Mislocated Fixations Can Account for Parafoveal-On-Foveal Effects in Eye Movements during Reading

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Abstract

Contrasting predictions of serial and parallel views on the processing of foveal and parafoveal information during reading were tested. A high-frequency adjective (*young*) was followed by either a high-frequency (*child*) or low-frequency $word_n$ (*tenor),* which in turn was followed either by a correct (*performing*) or an orthographic illegal $word_{n+1}$ (*pxvforming*) as a parafoveal preview. A limited *parafoveal-on-foveal effect* was observed: there were inflated fixation times on $word_n$ when the preview of $word_{n+1}$ was orthographically illegal. However, this parafoveal-on-foveal effect was a) independent of the frequency of $word_n$, b) restricted to those instances when the eyes were very close to $word_{n+1}$, and c) associated with relatively long prior saccades. These observations are all compatible with a mislocated fixation account in which parafoveal-on-foveal effects result from saccadic undershoots of $word_{n+1}$ and with a serial model of eye movement control during reading.

During reading, eye movements consist of a sequence of saccades and fixations. The main purpose of saccades is bringing new information into foveal vision, where visual acuity is highest. However, there is a large body of evidence demonstrating that information from the word to the right of fixation is extracted and used in reading as well (see Rayner, 1998 for a review)[1]. A typical finding is *parafoveal preview benefit*: fixation time on a target word is shorter when the letters of the word were visible during the prior fixation than when the letters were not visible. Thus, it is clear that processing of parafoveal information plays an important role in reading. However, there is some controversy concerning the extent to which information from the parafoveal word influences the fixation time on the currently fixated word. The finding that aspects of a parafoveal word influence fixation time on the prior word is referred to as a parafoveal-on-foveal effect; several suggestions of such effects have been observed (e.g. Drieghe, Brysbaert & Desmet, 2005; Hyönä & Bertram, 2004; Kennedy & Pynte, 2005).

Parafoveal-on-foveal effects are of interest because they bear on the question of whether readers process multiple words in parallel or are limited to processing a single word at a time. Indeed, parafoveal-on-foveal effects are considered damaging to serial lexical processing models such as the E-Z Reader model (e.g. Reichle, Rayner, & Pollatsek, 2003). The core assumption of the E-Z Reader model is that cognitive processes associated with processing the fixated word are the engine driving eye movements in reading. Word recognition is considered to be a serial process with the word in the attentional beam being the only word that is being processed lexically. The model also posits two phases of word recognition. It is the termination of the first phase which cues the oculomotor system to begin programming a saccade to the next word, whereas the termination of the second phase causes the attentional beam to shift to the next word. Earlier versions of the model outlined several alternative possibilities for what processing was needed for completion of the first and second stages. However, in the latest modeling work (Reichle, Pollatsek, & Rayner, 2007), it was decided that the most viable hypothesis is that both are related to obtaining the meaning of the word; the first stage could merely be the point at which meaning activation crosses a lower threshold than the threshold that this activation needs to cross in order to trigger the shift of attention. Because the shift of the attentional beam usually occurs before the eyes move to the next word, parafoveal processing occurs during the time that the attentional beam is on the next word (but the eyes are still on the previous word). This mechanism is how the E-Z Reader model accounts for parafoveal preview benefit. However, because parafoveal processing only starts after the programming of the saccade has started, and the time it takes to program the saccade is independent of parafoveal processing, it is often assumed that the E-Z Reader model cannot account for parafoveal-on-foveal effects. Other models, notably SWIFT (Engbert, Nuthmann, Richter & Kliegl, 2005) and Glenmore (Reilly & Radach, 2006), posit parallel processing of foveal and parafoveal words. From a parallel point of view on foveal and parafoveal processing, one could say parafoveal-on-foveal effects naturally arise as a direct prediction. However, although some studies report evidence of parafoveal-on-foveal effects, there are methodological problems associated with some of these studies, as well as failures to obtain consistent effects across experiments (see Rayner & Juhasz, 2004; Rayner, White, Kambe, Miller & Liversedge, 2003, for discussion).

Arguably the most robust observation of a parafoveal-on-foveal effect is the finding that the preview of an unusual beginning of a parafoveal word, such as an orthographically illegal beginning (e.g. *dfgburger*), can produce longer fixations on the foveal word (Inhoff, Starr, & Shindler, 2000). However, such an orthographic parafoveal-on-foveal effect is not necessarily inconsistent with a serial lexical processing model such as E-Z Reader because the model assumes that not all saccades land on the intended word. In fact, there is evidence indicating that eye movements have considerable variability and quite often do not land exactly on their target (McConkie, Kerr, Reddix & Zola, 1988; Engbert, Nuthmann, & Kliegl, 2007). It is not rare for saccades to fall short of the targeted word so that word_n is fixated even though word_{n+1} was the intended target (and presumably the word initially attended to when word_n is fixated). The current study attempted to study this phenomenon with minimal disruption of normal reading using the boundary paradigm with such an orthographically illegal string as a preview. In the boundary paradigm (Rayner, 1975), there is a display change from the preview to the target word when the reader crosses an invisible boundary location prior to the target word. However, if the preview is a nonword, when the reader intends to fixate the target word, but the saccade undershoots and falls on the prior word, the display change will not occur. Thus, the ‘word’ that is attended to after the saccade is a non-word (even though the reader is fixating the prior word). Following such an undershoot, this attended (but not fixated) ‘word’ is clearly difficult to encode and should produce long fixations on the word prior to it. We will refer to this hypothesis as the *mislocated fixation account* (see also Nuthmann, Engbert, & Kliegl, 2005). Needless to say, when readers undershoot a target word, they usually land on the end of the prior word. Indeed, in our previous work (Drieghe, Rayner, & Pollatsek, 2005), we observed a parafoveal-on-foveal effect of an unusual beginning of a parafoveal word restricted to those instances when the eyes were very close to the parafoveal word (i.e., 3 character positions or fewer).

One of the predictions that might be derived from a parallel model (that doesn’t have unlimited processing capabilities) is that this parafoveal-on-foveal effect (of the unusual parafoveal word beginning) will be more pronounced when the foveal word is a high-frequency word than when the foveal word is a low-frequency word. This is because the relatively easier processing of the high-frequency foveal word would leave more processing resources to be devoted to the processing of the parafoveal word. However, previous studies did not observe such an effect on the foveal word (Henderson & Ferreira, 1990; White & Liversedge, 2006; White, Rayner, & Liversedge, 2005). Therefore, in the current study, the foveal word (whose frequency was manipulated) was preceded by a high-frequency adjective; this should allow readers to devote even more processing resources to the parafoveal word than in previous studies. Also, because inconsistent parafoveal-on-foveal effects (or absence of them) have been attributed to a lack of control of word length (Kennedy & Pynte, 2005), we used a 5 letter adjective and a 5 letter noun to create presumably ideal circumstances to observe parafoveal-on-foveal effects.

The mislocated fixation account makes three clear predictions for this experiment, all originating from the view that the parafoveal-on-foveal effect is caused by saccades undershooting the intended target word:

1) Any observed parafoveal-on-foveal effect will be independent of the frequency manipulation on the foveal word. This is because the parafoveal-on-foveal effect originates from an undershoot of the parafoveal word, and it is the parafoveal word that is being processed, not the foveal word with the frequency manipulation.
2) Any parafoveal-on-foveal effect observed will be limited to those instances when the eyes are very close to the parafoveal word. We used the criterion used in the past (Drieghe, Rayner, & Pollatsek, 2005; Rayner, Warren, Juhasz, & Liversedge, 2004) of a distance of three character positions or fewer from the parafoveal word.
3) The fixation duration on the foveal word (when close to the unusual parafoveal word) should be correlated with the length of the saccade leading up to that fixation. The argument is as follows. McConkie et al. (1988) observed that the error between the intended and the actual landing position has a systematic component which can be described as range error: there is a tendency to overshoot nearby targets and undershoot far targets. Because the mislocated fixation account attributes parafoveal-on-foveal effects to undershoots, such effects should be associated with relatively long saccades prior to fixating the target word. In contrast, there should be little correlation for a normal parafoveal preview because the parafoveal word would not disrupt processing.

METHOD

Participants. Twenty-eight members of the University of Massachusetts community participated in the experiment for Psychology course credit or for $10. All were native speakers of American English with 20/20 vision or soft contact lenses.

Apparatus. Participants were seated 61 cm from a 15-inch NEC MultiSync FGE monitor. Sentences were displayed on a single line with a maximum length of 80 characters; 3.8 character positions equaled 1 degree of visual angle. An eye contingent *boundary* technique (Rayner, 1975) was used in which display changes occurred on average within 5 ms of detection of when an invisible "boundary" was crossed; the boundary was between the last letter of the 5 letter-word noun and the space preceding the subsequent word. Eye movements were recorded using a Fourward Technologies Dual Purkinje Eyetracker interfaced with a Pentium computer. Although reading took place binocularly, eye movements were recorded only from the right eye (sampling every millisecond).

Materials. 100 sentence frames were created so that each sentence featured three critical words: a high-frequency (HF) 5-letter adjective, either a high- or a low-frequency (LF) noun which was also 5 letters long, and a word consisting of at least 5 letters. The mean frequencies, as assessed in the Francis and Kuĉera norms (1982), were 253, 163, and 8 counts per million for the HF adjective, HF noun, and LF noun, respectively. A *close test* with 12 participants, who did not participate in the actual experiment, revealed that the target noun was not predictable from the preceding context; the probability of correctly guessing the HF target noun given the prior sentence context was .045 and the probability of guessing the LF target noun was .035. For the sake of convenience, we will refer to the target noun as word_n and the subsequent word as word_{n+1}. Two possible previews were created for word_{n+1}: a correct preview and a misspelled preview. In the misspelled condition, the second and third letters were replaced in such a way that the initial three letters were an orthographically illegal combination (e.g. *performing* became *pxvforming*). The combination of the two possibilities for word_n (a HF or LF noun) and the two possible previews of word_{n+1} (correct or incorrect) produced a 2 x 2 design (see Table 1). A counterbalanced design was employed in which each of the 100 sentence frames was read once by each participant, resulting in 25 sentences per condition per participant. The 100 experimental sentences were embedded in a pseudo-random order within a list including 60 filler sentences.

INSERT TABLE 1 ABOUT HERE

Procedure. When a participant arrived for the experiment, a bite bar was prepared, which served to eliminate head movements. Participants were given a general description of the experimental procedure and were asked to read sentences on the monitor as their eye movements were monitored. They were instructed to read for comprehension and were told that they would be asked questions about the meaning of the sentences. The initial calibration of the eye-tracking system required about 5 minutes. Each participant read 10 practice sentences to become familiar with the procedure. Prior to the presentation of each sentence, a series of five boxes appeared on the monitor. During this calibration check, participants looked at each box so that the experimenter could verify that the eye position was accurately recorded. If the calibration was not accurate, the participant was recalibrated. If the calibration was accurate, the participant looked at the first box and the experimenter displayed the sentence. Questions about the sentence were asked after 25% of the trials and participants had little difficulty answering the questions (the overall accuracy was 96%). The experiment lasted about 40 minutes.

RESULTS

Fixations of less than 80 ms and more than 1200 ms were removed from the analyses. Three standard eye movement measures were computed. First fixation duration is the duration of the first fixation on a word; single fixation duration refers to cases in which only one fixation is made on the word; gaze duration is the sum of all fixations on a word prior to moving to another word. All three measures are conditional on the word being fixated on the first pass through text. Trials on which the eye-tracker lost track of the eye position were also excluded from the analyses, as well as trials in which the eyes triggered the display change but remained on the word before the target (usually on the last letter)[2]. As a result, 27% of the trials were excluded from the analyses, and these trials were equally distributed across conditions (varying between 26% and 28% per condition). It is important to note here that even though 27 % of the trials were excluded from the analyses, we still had considerable statistical power for the analyses reported below (on average 73 trials per participant, corresponding to 18 observations per condition). Finally, when the duration of a fixation was more than three standard deviations from the mean for a participant in any condition, it was also removed for that specific analysis. A series of repeated measures analyses of variance (ANOVAs) were undertaken with participants (F1) and items (F2) treated as random variables.

Probability of fixating word$_n$. The probabilities of fixating word$_n$ are shown in Table 2. HF targets were fixated 7% less often than LF targets [$F1(1,27) = 10.06$, $p < .01$; $F2(1,99) = 8.16$, $p < .01$]. There was no effect of preview (all Fs < 1) and the interaction between frequency and preview was not significant (Fs < 1). We thus replicated the finding that a HF word is skipped more often than a LF word even though this is not a large effect and usually only appears in analyses restricted to launch sites close to the target word (see Brysbaert, Drieghe &

Vitu, 2005). Hence, we take this observation as an indication that our analyses have considerable statistical power.

Fixation durations on word$_n$. The various fixation duration measures on word$_n$ are shown in Table 2. However, the differences between first fixation duration, gaze duration, and single fixation duration are small because when word$_n$ was fixated, it was fixated exactly once 96% of the time. For first fixation duration, the 25 ms effect of the frequency of word$_n$ was significant [$F1(1,27) = 30.28$, $p < .001$. $F2(1,99) = 17.88$, $p < .001$]. In contrast, the 2 ms effect of preview was not significant ($Fs < 1$) nor was the interaction [$F1 < 1$, n.s.; $F2(1,99) = 1.10$, $p > .20$]. Similarly, for gaze duration, the frequency effect was 27 ms [$F1(1,27) = 27.41$, $p < .001$; $F2(1,99) = 22.54$, $p <.001$], and neither the 1 ms effect of preview nor the interaction between these two factors was close to significant ($Fs < 1$). For single fixation duration, there was a 22 ms frequency effect, [$F1(1,27) = 35.02$, $p < .001$; $F2(1,97) = 20.18$, $p < .001$], and neither the 1 ms effect of preview nor the interaction was significant ($Fs < 1$). The size of this frequency effect is comparable to frequency effects reported in other studies that examined single fixation durations on manipulated five-letter words (i.e. 33 ms in Rayner, Sereno, & Raney, 1996; 27 ms in Drieghe, Rayner, & Pollatsek, 2005). Clearly our frequency manipulation on word$_n$ elicited a robust frequency effect (see Rayner, 1998) with virtually no effect from the manipulation of the parafoveal word. In analyses below, we focus on single fixation durations, as that measure is the simplest to interpret with respect to parafoveal-on-foveal effects.

INSERT TABLE 2 AND FIGURE 1 ABOUT HERE

Single fixation duration on word$_n$ when the eyes were close to word$_{n+1}$. When we restricted the analyses of the single fixation duration on word$_n$ to those instances where the eyes were close to word$_{n+1}$ (i.e. 3 character positions or fewer) the 30 ms frequency effect was significant across participants [$F1(1,26) = 47.17$, $p < .001$] but only marginally significant across items [$F2(1,64) = 3.57$, $p < .10$]. Again, the effect of preview was not significant [$F1(1,26) = 2.61$, $p = .12$; $F2(1,64) = 1.08$, $p > .20$] nor was the interaction ($Fs < 1$). Because we wanted to make sure we didn't miss any parafoveal-on-foveal effect on these fixations and because our analyses have clearly shown that there is not the slightest hint of an interaction between the frequency of word$_n$ and the preview of word$_{n+1}$, we collapsed the data across frequency. The resulting single fixation duration was 275 ms in the correct preview condition and 289 ms in the incorrect preview condition. This 14 ms effect was significant via participants but not items [$t1(27) = 2.24$, $p < .05$; $t2(99) = 1.48$, $p >.10$]. The distribution of the average duration collapsed over the frequency conditions as a function of letter position on word$_n$ and parafoveal preview is shown in Figure 1. This figure reveals a pattern consistent with the Inverted Optimal Viewing Position effect for the correct preview condition: Fixations are longest at the optimal viewing position (Vitu, McConkie, Kerr, & O'Regan, 2001). This phenomenon is also observed for the incorrect preview condition with one exception: the mean duration on the last letter position in the incorrect preview condition clearly deviates from this pattern as fixation durations were 86 ms longer in the incorrect preview condition than in the correct preview condition [$t(39) = 2.95$, $p < .01$]. In contrast, there was virtually no difference between the correct and incorrect preview conditions for the other fixation locations with the possible exception of position 1. However, this 19 ms difference (in the opposite direction) was not close to significant [$t1(25) = 1.39$, $p > .10$; $t2 < 1$].

Saccade length and resulting single fixation duration on word$_n$. To test our hypothesis that the fixations responsible for this parafoveal-on-foveal effect were limited to fixations on the end of word$_n$ and were associated with relatively longer prior saccades, we also examined the effect of the length of those saccades on fixation durations on word$_n$. First, we wanted to be sure that the correctness of the preview had no effect on the length of the saccade leading to a single fixation on last three letters of word$_{n.}$ In fact, the mean saccade lengths leading to a single fixation on word$_n$ were 7.4 characters and 7.5 characters in the correct and incorrect preview conditions [$t1 < 1$; $t2(99) = 1.57$, $p > .10$]. In contrast, there was clear evidence that the consequence of landing near the end of word$_n$ was affected by the length of the saccade, but only when the parafoveal preview of word$_{n+1}$ was incorrect. Although the correlation between the length of this saccade and the duration of a single fixation on (the last three letters of) word$_n$ was not significant for the correct preview condition ($r = .09$, $t(372) = 1.74$, $p > .05$), it was highly significant when there was an incorrect preview ($r = .19$, $t(380) = 3.77$, $p < .001$). To further test the relationship between the prior saccade length and the resulting single fixation duration on the last three characters of word$_n$, we divided the data into two parts: a short incoming saccade (4-6 characters long, 37% of the data) and a long incoming saccade (7 characters or longer, 63% of the data). The resulting single fixation durations, again collapsing over the frequency conditions, are shown in Table 3. A repeated measures ANOVA was undertaken with participants (F1) treated as random variables. Due to a large number of empty cells we could not carry out the analysis with items treated as random variables. A significant effect of preview was observed [$F1(1,21) = 4.56$, $p < .05$], as well as an effect of saccade length [$F1(1,21 = 4.90$, $p < .05$]. When the saccade was long the resulting single fixation duration was 13 ms longer than when the saccade was short, probably due to reduced preview benefit. The interaction between these two factors was not significant [$F1(1,21) = 1.81$, $p < .20$]. A planned comparison showed that for long saccades the resulting single fixation duration was 18 ms longer in the incorrect preview condition than in the correct preview condition ($t1(27) = 2.71$, $p < .05$). In contrast, the 5 ms parafoveal-on-foveal effect was not significant for the short saccades ($t1 < 1$). We take these observations as evidence that the (limited) parafoveal-on-foveal effect was mostly associated with relatively long preceding saccades, as would be expected from a mislocated fixation account: after a long saccade the chances of undershooting the target word are higher, and as a consequence, readers try to process the incorrect parafoveal preview while fixating the prior word.

INSERT TABLE 3 ABOUT HERE

Fixation durations on word$_{n+1}$. Fixation times on word$_{n+1}$ are shown in Table 2. For the first fixation duration on word$_{n+1}$, there was only a 4 ms "spillover" effect of the frequency of word$_n$ (Fs < 1). Even though a spill-over effect of frequency has been reported numerous times in the literature (e.g. Drieghe, Rayner & Pollatsek, 2005; Henderson & Ferreira, 1990; Kennison & Clifton, 1995), it can be regarded as being somewhat of an elusive effect in the sense that some studies, like the current one, do not find significant spill-over effects (White et al., 2005; Rayner, Liversedge & White, 2006). When the preview was incorrect, first fixation duration on word$_{n+1}$ was on average 10 ms longer than when the preview was correct. This parafoveal preview benefit effect was significant via participants but not items [$F1(1,27) = 5.09$, $p < .05$; $F2(1,99) = 2.48$, $p > .10$]. The interaction between these 2 factors (the parafoveal preview benefit was 8 ms after a LF word$_n$ versus 11 ms after a HF word$_n$) was also not significant (*F*s < 1). The gaze duration on word$_{n+1}$ showed a significant 19 ms preview effect [$F1(1,27) = 10.88$, $p < .01$; $F2(1,99) = 9.14$, $p < .01$]. Although the interaction between the frequency of word$_n$ and whether there was a valid preview of word$_{n+1}$ on gaze duration was in the predicted direction – the parafoveal preview benefit on gaze duration was 14 ms after a LF word$_n$ and 24 ms after a HF word$_n$ – the difference was not close to significant [$F1 < 1$; $F2(1,99) = 1.11$, $p > .20$]. In addition, there was virtually no main effect of the frequency of word$_n$ on the gaze duration on word$_{n+1}$ (*F*s < 1). This failure to find a significant interaction between foveal frequency and parafoveal preview (see also Drieghe, Rayner, & Pollatsek, 2005) can be construed as a failure to replicate the findings of Henderson and Ferreira (1990). However, the difference between the studies is plausibly due to the difference in the "size" of the preview manipulations. Whereas both the current and our previous study constructed the incorrect preview by changing one or two letters of the correct preview, Henderson and Ferreira (1990) used complete nonsense previews (e.g. *zqdloyv*).

DISCUSSION

The possibility of parafoveal-on-foveal effects has become a major issue in recent research on eye movements in reading because it is seen as a critical test for determining whether the words in text are processed serially, or whether two or more words are processed in parallel. However, there are two reasons that must temper any enthusiasm with regards to the potential of these parafoveal-on-foveal effects to force a theoretical breakthrough. First, whereas some studies indicate the existence of such effects (Kennedy & Pynte, 2005), they seem to be difficult to replicate or lead to inconsistent results (Hyönä & Bertram, 2004; Rayner & Juhasz, 2004). Second, limited parafoveal-on-foveal effects are not necessarily inconsistent with a serial model, such as E-Z Reader, because this model incorporates saccadic error. We outlined a mislocated fixation account that explains parafoveal-on-foveal effects by means of the well-documented phenomenon of saccadic undershoot (McConkie et al., 1988).

Given that the most reliable parafoveal-on-foveal phenomenon has been an inflated fixation duration prior to a parafoveal preview containing an irregular letter sequence (Inhoff et al., 2000), we constructed our experiment to maximize such an effect and observed a small effect that was not close to significant. In addition, we examined whether this small effect was better explained by a parallel processing account or by a mislocated fixation account. One prediction that might result from a parallel architecture is that this parafoveal-on-foveal effect should be more pronounced when $word_n$ is a HF word than when $word_n$ is a LF word. Because previous studies did not yield this observation (Henderson & Ferreira, 1990; White et al., 2005) we let $word_n$ be preceded by a HF adjective which presumably allows even more processing resources (from a parallel perspective) to be devoted to parafoveal processing. However, we observed no interaction whatsoever between the frequency manipulation and the parafoveal preview manipulation. A second prediction, derived from a mislocated fixation account, is that parafoveal-on-foveal effects would be restricted to those occasions when the fixation on $word_n$ was near the end of it (i.e., parafoveal-on-foveal effects occur because the reader intends to fixate $word_{n+1}$ but falls short). We observed a large effect when the fixation on $word_n$ was on the final letter and no significant effects on the other letters (although, given more data, we would expect a more graded effect with at least some effect when the penultimate letter is fixated, as was previously observed, e.g. Drieghe et al., 2005). A third prediction, also derived from the mislocated fixation account, was that this parafoveal-on-foveal effect for a fixation near the end of $word_n$ was more likely to occur if the saccade prior to this fixation was long. (This is because an undershoot of $word_{n+1}$ is more likely to occur for long saccades.) In fact, we observed a significant correlation between saccade length and single fixation duration on $word_n$ when there was an orthographically illegal parafoveal preview, but little effect when there was a normal parafoveal preview. This pattern was also observed in the mean single fixation durations when we divided the data as a function of incoming saccade length into short and long incoming saccades.

In sum, we observed evidence for the predictions derived from the mislocated fixation account. Moreover, these data can be considered problematic for any parallel account of eye movements in reading for the following three reasons. First, the fact that – in both the current and many previous boundary experiments – the fixation time on $word_n$ was virtually the same when the preview was "garbage" as when the preview consisted of a normal word (Rayner, 1975) has to be acknowledged as being inconsistent with a parallel perspective. After all, we are comparing the difference between having a zero frequency, illegal non-word versus a normal word as the preview of $word_{n+1}$ and what is typically observed is very close to no effects when fixating $word_n$ (for a related discussion, see Rayner, Pollatsek, Drieghe, Slattery, & Reichle, 2007). Second, although we created close to ideal circumstances to observe an effect of the foveal word frequency on parafoveal-on-foveal effects (which would presumably be boosted in the case of a HF foveal word), we did not observe any hint of an interaction on $word_n$ between foveal frequency and parafoveal preview. Finally, even though we are aware that a significant correlation of .19 – between the length of the incoming saccade and the resulting single fixation duration on the final letters of $word_n$ preceding the incorrect preview of $word_{n+1}$ – is not the most persuasive piece of evidence for showing that the parafoveal-on-foveal effects were due to undershoots of $word_{n+1}$, we were mildly surprised that this correlation was observed, with all the other processes going on during reading. Moreover, the direction of this correlation is opposite to what one might expect starting from a parallel framework. That is, a longer saccade from $word_{n-1}$ (or even earlier in the sentence) would, on average, be launched from a location further from $word_n$, and thus $word_n$ should have less processing done on it. Therefore, more processing would be needed when the eyes land on it and thus less interference from the unusual preview of $word_{n+1}$ would be expected. By no means would this be the condition associated with the longest fixation durations in the case of the unusual parafoveal preview.

We do acknowledge that a parallel processing model can explain the latter two findings, though not particularly parsimoniously. That is, the fact that the frequency of $word_n$ has no effect on the size of the parafoveal-on-foveal effect can be attributed to a trade-off: the lower-frequency word takes more time and attention than the higher-frequency word (and thus doesn't allow for as much processing of $word_{n+1}$), but the longer fixation durations on $word_n$ compensate by allowing extra processing to occur. However, it is unlikely that the latter effect could completely annul the former effect: Controlled experiments have consistently shown a reduced parafoveal preview benefit after a low-frequency foveal word; however, the effect is sometimes statistically significant (e.g. Henderson & Ferreira, 1990, Schroyens, Vitu, Brysbaert, & D'Ydewalle, 1999) and other times it is a sizeable numerical effect but non-significant (e.g. the current study). Similarly, one could argue with a parallel model that the increased parafoveal-on-foveal effects with longer saccades prior to fixating $word_n$ are caused by the same competing mechanisms: (a) less processing of $word_n$ and $word_{n+1}$ due to being further away from them but (b) more processing of $word_{n+1}$ due to there being a longer fixation on $word_n$ and thus more time to process $word_{n+1}$. However, for this latter explanation to work, the latter effect must outweigh the former ones, which doesn't seem to flow naturally from any basic principles of parallel processing. Thus, although parallel models can't be ruled out on the basis of these latter two findings, a serial processing account seems simpler and more satisfactory.

In summary, our results are compatible with a model of eye movement control in reading that posits that encoding of $word_{n+1}$ begins only when encoding of $word_n$ is completed such as the E-Z Reader model. More specifically, we were able to show that a parafoveal-on-foveal effect, the inflated fixation duration prior to an unusual parafoveal word beginning, could be explained via a mislocated fixation account.

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Footnotes

[1] This word is usually referred to as the *parafoveal* word. Actually, the parafovea is a region which generally extends from about 2° to 5° on either side of fixation. Although the word to the right of fixation may not always begin 2° away from fixation, it is still typically referred to as the parafoveal word.

[2] On some occasions, the Dual Purkinje Eye-tracker will register a saccade that crosses the boundary (triggering the display change), but the eye then (within a few milliseconds) “hooks” back to land on a character prior to the boundary location.

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Table 1. An example sentence from the experiment illustrating each of the 4 conditions.

1. High frequency noun – correct preview

The opera was very proud to present the young child *performing* on Tuesday.

2. High frequency noun – incorrect preview

The opera was very proud to present the young child *pxvforming* on Tuesday.

3. Low frequency noun – correct preview

The opera was very proud to present the young tenor *performing* on Tuesday.

4. Low frequency noun – incorrect preview

The opera was very proud to present the young tenor *pxvforming* on Tuesday.

Note: The stimuli shown in italics indicate the preview for each condition prior to the eyes' crossing of the display change boundary. The preview was always replaced by the correct word after the boundary had been crossed.

Table 2. Mean Fixation Probability (FP), First Fixation Duration (FFD), Gaze Duration (GD), and Single Fixation Duration (SFD) on $word_n$, Single Fixation Duration on $word_n$ Close to $word_{n+1}$ (SFDC, i.e. 3 character positions or less), and Mean First Fixation (FF) and Gaze Duration (GD) on $word_{n+1}$ as a function of the frequency of $word_n$ and the parafoveal preview of $word_{n+1}$. Standard deviations are shown in parentheses.

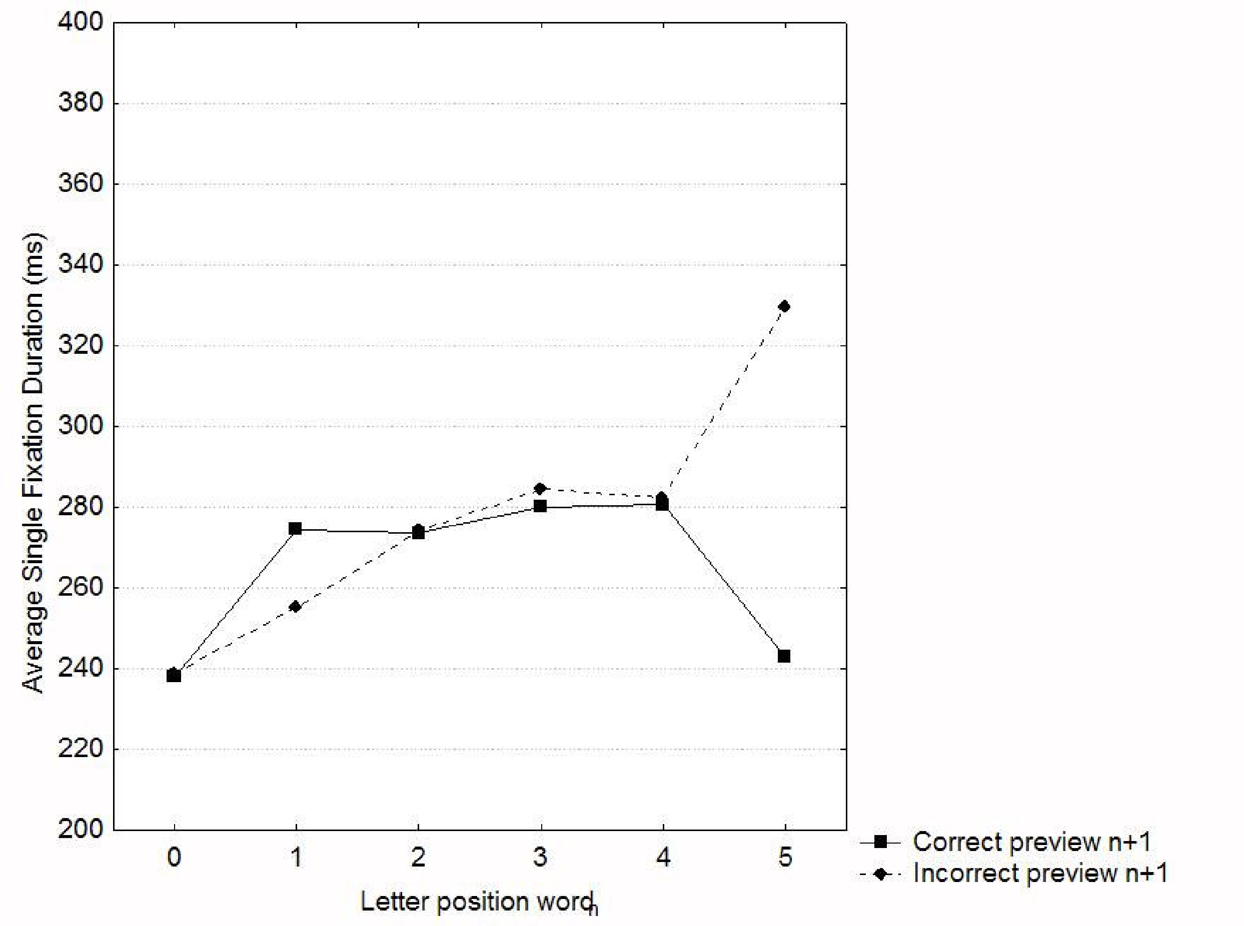
Frequency $word_n$	Preview	$word_n$					$word_{n+1}$	
		FP %	FFD (ms)	GD (ms)	SFD (ms)	SFDC (ms)	FFD (ms)	GZ (ms)
High Frequency	Correct	75 (18)	258 (41)	267 (46)	262 (45)	264 (50)	264 (30)	306 (48)
	Incorrect	75 (18)	262 (45)	268 (45)	264 (45)	276 (52)	275 (42)	330 (69)
Low Frequency	Correct	81 (18)	284 (46)	293 (48)	287 (45)	294 (54)	269 (40)	309 (60)
	Incorrect	83 (17)	285 (48)	295 (54)	289 (50)	306 (68)	277 (41)	323 (66)

Table 3. Mean single fixation duration (in ms) on the last three letter positions of word$_n$ as a function of parafoveal preview and length of the preceding saccade. A short saccade was 4, 5, or 6 character positions long, a long saccade was 7 character positions or longer. Standard deviations are shown in parentheses.

Preview	Saccade length	
	Short	Long
Correct	270 (46)	276 (49)
Incorrect	275 (68)	294 (51)

Figure Captions

Figure 1. Distribution of the average single fixation duration on $word_n$ as a function of the preview of $word_{n+1}$. Letter position 0 is the blank space in front of $word_n$.



Average Single Fixation Duration (ms)
400
380
360
340
320
300
280
260
240
220
200
0
1
2
3
4
5
Letter position word$_n$
Correct preview n+1
Incorrect preview n+1