rayner et al. (2004) confirm that both word frequency and contextual predictability affect word skipping during reading, though their results also showed some inconsistencies in how these factors influenced skipping of words as compared to fixation times on words when they were not skipped.

Word Skipping in two Alternative Models of Eye-Movement Control During Reading

Patterns of word skipping have provided important data for the evaluation of models of eye-movement control during reading. In this section two classes of eye-movement control models are introduced in order to account for word skipping: E-Z reader (Pollatsek, Reichle, Rayner, 2006) and SWIFT (Engbert, Nuthmann, Richer, & Kliegl, 2005). In addition to taking into account the relevant linguistic factors, these two models also offer distinct characterizations about the amount of parafoveal processing used during reading.

The E-Z reader model is one of the best established quantitative models of eye-movement control during reading (Pollatsek et al., 2006). This model assumes that the process of word recognition occurs serially and is associated with an attentional beam that is allocated to one word in a text at a time. In addition to these characteristics, the model has two stages of word recognition processes associated with saccadic programming and attentional movement. More specifically, saccade programming is triggered by the completion of the first stage of word recognition, which is called the familiarity check. This is followed by the second stage of word recognition, called lexical access, which signals attention to shift to the next word (Pollatsek et al. 2006). In other words, after a familiarity check has been completed on $word_N$, the reader then programs a saccade to the next word. During the second stage of word recognition for $word_N$, the reader's attentional beam shifts to $word_{N+1.}$ With this mechanism, the E-Z reader model can explain how words are skipped during reading. If the eyes fixate $word_N$, after the completion of the second stage of $word_N$ recognition, attention is moved to a next word, $word_{N+1,}$ and the first stage of $word_{N+1}$ recognition in parafoveal region is finished, then the programming of the eye movement to $word_{N+1}$ is cancelled and reprogramming of the eye movement to $word_{N+2}$ occurs. The mechanism for word skipping proposed by the E-Z reader model is described in Figure 1. With respect to word skipping, one important characteristic of the E-Z reader model is that word skipping occurs when the word in parafoveal preview has been completely recognized because saccadic movement and attentional shift are determined by the completion of word recognition.

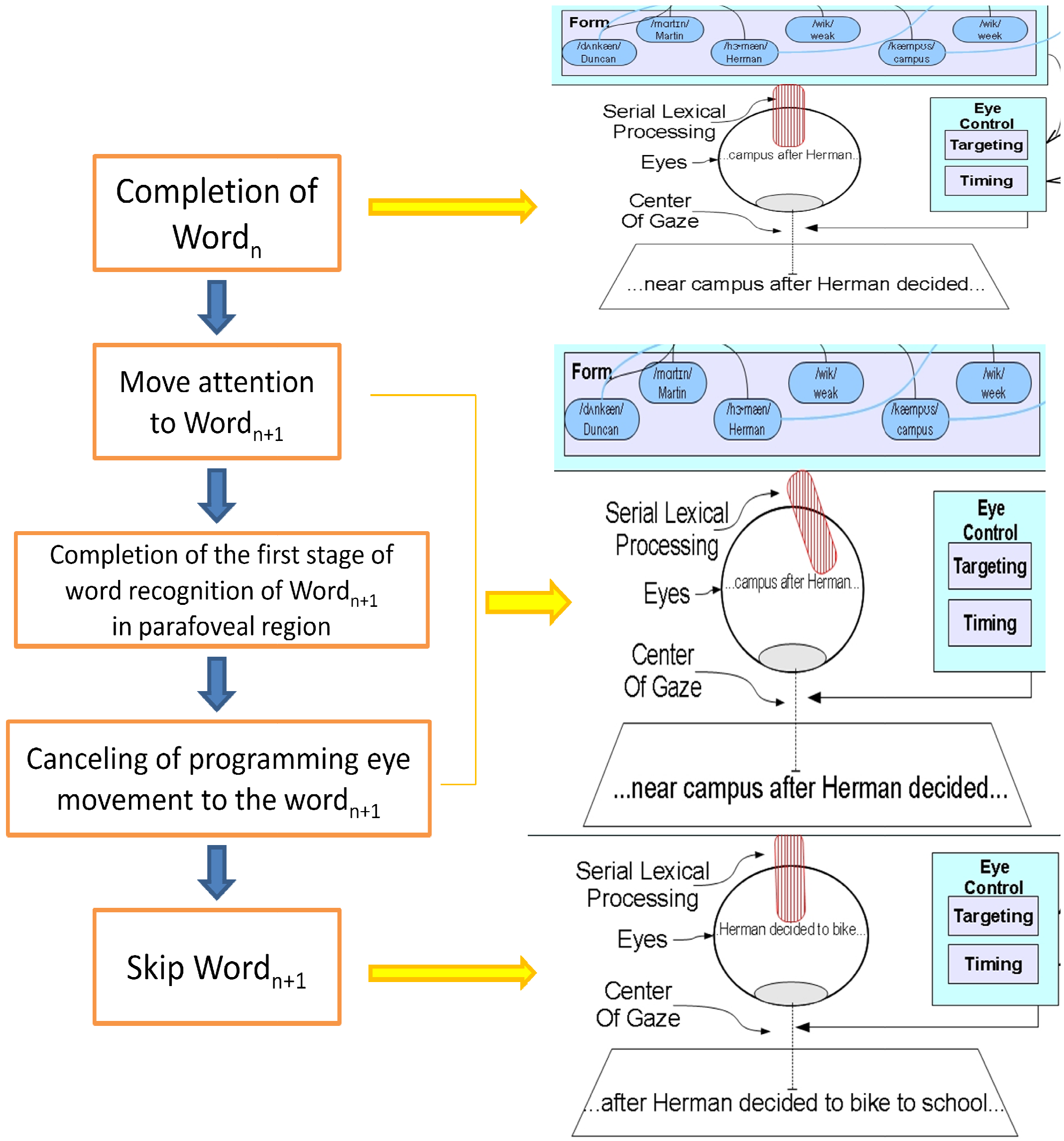

Figure 1. A schematic of word skipping proposed by EZ reader model

The mechanism that the SWIFT model uses to account for word skipping differs from that of the E-Z reader model (Engbert et al. 2005). The model assumes guidance by attentional gradients, allowing for parallel processing of more than one word in a text. The main difference between SWIFT and E-Z reader is the range of the attentional beam. Specifically, the SWIFT model posits that approximately four words fall within the attentional gradient and are processed in parallel during sentence reading, while the E-Z reader model assumes that only one word is processed at a time. The characteristic of the SWIFT model which includes gradient-type attentional distribution over the fixated word permits a different type of explanation for word skipping. Because saccadic movement is supposed to go toward the word that has the maximum level of activation within the current attentional gradient, either $word_{n+1}$ or $word_{N+2}$ can be the next target word. If $word_{N+1}$ is already at a relatively high activation level (e.g. because it is more predictable from the preceding context or is a high-frequency word) and passed its threshold level, $word_{N+2}$ might have a higher level of excitation than $word_{N+1.}$ Consequently, $word_{N+1}$ would be skipped, and then the eyes would progress to $word_{N+2}$. In the SWIFT model, $word_{N+1}$ can be skipped even if it is not fully recognized. $Word_{N+1}$ can be skipped simply because the level of excitation of $word_{N+2}$ is greater than that of $word_{N+1}$.

Skipping of Nonwords

Brysbaert et al. (2005) conducted a meta-analysis on skipping rates of eye movements during reading to examine the relative importance of visual and linguistic factors. They found that visual factors (specifically word length and launch site) were more powerful than language-related factors (word frequency and contextual predictability), but that language-related factors do have robust effects on skipping rates. As mentioned earlier, Drieghe et al. (2005) showed that only a highly-predictable word is skipped more frequently than an orthographically similar nonword or a neutral word, irrespective of the launch site, suggesting that language-based variables like contextual predictability influence people's decision regarding whether or not to skip a word in the parafoveal region. As mentioned earlier, the five unpredictable conditions including visually similar nonwords did not produce any difference in skipping rates, and showed less skipping rates than the predictable word condition.

An interesting but problematic result in the Drieghe et al. (2005) paper concerns the relatively high skipping rates observed for nonwords. More specifically, in Experiment 1, overall skipping rates for the orthographically-illegal condition is 12%, and restricted skipping rates (saccades launched from 5 or fewer characters before the target word) is 37%, which is very similar to the skipping rate in the other four unpredictable word or nonword conditions. Drieghe et al. (2005) proposed two kinds of mechanisms assumed by the E-Z reader model for explaining the high skipping rates of unpredictable word or nonword conditions: (1) error in saccadic programming and (2) skipping on the basis of predictability. Even though these explanations seem plausible, it is questionable whether they can adequately explain such a high skipping rate for the unpredictable conditions. Another mechanism for the phenomenon of nonword skipping is misidentification. That is, readers can misidentify the nonword as the word. If this were true, then skipping rates should vary as a function of visual similarity of the nonwords to the target words. However, the results did not support the misidentification explanation, showing that skipping rates for all unpredictable conditions were not significantly different regardless of the visual similarity of the nonword to the target word (Drieghe et al. 2005).

Gordon, Plummer, and Choi (2010) examined how word repetition and parafoveal preview information affect the process of word recognition during sentence reading. To manipulate preview information, a boundary technique was used (Rayner, 1975). In this technique, an invisible boundary is specified to the left of a target word. The target word is replaced by a preview stimulus, but this preview changes to the target word as soon as the reader's eyes cross the boundary. Because visual processing is inhibited during the saccade, readers cannot notice any alternation between the preview stimulus and the target word in their foveal vision once the saccade has landed. In Gordon et al. (2010)'s experiment, transposed-letter (hereafter TL) nonwords were used in their experimental sentences like "Over the summer Harriet and Jillian drove to the lake so that Harriet could go swimming" to investigate the influence of parafoveal preview information and of word repetition. The parafoveal preview of the target word Harriet was either Harriet (valid preview) or Hrariet (TL preview). Because a boundary technique was employed readers were not able to notice the display change when they read the sentence. If, as assumed in the E-Z reader model, word skipping occurs only when letter strings are fully recognized in the parafoveal region, the skipping rate for valid preview should be higher than that for TL preview. Although the result showed that skipping rate of the TL nonword preview condition lower than that of the full-preview condition, the TL-preview condition had around 10% skipping, indicating that there is a skipping mechanism driven by oculomotor factors irrespective of how ease of lexical processing is involved during parafoveal preview (Brysbaert et al., 2005).

This consistent finding (Drieghe, et al. 2005; Gordon, et al. 2010) provides evidence supporting the importance of oculomotor factors like word length. Specifically, if word length is controlled, skipping rates for each condition in which specific language-related factors are manipulated would be similar regardless of the manipulated linguistic variables. However, these results showed that linguistic factors are also an important determinant of word skipping. For example, Gordon et al. (2010) obtained the highest skipping rates in the repeated and valid parafoveal preview condition out of all the experimental conditions, meaning that linguistic variables had a crucial influence on skipping behavior above and beyond oculomotor factors. Accordingly, it is critical to know what linguistic information is extracted or processed in parafoveal preview to figure out how exactly linguistic variables can influence skipping, which is a critical measure of the relationship between language processing, attention and perceptual-motor processes.

<u>Lexical Access in Parafoveal Preview</u>

The fact that reading performance is impaired when parafoveal preview information is unavailable is evidence that some portion of lexical processing is based on processing information in parafoveal preview; this general phenomenon is called *parafoveal preview benefit* (Rayner, McConkie, & Zola, 1980). Fine-grained information, such as the sub-lexical representation of a word, is extracted from the parafoveal region along with information about word frequency. For example, phonological information is extracted from parafoveal preview (Ashby, Treiman, Kessler, & Rayner, 2006; Chace, Rayner, & Well, 2005; Lee, Binder, Kim, J. O., & Rayner, K., 1999; Pollatsek, Lesch, Morris, & Rayner, 1992; Rayner, Pollatsek, & Binder, 1998). Ashby et al. (2006) used the boundary paradigm to examine if sub-lexical representation can be extracted in parafoveal preview. Target words were presented in sentences preceded by parafoveal previews in which the vowel phoneme was consistent or inconsistent with the vowel phoneme in the target word. They found shorter reading times of target words preceded by parafoveal preview with consistent vowels compared with inconsistent vowels.

Fine-grained orthographic information in parafoveal previews can be also used in accessing a lexical entry during reading (Johnson, Perea, & Rayner, 2007). Johnson et al. (2007) conducted an eye-tracking study using the boundary technique to examine the role of letter identity and letter position of a word during sentence reading. In priming studies of isolated word recognition, the TL nonword primes cause greater facilitation in recognizing word targets than do substituted-letter nonword primes (Perea & Lupker, 2003a; 2003b; 2004). For example, the reaction time for the target word “judge” is shorter when the prime is the TL string “jugde” than when the prime is the substituted letter string “jupte”. Recent orthographic coding theories account for the TL effect by assuming the extraction of bigram representation of words occurs before the completion of lexical access (Grainger & Van Heuvan, 2003; Whitney, 2001), or by assuming early computation of similarity between two strings should be done at the front-end stage of lexical access (Gomez, Perea, & Ratcliff, 2008; Davis, 2010). More interestingly, the eye-tracking study performed by Johnson et al. (2007) obtained results similar to those found for the recognition of isolated words (Perea & Lupker, 2003b). Two studies used the same target word stimuli and prime nonword stimuli in their experiment, indicating that a similar mechanism was employed at both isolated word recognition and the eye-tracking study with respect to lexical access (Johnson et al., 2007; Sears, Campbell, & Lupker, 2006). Given that fine-grained linguistic information of words is extracted from parafoveal preview, this information may affect word skipping. Although Johnson et al. (2007) obtained fixation time results supporting the idea that sub-lexical orthographic codes are processed in parafoveal preview, they did not report any word skipping results in their study. More specifically, fixation times for target words were shortest when full preview was available as compared to when preview showed a transposed or substituted letter string (Johnson et al. 2007; Perea & Lupker, 2003b). If word skipping is modulated by linguistic variables in parafoveal previews, skipping rates should show a reverse pattern of fixation times in Johnson et al. (2007)'s study.

Current Study

Two experiments were conducted to examine how ease of lexical processing and letter identity/position affect lexically-based word skipping during reading. Specifically, letter transposition was manipulated to investigate the relationship between processes of word recognition and eye movement control. The main purpose of Experiment 1 was to address the question of how early the effect of word frequency emerges when nonwords (created by letter transposition) activate their base words during sentence reading. Although Johnson et al. (2007) previously used TL nonwords in the parafovea to examine how letter position and identity contribute to preview processing, they did not report data on skipping rates. For this reason their research did not provide information about whether the targeting of saccades in relation to skipping depends on complete word recognition. In addition, the role of base-word frequency of the parafoveal TL string has not been explored in reading research. In part this is because previous results on isolated word recognition have shown the TL effect over a wide range of word frequencies (Perea and Lupker, 2003b; Foster, Davis, Schoknecht, & Carter, 1987), and also because many visual-word recognition models have regarded the TL effect as operating at early levels of visual word recognition that operate before lexical processing (Gomez et al. 2008; Grainger & van Heuven, 2003; Whitney, 2001). However, word frequency is one of the most important factors in determining the targeting of fixations as they are related to word skipping (Pollatsek et al, 2006; Engbert et al., 2005). Furthermore, O'Connor and Foster (1981) found an interaction between word frequency and letter alternation. In a lexical decision task they found higher error rates for TL nonwords with high-frequency base words (e.g. mohter) as compared to those with low-frequency base words (e.g. bohter). Although the result obtained by O'Connor and Foster (1981) was based on a single-word lexical decision task, it suggests that the base-word frequency has an important role in processing TL nonword letter strings. If word skipping occurs when words in parafoveal preview are completely recognized, as described by the E-Z reader model, it would be expected that the word-frequency effect on skipping rates would appear only when preview information is valid. Because TL strings are not words, skipping based on base-word frequency should not occur in these conditions, leading to the prediction that there should be no word-frequency effect on skipping rates for TL nonword string previews while a frequency effect should be observed for full previews. In contrast, if TL strings can effectively activate their base words early in processing through lexical or pre-lexical information available from parafoveal preview, a word-frequency effect on skipping should be observed in the TL preview conditions.

Experiment 2 examines the role of lexical status in parafoveal preview by using TL neighbors (e.g. calm-clam), where transposing letters results in a word rather than a nonword. Research on such items is limited in part because there are not very many word pairs that can be created by transposing letters. Chambers (1979) was the first to find a TL confusability effect, in that the lexical decision times for transposed-letter neighbors were slower than control words. For example, reaction time for the TL neighbor word, *blot*, is slower than that for the control word, *clip*, which has the same word length and word frequency, indicating that visually similar TL word pairs can be activated before a lexical decision and the competitor(s) interfere the TL target word processing. Andrews (1996) performed a masked-priming task with TL neighbors. The naming latency for a target word preceded by a TL neighbor word was longer than that for the target word preceded by an unrelated-prime word. Furthermore, naming errors were more frequently produced in low-frequency target words as compared to control words, indicating that high-frequency TL pair for low-frequency TL word (e.g. wrap for warp) inhibits the processing of the low-frequency TL target word. However, Castles, Davis, and Foster (2003) did not find an inhibitory effect of TL neighbors, and even found a facilitative TL priming effect in third grade children. Moreover, Dunabeitia, Perea, and Carreiras (2009) found no TL word priming effect with Spanish stimuli irrespective of relative word frequency. While the results of isolated visual word recognition are inconclusive, sentence-reading studies (discussed below) have shown that an inhibitory TL effect appears when TL neighbors are substituted in text.

Acha and Perea (2008) examined how TL neighbors affect the processing of a target word in natural reading situations with Spanish TL words embedded in real sentences. They found inhibitory effects of TL neighbors that had higher frequency for target words compared with control words. Recently, Johnson (2009) reported similar eye-tracking experiments with English TL neighbors embedded in real sentences. She found very late inhibitory effects of TL word neighbors in processing (e.g. total time, regression rates etc.) and the inhibitory effect was observed regardless of relative word frequency of TL neighbors. Moreover, previous studies on the neighborhood frequency effect have produced similar findings showing that an inhibitory effect occurs in late stages of word recognition during sentence reading (Paterson, Liversedge, & Davis, 2009; Perea & Pollatsek, 1998; Pollatsek, Perea, & Binder, 1999). In contrast to the consistent results collected by normal sentence reading studies, a reading study employing a boundary paradigm showed a different role for neighbor words (Williams, Perea, Pollatsek, & Rayner, 2006). Williams et al. (2006) found a facilitative effect of orthographic neighbors presented in parafoveal preview, meaning that letter information extracted in parafoveal region helped in the processing of target words once they were fixated. In particular, the facilitative effect occurred only when higher-frequency words than target words were used in parafoveal preview. For example, the fixation times for the target word, *witch*, preceded by the preview word, *watch*, were faster than when preceded by the orthographic-control nonword, *wetch*, but there was no effect in the reverse condition in which low-frequency words were used as previews and high-frequency words were used as targets.

How does this finding relate to the current experiment? As described earlier, previous studies on TL neighbor word pairs have mainly focused on the inhibitory effect of TL neighbors for the processing of the target words. In particular, the results obtained by sentence-reading studies have shown that TL neighbors have inhibitory effects on target word processing, occurring on the late measures of eye movements such as total time, proportion of regression (Acha, & Perea, 2008; Johnson, 2009). In contrast, Experiment 2 of this paper examines how TL neighbor words influence on the early stages of word recognition by observing first-pass measures such as proportion of word skipping. In Experiment 2, TL word primes were presented in parafoveal preview instead of TL nonword primes which were to be used in Experiment 1. With respect to the low-level orthographic similarity (e.g. letter identity, bigram similarity), TL words have similar features with TL nonwords. For instance, the relation between *trail* and *trial* as a TL match is the same as that between *jugde* and *judge*. The main difference between *trail* and *jugde* is whether these letter strings have lexical status. It would be interesting to understand if the same mechanism operates even though the letter string with lexical representation is seen in parafoveal preview. To address this issue, word repetition and preview type are manipulated in Experiment 2. While word frequency is manipulated in Experiment 1 to vary lexical features that influence the process of word recognition, word repetition is manipulated in Experiment 2 because it is relatively difficult to manipulate word frequency with TL word pairs given the limited number of such words. The finding that repeated words are recognized easier than new words is observed not only in masked priming studies (Foster & Davis, 1984) but also in normal sentence reading studies (Gordon, Lowder, & Choi, 2010; Gordon, et al. 2010). Accordingly, we will test whether word skipping can also be influenced by word repetition in Experiment 2 as we will do by word frequency in Experiment 1. With respect to the manipulation of the preview type, lower-frequency TL neighbor pairs are always presented in parafoveal preview as the preview string (e.g. calm is a target, and clam is a preview string). Because the main purpose of this study is to examine how much linguistic factors (e.g. word frequency, word repetition) can influence the targeting of saccade, it is important to keep the strings in parafoveal preview as lower-frequency TL neighbors. This issue will be addressed in detail in the Experiment 2 section.

Experiment 1

This experiment tests the hypothesis that recognition-based word skipping depends on complete recognition of the word in parafoveal preview; it does so by examining whether the frequency of the baseword affects skipping rates when TL words are seen in parafoveal preview. Eye movements are recorded as participants read sentences. The boundary technique is used to manipulate the information that is available about a word during parafoveal preview. Two variables are manipulated in this experiment: (1) word frequency (high vs. low) and (2) preview condition (valid vs. transposed letter). If word skipping occurs after the letter string is fully recognized in parafoveal preview (E-Z reader's view), then word frequency should increase skipping in the valid preview condition but not when the preview stimulus is a nonword (transposed letters). More specifically, E-Z reader posits that skipping occurs when the letter string in parafoveal preview is completely recognized before the oculomotor system finishes programming a saccadic movement to the next word, which is mainly influenced by lexical variables, such as word frequency. A word-frequency effect can be observed only in the valid preview condition in which words are presented in parafoveal preview because there would be more possibility for high-frequency words to be completely recognized in parafoveal preview as compared to low-frequency words (Inhoff & Rayner, 1986; White, 2008). But the word-frequency effect should not be found in the TL preview condition because the letter string presented in parafoveal preview is not a word.

However, if lexically-based word skipping does not depend on full recognition then word frequency should influence the amount of skipping in both full preview and TL preview because TL previews have been shown to be effective in activating the base words from which they are derived. This result can be observed by allowing for skipping the target word based on coarse information in parafoveal preview (Engbert, et al. 2005). Skipping does not necessarily occur based on full recognition of the letter string in preview, but because a TL nonword string is similar to its base word it can activate the base word of TL nonword as if it would serve as the real word.

Alternatively, if the TL nonwords with high-frequency base word relatively easily activate their base word (O'Conner & Foster, 1981), the skipping rates for both high-frequency words and TL strings with high-frequency base words are higher than low-frequency pairs. In particular, the skipping rates for TL strings with low-frequency base words are lower as compared to when low-frequency words are presented in parafoveal preview, indicating that the degree of activating base words is a function of word frequency. While TL strings with high-frequency base words can easily activate the base word, TL strings with low-frequency base words cannot activate the base word easily. Williams et al. (2006) reported a similar finding that a high-frequency neighbor word presented in parafoveal preview facilitated the processing of a target word, but low-frequency neighbor words did not do so.

Method

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

Materials and Design. One hundred twenty five-letter words were used as targets and embedded in a single line sentence in the Experiment. Some target words were selected from Johnson et al. (2007), and other target words were selected from the CELEX corpus (Baayen, Piepenbrock, & Gulikers, 1995). Sixty targets were high-frequency words and 60 were low-frequency words. Two parafoveal preview conditions were employed for target words: (a) full preview, where the preview string is identical to the target word (*house* as the preview of *house*) and (b) transposed letter preview, where the preview string was created by transposing the second and the third letter of the target word (*huose* as the preview of *house*).

In order to balance orthographic familiarity across conditions the frequencies of the target words and of their letter n-gram frequencies were calculated from the N-Watch program (Davis, 2005) in which the default vocabulary was selected from the CELEX English word-form corpus (Baayen, et al., 1995). Because orthographic familiarity influenced lexical or sub-lexical processing of words during reading (Lima & Inhoff, 1985; White, 2008; White & Liversedge, 2004, 2006a, 2006b), n-gram frequencies and number of orthographic neighbors should be controlled across high and low word frequency conditions. Type and token frequency were assessed for two kinds of n-gram (bigram and trigram). Type frequency is the number of different words that include an n-gram, while token frequency is the number of individual instances of a specific type including the n-gram (for the exact rules of computing these n-gram frequencies, see Davis, 2005). High-frequency targets had a mean word frequency of 251 per million and low-frequency targets had a mean word frequency word of 2.72 per million (t (118) = 11.81, $p < .001$). Other orthographic characteristics of target words are shown in Table 1. All letter n-gram frequencies of target words are not statistically different in high and low frequency condition, ($t < 1$, $p > .05$).

Table 1

Orthographic Characteristics for the Target Words Used in Experiment 1

	FREQ	**BF_TK**	**BF_TP**	**TRF_TK**	**TRF_TP**	**NofN**
HF	225	1651	36	425	6.2	3.0
LF	2.94	1617	37	339	7.0	3. 3

Note. FREQ = word frequency, BF_TK = Bigram Token Frequency calculated as the mean of the token frequencies of the bigrams in the stimulus, BF_TP = Bigram type Frequency calculated as the mean of the type frequencies of the bigrams in the stimulus , TRF_TK = Trigram Token Frequency calculated as the mean of the token frequencies of the trigrams in the stimulus, TRF_TP = Trigram Type Frequency calculated as the mean of the type frequencies of the trigrams in the stimulus, NofN = Number of Orthographic Neighbors.

Two additional characteristics of TL preview letter strings were assessed: pronounceability and number of orthographic lexical neighbors (see Table 2). Two native English speakers rated the pronounceability of the first three letters of the TL strings and of the entire TL string. Neither rating (initial-component pronounceability or overall prounceability) showed a statistically significant difference between TL non-words generated from the high and low frequency base words. The second concern is the number of orthographic neighbor words for preview stimuli, which could affect skipping rates and the processing of target word (Pollatsek et al., 1999). The number of orthographic neighbors was computed by N-Watch program developed by Davis (Davis, 2005). The statistics did not show any difference between two frequency conditions ($t<1$, $p>.5$).

Table 2

The Orthographic Characteristics of TL primes by Frequency Conditions

	TL Primes in High Frequency Condition	TL Primes in Low Frequency Condition
Pronounceability of the first three letters	0.75	0.68
Pronounceability of whole letter string	0.5	0.61
Number of Orthographic Neighbor words	0.52 (1.08)	0.5 (0.7)

Note. The first two rows refer to the proportion of pronounceable letter strings of the transposed- preview stimuli, and the third row represents the mean number of orthographic neighbor words of the transposed-preview stimuli and the standard deviation is shown in parentheses.

A measure of the predictability of the target words in context (corpus-based measures of transitional probability from the previous word) was obtained because predictability affects where and when the eyes move during reading (Calvo and Meseguer, 2002; Rayner and Well, 1996). Transitional probability was calculated as the ratio of joint and marginal frequencies of the target word as has been done in previous eye-tracking studies of reading (McDonald and Shillcock, 2003a; 2003b). This calculation is shown in the formula below where WORD_N is the target word and WORD_{N-1} is the immediately preceding word.

$$\mathrm{P}(\mathrm{WORD}_{\mathrm{N}} | \mathrm{WORD}_{\mathrm{N}-1}) = \frac{\mathrm{f}(\mathrm{N}-1, \mathrm{N})}{\mathrm{f}(\mathrm{N}-1)}$$

Frequency information was obtained from the online version of The Corpus of Contemporary American English (COCA) (released in 2008). COCA is a large, diverse corpus of American English which includes more that 385 million words produced from 1990 – 2008 (20 million words each year), balanced between spoken language and written language of several genres: fiction, magazines, newspapers, academic journals (Davies, 2009). Table 3 shows average transitional probabilities for each frequency condition. There were no significant differences between in any of the measures of transitional probability for high-frequency target words and low-frequency target words ($p > 0.15$).

Table 3

Mean Transitional Probabilities by Frequency Condition Shown Individually for the Various Genres in The Corpus of Contemporary English

	Spoken	**Fiction**	**Magazine**	**Newspaper**	**Academic**
HF	0.0043(0.01)	0.0065(0.013)	0.0044(0.009)	0.0039(0.009)	0.0032(0.0096)
LF	0.0042(0.02)	0.0026(0.016)	0.0070(0.047)	0.0118(0.086)	0.0088(0.065)

Note. HF represents High Frequency target word(s), LF represents Low Frequency target word(s). Standard deviations are given parentheses.

The words preceding the target word were 5 to 11 letters long. Word length and word frequency of the word preceding the target word was not statistically significant across two frequency conditions ($ts < 1.2$).

Word frequency (High and Low) and parafoveal preview (Valid and Transposed letter) were manipulated in Experiment 1. Four counterbalanced lists were constructed and each list included four different conditions (High-Valid, High-TL, Low-Valid, and Low-TL) with 30 critical words per condition. The same numbers of participants were tested in each counterbalanced list and the presentation orders of sentences are randomized. Table 4 shows an example sentence in each of the four conditions used in the experiment.

Table 4

An Example Sentence From the Experiment With Each of the Four Conditions

Condition	*Sentence*
HF, VP	The visitors saw that the base was slightly [*north*:**north**] of their current location.
HF, TLP	The visitors saw that the base was slightly [*nroth*:**north**] of their current location.
LF, VP	The only sign of life was the momentary [*blink*: **blink**] of his left eye.
LF, TLP	The only sign of life was the momentary [*bilnk*: **blink**] of his left eye.

Note. The letter strings in brackets shown in italics are presented in parafoveal preview before the eyes cross the invisible boundary. The words in bold are the target stimuli. HF = High Frequency, LF = Low Frequency, VP = Valid Preview, TLP = Transposed Letter Preview.

Post hoc Predictability Assessment. Even though contextual predictability was controlled by a corpus-based transitional predictability measure, a behavioral measure of predictability measure was obtained in addition. A Cloze (Taylor, 1953) test in which a next word must be guessed based on preceding context was performed by a separate group of participants who were not involved in the actual experiment. Twenty participants were provided with the first part of the critical sentence (right before the target word) and asked to fill in the next word(s) in the sentence. The results showed that 5 target words were predictable from preceding context (over 40%), so these items were excluded from statistical analyses of the eye-movement data from the main experiment. The mean predictability scores for the rest of target words were less than 5% and the difference between high-frequency (5.9%) and low-frequency (3.6%) condition was not statistically significant ($t = 1.3$, $p > .19$).

Procedure. Eye movements were recorded with an Eyelink 1000 model (SR Research, Ontario, Canada) interfaced with a Pentium computer. Stimuli were presented on a 21 inch ViewSonic G225f Monitor with a display resolution of 1024 x 768. A headrest was used to minimize head movement. Eye movements were recorded from the reader's dominant eye at a sampling rate of 1000 Hz. Sentences were presented in black color on a white background, with characters presented in Courier font (a mono-spaced font). The distance between the participant and the display monitor was 61cm; 3.8 characters subtend 1° of visual angle. After the initial calibration and validation were completed, participants were asked to read sentences on the monitor naturally and respond to the subsequent yes-no question. Sentences were presented at the center of the screen in a random order. Eye movements were measured when participants started to fixate the first letter of the sentences.

The boundary paradigm (Rayner, 1975) was used to manipulate preview conditions. Participants read sentences without recognizing that words in parafoveal preview were changed when the eyes crossed the invisible boundary. Because the display was changed during a saccade, participants could not notice the screen change.

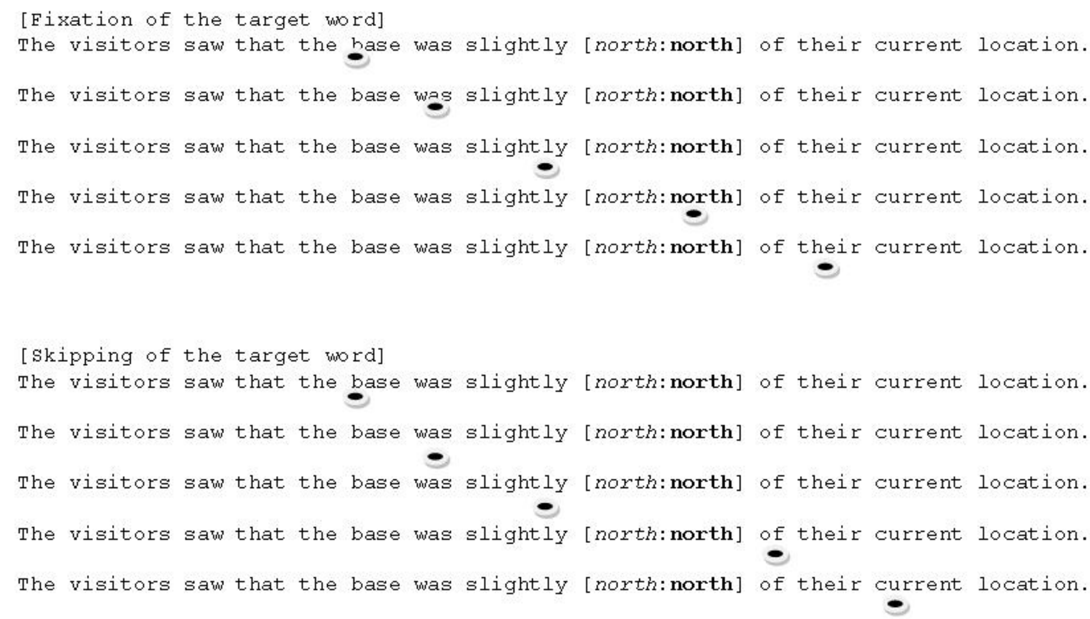

Figure 2. The progression of the eyeball shows fixation or skipping of the target word. One of the letter strings in brackets is presented in parafoveal preview and is changed when the eyes cross the invisible boundary located just before the target word. The black and white oval represents the position of the eyes in the sentence. After crossing the invisible boundary, only the target word is present.

Results

Analysis of eye movements. All trials in which the subject blinked during first-pass reading of the critical region consisting of the pre-target 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. For the final analysis 4.8% of trials were excluded by these criteria. Four of 28 subjects and 2 of 120 sentences that each lost more than 15% of data by these criteria were eliminated from further analyses. And as a result of the *Cloze* test, 5 sentences in High-frequency condition were excluded in the analysis because the target word was relatively predictable from prior sentential context. Therefore, 24 subjects and 113 target words embedded in sentence (54 high frequency words and 59 low frequency words) were included at the final analysis.

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. Restricted skipping rates were calculated after reclassifying as non-skips instances where the target word was skipped but there was 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 (Dreighe, et al., 2005). Skip reclassification affected 1.7% of the valid trials.

Reading-time measures were calculated after substituting outliers with durations less than 80 ms or greater than 700 ms to those boundaries. 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. S*ingle-fixation duration* was the average of the duration of the initial, first-pass fixation on a word given that the word received only one first-pass fixation. *First-fixation duration* 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. G*aze duration* was the average of the sum of all first-pass fixation durations on a word.

Target-word skipping. The left panel of Figure 3 shows the proportion of first-pass skipping rates for the target word as a function of the experimental conditions and the right panel shows the same breakdown for restricted skipping rates where first-pass skips followed immediately by a regression to the target word were counted as non-skips. Four conditions were analyzed by a 2 (type of preview: Full Vs. Transposed) X 2 (word frequency: High Vs. Low) analysis of variance (ANOVA). Error variance was calculated by participants (F_1) and by items (F_2). Both measures of skipping showed higher rates when the target word was high frequency as compared to when it was low frequency [F_1 (1,23) = 6.55, $p < 0.05$; F_2 (1,111) = 10.24, $p < 0.05$ for raw skipping rates and F_1 (1,23) = 4.91, $p < 0.05$; F_2 (1,111) = 9.28, $p < 0.05$ for restricted skipping rates]. In addition, both measures of skipping showed higher rates with full preview of the target than with TL preview of the target [F_1 (1,23) = 12.13, $p < 0.05$; F_2 (1,111) = 19.06, $p < 0.05$ for raw skipping rates and F_1 (1,23) = 15.13, $p < 0.05$; F_2 (1,111) = 28.36, $p < 0.05$ for restricted skipping rates]. Critically, there was a significant interaction of these two factors such that the increase in skipping rates due to word frequency effect was greater in the full preview condition than in the TL preview condition [F_1 (1,23) = 7.35, $p < 0.05$; F_2 (1,111) = 5.47, $p < 0.05$ for raw skipping rates and F_1 (1,23) = 6.56, $p < 0.05$; F_2 (1,116) = 3.78, $p = 0.054$ for restricted skipping rates]. Although the interaction effect of the item analysis for restricted skipping rates was marginally significant, the numerical trend was in line with other results of analyses.

Planned comparisons between high-frequency and low-frequency condition were conducted in each preview type. There was a word-frequency effect of the raw skipping measure (t_1 (23) = 2.92, $p < 0.05$; t_2 (111) = 3.64, $p < 0.05$), and of the restricted skipping measure (t_1 (23) = 2.60, $p < 0.05$; t_2 (111) = 3.13, $p < 0.05$) in full-preview condition, but not in TL-preview condition (all ts <1, n.s.). The finding that the difference of skipping rates of the word-frequency effect was observed only in full preview condition, not in TL preview condition, demonstrates that the process of word recognition in parafoveal preview is based on accurate orthographic analysis. This pattern is consistent with serial-attention models of eye-movement control during reading where lexically-based word skipping can occur only when the preview string is completely recognized. It is not consistent with parallel models of eye-movement control during reading where lexically-based word skipping can make use of context and coarse visual information about a letter string seen in the parafovea.

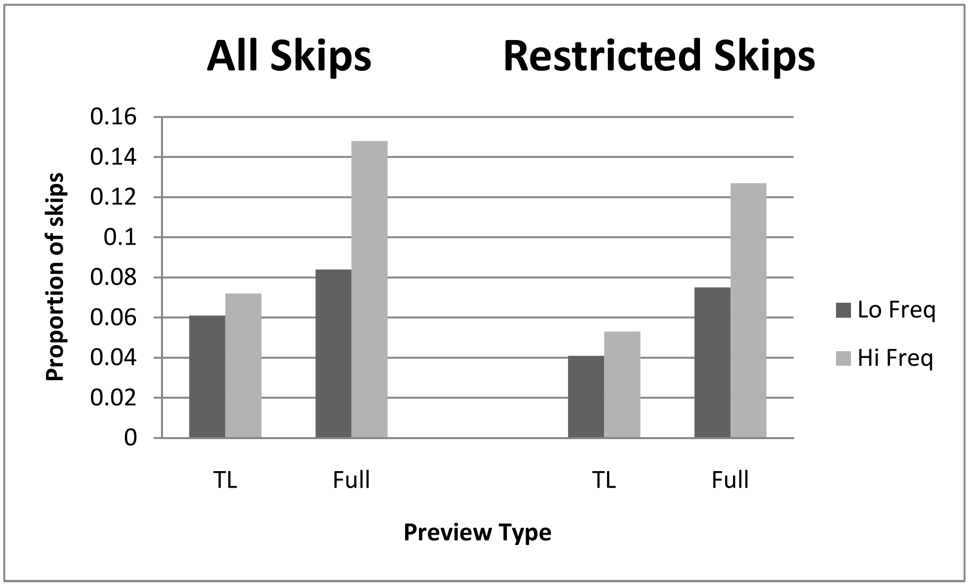

Figure 3. Proportion of trials on which the target word was skipped during first-pass reading, broken down by preview type and word frequency. The restricted skips excludes the cases that are immediately followed by a regression to the target word from skips.

Reading time on word preceding target. Table 5 shows mean first-pass reading times on the word preceding the target word. There were no main effects or interactions of the condition of experimental factors (word frequency and preview). The absence of such effects is consistent with the view that the processing of currently-fixated word is not influenced by the word in parafoveal preview (no parafoveal-on-foveal effects, Rayner, White, Kambe, Miller, & Liversedge, 2003; cf. Kennedy & Pynte, 2005). In addition, single-fixation durations on the word preceding the target were analyzed as a function of whether the target word was subsequently skipped. In the subject analysis, single-fixation durations were slightly longer when the target word was subsequently skipped (230 ms) as compared to when it was subsequently fixated (224 ms), though this difference was not close to significant ($F_1 = 0.6$, $p = 0.448$), but in item analysis, there was a 21ms skipping cost when the target words were skipped as compared to when they were fixated (245 ms vs. 223ms, $F_2 = 4.24$, $p < .05$). This result provides some very modest support for serial-attention-shift models (such as EZ Reader) in which longer fixations before skipping are the consequences of saccade cancelation and reprogramming (Reichle, Rayner, & Pollatsek, 2003). The absence of statistical significance is undoubtedly related to challenges in measuring the duration of an infrequent event (fixations prior to saccades), a problem that has contributed to empirical uncertainty about the presence of this effect (Kliegl & Engbert, 2005).

Table 5

Reading Times (ms) on the Word(s) Preceding the Target Broken Down by the Experimental Condition of Target Words. The Measures of Reading Time are: Single Fixation Duration (SFD), First Fixation Duration (FFD), and Gaze Duration (GZD).

	High Full	Low Full	High TLP	Low TLP
SFD	222	222	216	227
FFD	219	222	215	224
GZD	267	272	261	273

Reading times on target word. Table 6 shows reading times on the target word as a function of word frequency and preview. Three first-pass measures were considered: single-fixation duration (SFD), first-fixation duration (FFD) and gaze duration (GZD). For all three measures, Reading times were shorter for high-frequency target words as compared to low-frequency target words: SFD [F_1 (1,23) = 31.25, $p < 0.05$; F_2 (1,111) = 37.42, $p < 0.05$], FFD [F_1 (1,23) = 23.43, $p < 0.05$; F_2 (1,111) = 36.49, $p < 0.05$], and GZD [F_1 (1,23) = 72.73, $p < 0.05$; F_2 (1,111) = 37.45, $p < 0.05$]. In addition, all three measures showed shorter times for target words seen with full preview as compared to target words seen with TL preview: SFD [F_1 (1,23) = 20.7, $p < 0.05$; F_2 (1,111) = 18.7, $p < 0.05$], FFD [F_1 (1,23) = 14.86, $p < 0.05$; F_2 (1,111) = 13.81, $p < 0.05$], and GZD [F_1 (1,23) = 28.83, $p < 0.05$; F_2 (1,111) = 16.54, $p < 0.05$]. These results indicate that recognition of the target word received more benefit from the processing of parafoveal information on the preceding fixation when the full word was available in preview than when preview consisted of a TL non-word. Finally, there was a numerical tendency (or marginal significance) across all three first-pass measures for the word frequency effect to be larger following TL preview than full preview, but the interaction between type of preview and word frequency was marginally significant or has numerical tendency for these first-pass measures: SFD [F_1 (1,23) = 3.94, $p = 0.059$; F_2 (1,111) = 1.15, $p < 0.285$], FFD [F_1 (1,23) = 0.584, $p =0.452$; F_2 (1,111) = 0.083, $p = 0.774$], and GZD [F_1 (1,23) = 2.69, $p =0.115$; F_2 (1,111) = 1.38, $p = 0.242$]. This finding is consistent with the idea that more lexical processing occurred for full previews than TL previews such that the linguistic processing like the word frequency effect was started earlier in the full-preview condition and therefore somewhat less word frequency effect was observed during first-pass fixations on the target word itself.

Two late measures of reading time – regression-path duration and total reading time – were also calculated. Reading times were shorter for high-frequency target words as compared to low-frequency target words on both measures: regression-path duration [F_1 (1, 23) = 16.68, $p < 0.01$; F_2 (1, 111) =15.95, $p < 0.01$] and total time [F_1 (1, 23) = 33.79, $p < 0.01$; F_2 (1, 111) = 13.79, $p < 0.01$]. In addition, there was a significant main effect of preview type (significant in regression-path duration and marginally significant in total time), showing shorter fixation duration for the full preview as compared to the TL preview: regression-path duration [F_1 (1, 23) = 8.83, $p < 0.01$; F_2 (1, 111) =4.43, $p < 0.05$] and total time [F_1 (1, 23) = 3.73, $p = 0.066$; F_2 (1, 111) = 3.15, $p = 0.07$]. In contrast, there were no suggestions of interactions between word frequency and preview type (Fs <1).

Table 6

Reading Times (ms) on the Target Broken Down by the Experimental Condition of Target Words. The Measures of Reading Time are: Single-Fixation Duration (SFD), First-Fixation Duration (FFD), Gaze Duration (GZD), Regression-path Duration (RegDur), and Total Time (TTime) .

	High Full	Low Full	High TLP	Low TLP
SFD	211	233	224	259
FFD	210	231	221	246
GZD	228	260	240	284
RegDur	272	328	295	344
TTime	296	359	318	369

Reading times on word after target. Table 7 shows the first-pass reading times on the word immediately after the target word, selected for those trials where first-pass reading of the target was followed by a saccade to that word. Previous studies have shown that the ease of processing of the word after the currently-fixated word is modulated by the ease of processing of currently-fixated word by demonstrating that more time was available for processing the next word during fixation on high-frequency target words than was available during fixation on low-frequency target words (Kennison & Clifton, 1995; Rayner & Duffy, 1986). This spillover effect of word frequency was significant for the first-pass reading time measures in subject analysis: SFD [F_1 (1, 23) = 7.27, $p < 0.05$], FFD [F_1 (1, 23) = 5.69, $p < 0.05$], and GZD [F_1 (1, 23) = 11.09, $p < 0.01$], and there was numerical trend in item analysis: SFD [F_1 (1, 23) = 4.19, $p < 0.05$], FFD [F_1 (1, 23) = 1.84, $p = 0.18$], and GZD [F_1 (1, 23) = 1.43, $p = 0.24$]. Preview type did not have a significant effect on any reading time measure (all Fs <1) nor did it interact significantly with word frequency (all Fs <1). The null effects of the spillover effects of the preview type of the target word were consistent with the idea that the parafoveal preview affected only early processing of that word.

Table 7

Reading Times (ms) on the Word(s) After the Target Broken Down by the Experimental Condition of Target Words. The Measures of Reading Time are: Single Fixation Duration (SFD), First Fixation Duration (FFD), and Gaze Duration (GZD).

	High Full	Low Full	High TLP	Low TLP
SFD	197	215	195	210
FFD	199	214	198	214
GZD	214	238	217	254

Discussion

Experiment 1 designed to examine if word skipping occurs based on complete recognition of the string in parafoveal preview by manipulating word frequency and letter transposition. In order to minimize the influence of other confounding variables, other linguistic variables that can influence eye movements during reading such as word length, orthographic familiarity, and number of neighbor words were controlled. And also contextual predictability was controlled by two ways: Cloze test (Taylor, 1953), transitional probability (Mcdonald, & Schillcock, 2003a, 2003b).

The most interesting finding in Experiment 1 was that the interaction effect in skipping rates for the target region was observed such that the skipping rates for the high-frequency words was higher than those for the low-frequency words in full preview, whereas there was no word-frequency effect in the TL preview condition. This result supports the view that linguistic factors influence the targeting of saccade, and that word skipping occurs when the letter string in parafoveal preview is completely recognized (Pollatsek et al., 2006). If the letter string in parafoveal preview is a TL nonword string, lexical processing of the string in parafoveal preview is disturbed, resulting in lower skipping rates in the TL preview condition. This argument receives some support from the results on first-pass reading time measures, where there was a trend toward an interaction between word frequency and preview type such that the word frequency effect in full preview condition was smaller than in TL preview condition (SFD: 22ms vs. 35ms, GZD: 32ms vs. 44ms); this trend is consistent with the idea that full preview provides a greater head start for lexical processing.

Although there is some evidence that words can be misperceived during normal sentence reading for different reasons, such as predictable context or higher-frequency neighbor words (Drieghe et al., 2005; Slattery, 2009), the result of Experiment 1 showed that word frequency did not have an effect on misperception of the letter string in parafoveal preview. If the base-word activation of a TL nonword string is modulated by the frequency of base word (O'Conner & Foster, 1981), skipping rates for TL nonword with high-frequency base word would be higher as compared to the skipping rates for TL nonword with low-frequency base word. But the skipping rates across frequency were not different in TL preview condition, which contrasts with the finding that O'Conner & Foster (1981) observed in a lexical decision task with isolated words. This contrast could be due to task differences between sentence reading and lexical decisions with isolated letter strings; it could also be due to differences in the materials used in the two different experiments. Although it is not clear why the contrasting results were observed, the crucial finding of the present experiment is that lexical analysis for the letter string in parafoveal preview during reading is done to a high level of accuracy, at least when the word is not predictable based on sentential context (Johnson et al., 2007).

Experiment 2

Experiment 2 used eye tracking during reading to examine how ease of linguistic processing elicited by word repetition and the quality of linguistic information in parafoveal preview affect the targeting of a saccade as measured by skipping rates for critical words. The crucial feature of the experiment was that the letter strings in parafoveal preview that were made by transposing a pair of adjacent letters were TL words, not TL nonwords. In addition, repetition of the target word was manipulated because repeated words are recognized easier and/or faster than new words during reading (Gordon et al. 2010). If word skipping occurs when the letter string in parafoveal preview is completely recognized, as claimed by the EZ Reader model (Pollatsek et al 2006), then skipping rates for the repeated words should be higher than when the word is not repeated (Gordon et al, 2010). Alternatively if word skipping occurs based on coarse information in parafoveal preview (Engbert et al. 2005), misidentification of TL neighbor words would occur frequently and the word-repetition effect could not be expected. And if word skipping occurs based on complete word recognition, we would expect higher skipping rates for the full preview condition (higher-frequency words) than for the TL preview condition (lower-frequency words) because the TL words used in this study were always lower-frequency than the base/target words from which they were derived. For example, if the target/base word was *calm*, then the string *calm* appeared in the parafovea in the full preview condition, but the string *clam* appeared in the parafovea in the TL preview condition; *calm* has higher frequency than *clam*. Given that skipping rates are higher in high-frequency word as compared to in how-frequency word (Rayner et al, 2004; Rayner and Raney, 1996; Rayner and Fisher, 1996; White, 2008), the skipping rates for *calm* (high-frequency word) would be higher than for *clam* (low-frequency word).

It should be noted that the mechanisms for repetition priming in this study differ for skipping and for first-pass reading time on the target. Figure 4 shows the different paths whereby the prime word affects these two measures. Skipping is based on processing information in parafoveal preview, therefore priming effects on skipping reflect an effect of the earlier prime on processing of the preview string (path B in Figure 4). In contrast, first-pass reading time reflects processing of the target string in the fovea, thus priming on this measure reflects both direct effects of the prime on processing the target word (path A in Figure 4) and effects of the prime that are mediated by processing of the preview string (path C in Figure 4).

The central question in this experiment is whether the repetition priming in word skipping measure (mediated only by path B) can occur when the TL neighbor word is presented in parafoveal preview. Note that the TL string (e.g. clam) seen in parafoveal preview in this experiment is different from the word (e.g. calm) presented in the earlier region of the same sentence, but still has a lexical representation because it is a word. Sentence frame 1 is an example from Experiment 2, and sentence frame 2 is an example from the Gordon et al. (2010)'s experiment. With respect to skipping rates, Gordon et al. (2010) observed repetition priming effect in full preview, but not in TL preview, demonstrating that previously-exposed word (e.g. Herman) facilitated to recognize the word letter string in parafoveal preview(e.g. Herman), whereas same prime word did not help recognizing TL nonword letter string (e.g. Hreman) in parafoveal preview. Although the TL nonword in parafoveal preview had relatively similar orthographic features to a prime word, the nonword did not take advantage of the prime word. Experiment 2 examines how word skipping by repetition priming is affected when a TL word, not a TL nonword, is presented in parafoveal preview. Note that the only difference between TL words and TL nonwords is whether they have lexical representation. If the prime word can facilitate the processing of TL word preview via partial overlap between the prime word and the parafoveal preview, a repetition-priming effect would be observed (Foster & Davis, 1984; Foster et al., 1987; Castles et al., 2003). In contrast, if the prime can not facilitate the processing of TL word preview because they are not exactly same, the repetition-priming would not be obtained in TL preview condition (Gordon et al., 2010). This issue will be discussed in general discussion.

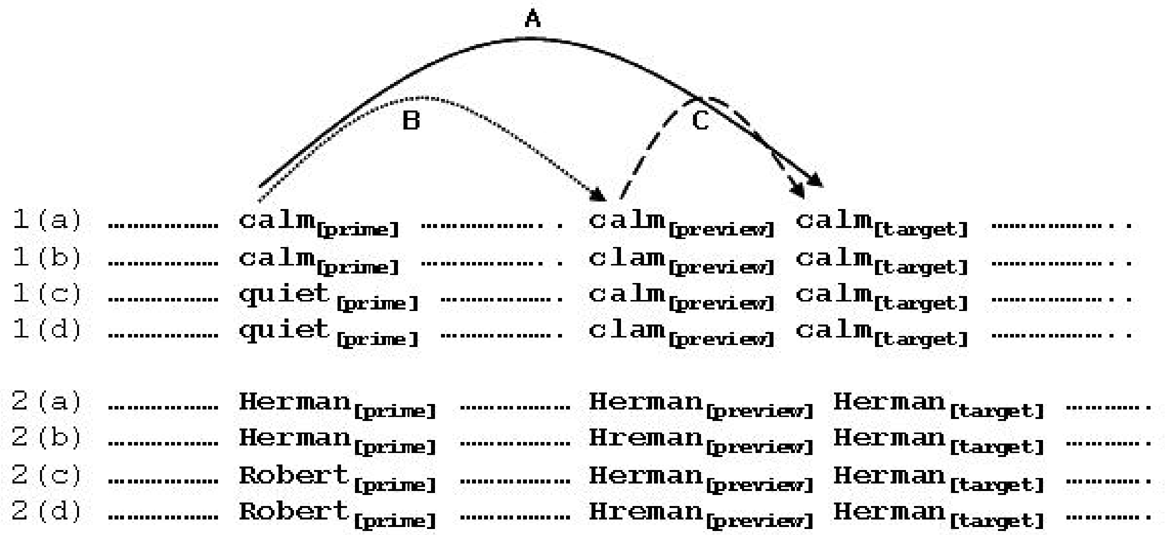

Figure 4. A schematic of the mechanism for the repetition priming effects within a sentence. The processing of the target word is affected by three paths represented with capital letters A, B, and C. Path A represents the direct priming effect of the prime word on target word. Path B represents the effect of prime word on the processing of preview string. And path C represents the effect of prime word that mediated by the processing of preview string. Priming through Paths A and C would be manifested in first-pass reading time effects on the target word. In contrast Path B would be manifested by changes in skipping rate.

Method

Participants. Forty undergraduates at the University of North Carolina at Chapel Hill participated for course credit. All participants were native English speaker with normal or corrected-to-normal vision and were naïve about the goals of the experiment.

Materials and Design. Forty words that have a TL neighbor word were used as targets and embedded in a single line sentence in the Experiment. The example set of sentences of the Experiment were shown in Table 8.

Table 8

An Example Sentence From the Experiment With Each of the Four Conditions

Condition	***Sentence***
Rept, VP	Zach isn't scared of bugs, but he is definitely [*scared*:**scared**] of the snakes in the forest.
Rept, TLP	Zach isn't scared of bugs, but he is definitely [*sacred*:**scared**] of the snakes in the forest.
New, VP	Zach isn't afraid of bugs, but he is definitely [*scared*:**scared**] of the snakes in the forest.
New, TLP	Zach isn't afraid of bugs, but he is definitely [*sacred*:**scared**] of the snakes in the forest.

Note. The letter strings in brackets shown in italics are presented in parafoveal preview before the eyes cross the invisible boundary. The words in underline are the prime words and the words in bold are the target stimuli. Rept = Repeated condition at which prime and target are identical, New = New condition at which prime and target are different, VP = Valid Preview, TLP = Transposed Letter Preview. There were no font changes, underlines or brackets in the actual stimuli.

Target words were selected from Johnson (2009), Andrews (1996), and Chambers (1979). Word length of target words ranges 3 to 7 letter words, but 85 % of the target words were 4 or 5 letters words (16 cases in 4 letter words, and 18 cases in 5 letter words). In order to manipulate the *repetition* variable, forty control prime words were selected from CELEX English word-from corpus (Baayen, et al., 1995) and were allocated in *New* condition. Average word frequency and word length is not different across these two conditions (word frequency: 49 per million (Repeated) vs. 49 per million (New), word length: 4.7 letters (Repeated) vs. 5.1 letters (New), ts <1).

As seen in Table 8, prime and target pairs were inserted into identical sentential frames. Two variables were manipulated: 1) Word repetition: (a) priming condition, where prime and target word were same (*calm* and *calm*) and (b) unrelated condition, where prime and target word were different, but semantically similar to the prime word in repetition condition (*quiet* and *calm*). 2) Preview type: (a) full preview, where the preview string is identical to the target word (*calm* as the preview of *calm*) and (b) transposed letter preview, where the preview string was created by transposing two consecutive letters of the target word (*clam* as the preview of *calm*). Note that the higher-frequency TL pair (e.g. calm) was used as a target word in every sentence frame because it was somewhat hard to make plausible sentences with the lower-frequency TL pair (e.g. clam). Four counterbalanced lists of 40 sentence frames were generated based on the four experimental conditions (repetition by preview type), and each subject was allocated at just one counterbalanced list. Eighty filler sentences were mixed with the critical sentences in each list, all of with were preceded by four practice trials. 124 sentences in each list were presented with random order.

Procedure. The procedure of the Experiment 2 was exactly same with that of the Experiment 1.

Results

Analysis of eye movements. All restrictions that were applied to the analysis of the Experiment 1 were also considered in the Experiment 2. The fixation points that had long saccadic length (over 100ms), blink, and track loss were excluded in the analysis, and also the data points in which the display change occurred prior to the first saccade that crossed the invisible boundary were taken out from the data set. For the final analysis 7.6% of data points were excluded by these restrictions. First-pass and late reading-time measures were the same as in Experiment 1.

Target-word skipping. The left panel of Figure 5 shows the proportion of first-pass skipping for the target word as a function of the experimental conditions and the right panel shows the same breakdown for restricted skipping rates where first-pass skips followed immediately by a regression to the target word were counted as non-skips. Four conditions were analyzed by a 2 (type of preview: Full Vs. Transposed) by 2 (word repetition: Repeated Vs. New) analysis of variance (ANOVA). Error variance was calculated by participants (F_1) and by items (F_2). Both measures of skipping showed higher rates when the target word was repeated as compared to when it was new [F_1 (1,39) = 6.89, $p < 0.05$; F_2 (1,39) = 4.73, $p < 0.05$ for raw skipping rates and F_1 (1,39) = 11.03, $p < 0.05$; F_2 (1,39) = 8.47, $p < 0.05$ for restricted skipping rates]. In addition, both measures of skipping showed higher rates with full preview of the target than with TL preview of the target [F_1 (1,39) = 29.97, $p < 0.05$; F_2 (1,39) = 19.6, $p < 0.05$ for raw skipping rates and F_1 (1,39) = 34.12, $p < 0.05$; F_2

$(1,39) = 14.33$, $p < 0.05$ for restricted skipping rates]. There was no interaction between repetition and preview type (all $Fs < 1$, ns).

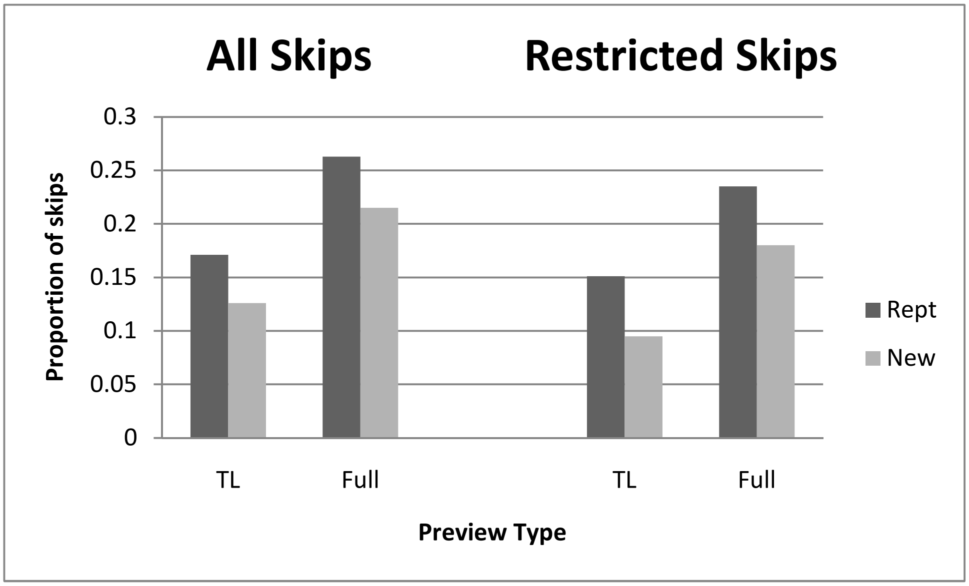

Figure 5. Proportion of trials on which the target word was skipped during first-pass reading, broken down by preview type and repetition. The restricted skips excludes the cases that are immediately followed by a regression to the target word from skips.

Reading time on word preceding target. Table 9 shows mean first-pass reading times on the word preceding the target word. There were no main effects or interactions of the condition of experimental factors (word repetition and preview type). The absence of such effects is consistent with the view that processing of currently-fixated word is not influenced by the word in parafoveal preview (no parafoveal-on-foveal effects, Rayner et al., 2003; cf. Kennedy & Pynte, 2005). In addition, single-fixation durations on the word preceding the target were analyzed as a function of whether the target word was subsequently skipped. Although the reading times were not statistically significant as a function of subsequent skipping, SFD on preceding words was longer when the target word was skipped than when the target word was fixated (223ms Vs. 215ms, $F_1 = 2.25$, $p=0.141$, $F_2 = 1.04$, $p = 0.315$). In particular, when the investigation region was restricted to the $word_{N-1}$, the numerical trend that longer SFD on the preceding word ($word_{N-1}$) when target word was skipped was even slightly increased ($F_1 = 2.74$, $p=0.106$, $F_2 = 2.41$, $p = 0.128$), reflecting the view of serial attention shift (such as EZ Reader model) model in which longer fixations before skipping are the consequences of saccade cancelation and reprogramming (Reichle et al., 2003).

Table 9

Reading Times (ms) on the Word(s) Preceding the Target Broken Down by the Experimental Condition of Target Words. The Measures of Reading Time are: Single Fixation Duration (SFD), First Fixation Duration (FFD), and Gaze Duration (GZD).

	Rept Full	New Full	Rept TLP	New TLP
SFD	210	203	216	213
FFD	212	215	206	213
GZD	251	251	247	246

Note. Rept Full: repeated target word, full preview, New Full: new target word, full preview, Rept TLP: repeated target word, transposed-letter preview, New TLP: new target word, transposed-letter preview

Reading times on target word. Table 10 shows reading times on the target word as a function of word repetition and preview type. Three first-pass measures were considered: single-fixation duration (SFD), first-fixation duration (FFD) and gaze duration (GZD). For all three measures, reading times were shorter for repeated target words as compared to new target words: GZD [F_1 (1,39) = 4.23, $p < 0.05$; F_2 (1,39) = 5.74, $p < 0.05$], FFD [F_1 (1,39) = 6.86, $p < 0.05$; F_2 (1,39) = 7.1, $p < 0.05$], and SFD [F_1 (1,39) = 3.08, $p = 0.087$; F_2 (1,39) = 4.68, $p < 0.05$]. In addition, GZD showed shorter times for target words seen with full preview as compared to target words seen with TL preview in subject analysis (marginally significant in item analysis) [F_1 (1,39) = 4.59, $p < 0.05$; F_2 (1,39) = 3.9, $p = 0.055$]. FFD and SFD showed a strong numerical trend that shorter fixation duration in full preview than in TL preview: FFD [F_1 (1,39) = 2.68, $p = 0.11$; F_2 (1,39) = 1.73, $p = 0.196$], and SFD [F_1 (1,39) = 1.64, $p = 0.207$; F_2 (1,39) = 2.92, $p = 0.095$]. Finally, there was no interaction effect between word repetition and preview type (all Fs <1, ns).

Two late measures of reading time – regression-path duration and total reading time - were also calculated. Reading times were shorter for repeated target words as compared to new target words on both measures: regression-path duration [F_1 (1,39) = 14.58, $p < 0.05$; F_2 (1,39) = 11.9, $p < 0.05$] and total time [F_1 (1,39) = 6.32, $p < 0.05$; F_2 (1,39) = 9.96, $p < 0.05$]. In addition, there was a significant main effect of preview type (significant in total time and numerical trend in regression path duration), showing shorter fixation duration for the full preview as compared to the TL preview: regression-path duration [F_1 (1,39) = 2.17, $p = 0.149$; F_2 (1,39) = 2.38, $p = 0.131$] and total time [F_1 (1,39) = 3.08, $p = 0.087$; F_2 (1,39) = 5.49, $p < 0.05$]. In contrast, there were no suggestions of interactions between word frequency and preview type (Fs <1, ns).

Table 10

Reading Times (ms) for the Target Word Broken Down by the Experimental Conditions. The Measures of Reading Time are: Single-Fixation Duration (SFD), First-Fixation Duration (FFD), Gaze Duration (GZD), Regression-path Duration (RegDur), and Total Time (TTime)

.

	Rept Full	New Full	Rept TLP	New TLP
SFD	211	224	221	225
FFD	209	221	216	226
GZD	226	239	240	251
RegDur	273	313	291	337
TTime	301	314	310	345

Reading times on word after target. Neither the main effects nor the interaction effect reached significance by both participants and items.

Discussion

The results of Experiment 2 are very clear. The main effects of word repetition and main effect of preview type were significant for both skipping rates and first-pass reading time measures, indicating that linguistic factors play an important role in deciding where to move eyes and when to move eyes. Specifically, in the full preview, the string in parafoveal preview is the target word, while in TL preview the string in parafoveal preview is the lexical neighbor of the target word. The items used were such that the target word was always higher frequency than its neighbor. Therefore, if skipping is based on recognition of the word in parafoveal preview, we would expect a greater rate of skipping when that word is the target (higher frequency) than when it is the neighbor (lower frequency). If recognition of words is primed by prior exposure to the same word, or a TL neighbor, then we expect greater skipping when the preview string is “repeated”, whether it is fully repeated or is a TL repetition. The finding that we obtained is consistent with the view that word skipping occurs based on the word recognition in parafoveal preview proposed by E-Z reader model (Pollatsek et al, 2006).

Given that word skipping occurs when word is completely recognized in parafoveal preview, one question can be raised that why no interaction effect appeared in Experiment 2. Gordon et al. (2010) found a clear interaction effect between word repetition and preview type, demonstrating clear word-repetition effect in full preview condition, no effect in TL preview. It should be noted that critical items in Gordon et al. (2010) were proper names.

So the proper name that was used in the new condition does not have any relationship with that in the repeated condition, meaning that the lexical properties of the prime word can not help to activate the target word. In contrast to the items used in Gordon et al. (2010), the items used in Experiment 2 were content words. In order to minimize semantic difference between repeated and new conditions, semantically very similar words were used as *new words* in the new condition. For example, when a target word is calm, calm was used in a prior region of the sentence in the repeated condition, but quiet was used in the new condition. With respect to the semantic relationship between repeated and new conditions, the two sentences have very similar semantic representation. And the two words (e.g. quiet and calm) in the new condition have strong semantic relationship, which makes an associative priming effect possible. Therefore, the characteristics of the sentences used in Experiment 2 increased the skipping rates for new-full preview condition, which makes the interaction effect go away.

The result also showed a clear inhibitory effect of TL word pairs in both early and late measures. Previous studies had observed an inhibitory effect of TL neighbor pair only in the late measures (Acha & Perea, 2008; Johnson, 2009). In particular, Johnson (2009) obtained an inhibitory effect from lower frequency TL neighbor words in late measures of eye movements. Why does it have inhibitory effects in both early and late measures from the TL neighbor word? A possible reason is the difference of experimental method. Johnson (2009) used normal sentence reading in which only the target word embedded in a sentence, while Experiment 2 of current study implemented a boundary technique in which TL neighbor word actually presented in parafoveal preview. Accordingly, TL preview as compared to the full preview cannot provide the same amount of linguistic representation as full preview does, which makes inhibitory processing occur early. Similarly, Williams et al. (2006) used a boundary technique where orthographic neighbors were used as the string in parafoveal preview. The finding they obtained was consistent with the current result, showing that reading time measures were shorter when full preview was presented than when lower-frequency orthographic neighbor word was presented in parafoveal preview.

Although the result of Experiment 2 showed inhibitory processing of TL neighbor words by comparing full preview to TL preview, it is still difficult to tell what kind of processes exactly happens in parafoveal preview because only full and TL preview was compared in Experiment 2. Future research can explore more fine-grained mechanism of the word recognition during reading can be clarified by comparing different kinds of manipulation.

General Discussion

The experiments reported in this study examined how linguistic information processed in parafoveal preview influences eye movements during reading. The results showed that skipping rates and the first-pass reading time measures for the target word were selectively influenced by lexical information in parafoveal preview, and critically, that word skipping occurs when the letter string in parafoveal preview is completely recognized. Here, the results from each experiment will be discussed with respect to current eye-movement control models. And then the relationship between visual word recognition and eye movements will be discussed.

As described in the introduction, eye movements during reading are involved in a fairly complicated process including different aspects of human cognitive abilities. Some mathematical models for explaining eye movements during reading have been proposed, which can be broadly divided into three kinds of models with respect to how cognitive (linguistic) and oculomotor factors influence eye movements during reading (Reichle et al.. 2003). The first class of models considers mainly cognitive factors to account for eye movements (e.g. E-Z Reader model, Pollastek et al., 2006). These models assume the serial allocation of attention from one word to the next during reading. The second class of models considers primarily of oculomotor factors to explain eye movements during reading, where no particular assumptions about the influence of attention allocation during reading (e.g. Yang & McConkie, 2001). The last class of models is a hybrid models in which the attention is distributed as a gradient for certain range of letter strings and both cognitive and oculomotor factors have critical roles on eye movements during reading (e.g. SWIFT model, Engbert et al., 2005). In particular, these three kinds of models have different explanation and prediction on word skipping which is the critical measure of the current study. For example, E-Z Reader model posits that a word in parafoveal preview can be skipped only when the word is completely recognized on the prior fixation. The oculomotor models, however, assume that word skipping occurs based on the length of the word in parafoveal preview or on the distance of that word from the current fixation point, suggesting that linguistic factors can not influence a decision to skip or not. The SWIFT model is located in between above two models. This model assumes that more linguistic processing can influence eye movements as compared to the oculomotor models, but critically, saccade movements are generated autonomously in SWIFT model. Therefore, word skipping is not tightly linked to linguistic processing in parafoveal preview. And because attentional-gradient could be allocated in four successive words, lexically-driven word skipping can occur based on somewhat rough lexical information.

The finding that skipping rates for high-frequency words was higher than those for low-frequency in full-preview condition, but no difference in skipping rates for the high and low frequency words in TL preview condition was observed, is consistent with the mechanism which is suggested by E-Z Reader model. But oculomotor models or the SWIFT model cannot fully explain the result of Experiment 1. Because all target words had the same length, significant effect of word frequency and of preview type cannot be accounted for by the oculomotor model. Additionally, although TL nonwords provided relatively good information to activate the base word (O'Connor & Foster, 1981; Perea & Lupker, 2003b), which makes it possible to skip the TL nonword letter string via partial word recognition, the word-frequency effect in skipping rates was not observed in TL preview condition, indicating that the parallel models like SWIFT cannot explain the results of Experiment 1. The result reported from Experiment 2 can also be explained by the manner which E-Z Reader model posits. The effect of word repetition, in which a repeated word from prior region within a sentence was skipped more than a new word, and the effect of preview type, in which the full-preview condition where the target word seen in parafoveal preview had less skipping rates than the TL-preview condition where the TL neighbor word seen in parafoveal preview indicate that the lexically-based skipping is strongly influenced by linguistic factors.

Given that word skipping is affected by the lexical information in parafoveal preview, it is important to understand how exactly the letter string in parafoveal preview is processed during reading. Although previous studies have shown that fairly exact orthographic (and or phonological) representation is extracted in parafoveal preview, which is well demonstrated in the first-pass reading time measures, they have not intensively attempted to examine the influence of lexical information on the process of targeting of saccade which can be captured by word skipping (Johnson et al., 2007; Williams et al., 2006; Pollastek et al., 1992; cf. Drieghe et al., 2005; Gordon et al., 2010). In contrast to previous studies, current study focused on how lexical information given in parafoveal preview affects where to move eyes next. Although relatively robust evidence that lexical information affects targeting of saccade was observed across two experiments, one interesting difference between these two experiments appeared. When TL nonword preview was presented, it was hard to extract lexical information, demonstrating that there was no word-frequency effect in TL preview condition (Experiment 1, and also no repetition-priming effect in TL nonword preview in

Gordon et al., 2010). But when TL word preview was presented, lexical information was extracted much easier, demonstrating the robust repetition-priming effect was observed in TL preview condition (Experiment 2). As described earlier, the only difference of letter string in parafoveal preview across two experiments was whether they had lexical representation. The finding that the repetition-priming effect was observed in TL word preview, not in TL nonword preview, implies that the lexical status of the letter string in parafoveal preview may modulate the processing of targeting of saccade. Williams et al. (2006) observed similar finding with the current study. They used an eye contingent boundary technique in order to investigate the influence of orthographic neighbors on the process of word recognition during reading. The first-pass reading time measures on the target (e.g. sleet) word were faster when a higher-frequency orthographic neighbor was presented in parafoveal preview (e.g. sweet) as compare to when a nonword that is orthographically similar to the target word was presented in parafoveal preview (e.g. speet), indicating that even though the nonword has relatively similar visual representation to the target word, the non-lexical status may hinder linguistic processes in parafoveal preview. Unfortunately, it is somewhat difficult to compare their result to the current result because Williams et al. (2006) did not report a result of skipping rate for each condition. More fine-grained research would be needed in the future to understand how lexical status affects the process of word skipping.

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