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Eye movements and the modulation of parafoveal processing by foveal processing difficulty: A reexamination

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Henderson and Ferreira (1990) found that foveal load (manipulated via word frequency) modulates parafoveal processing, thereby affecting the amount of preview benefit obtained from the word to the right of fixation. The present experiment used the eye-contingent boundary paradigm and, consistent with Henderson and Ferreira, showed that foveal load modulated preview benefit for participants who were not aware of the display changes during reading. Also, for these participants, foveal load modulated preview benefit regardless of fixation durations on the foveal word. For participants who were aware of the display change, preview benefits occurred regardless of foveal processing difficulty. These results have important implications for understanding the way in which foveal load influences parafoveal processing during reading.

During reading, information is extracted from each fixated word and from the word to the right of fixation. A fundamental issue for understanding eye movement control in reading is whether the processing of nonfixated text remains constant, or whether it is influenced by foveal processing load (Liversedge & Findlay, 2000; Rayner, 1998; Starr & Rayner, 2001). The results of an important experiment by Henderson and Ferreira (1990) suggest that parafoveal processing is modulated by foveal processing load. This notion is a major constraint for the architecture of the E-Z reader model of eye movement control (Reichle, Pollatsek, Fisher, & Rayner, 1998; Reichle, Rayner, & Pollatsek, 1999, 2003). Other research suggests that a similar phenomenon may occur in tasks other than reading as well (e.g., Mackworth, 1965; Williams, 1988).

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In the present study, we used a manipulation similar to that of Henderson and Ferreira (1990) in order to address three important issues. First, the modulation of parafoveal processing by foveal load is so central to our understanding of eye movement control in reading that it is crucial to establish that this phenomenon is reliable. Second, Henderson and Ferreira excluded trials in which participants detected saccade-contingent display changes, whereas we tested whether foveal load also modulates parafoveal processing for participants who detect the changes. Third, Schroyens, Vitu, Brysbaert, and d'Ydewalle (1999) suggested that the effects of foveal load on parafoveal processing are due to spillover processing following short previous fixations. In the present experiment, we also tested whether foveal load modulates preview benefit regardless of preceding fixation durations.

Studies have shown that the processing of a parafoveal word facilitates the processing of that word when it is subsequently fixated. This *preview benefit* (Rayner & Pollatsek, 1989) is measured using the saccade-contingent boundary change technique (Rayner, 1975). This technique involves changing the preview (which may be correct or incorrect) when the eye crosses an invisible boundary prior to fixation such that the word is correct when it is fixated. The difference in reading times between when the preview is correct and when it is incorrect provides the preview benefit (which measures the extent to which the processing of the correct preview facilitates processing once the word is fixated).

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Henderson and Ferreira (1990) used the boundary paradigm to show that foveal processing difficulty reduces parafoveal processing. They compared reading times on critical target words (e.g., *despite*) when the preview of that word was correct (*despite*) and when it was incorrect (*zqdioyv*) and when the word prior to the critical word was frequent (*chest*) and when it was infrequent (*trunk*). They showed that the preview benefit for the critical target word was larger when the previous word was frequent than when it was infrequent.[1] That is, the preview benefit was smaller when foveal processing was difficult than when it was easy. Two other studies yielded similar results (Kennison & Clifton, 1995; Schroyens et al., 1999). However, Kennison and Clifton showed the effect only for saccades launched from near the critical word and only for analyses across participants, not items. Schroyens et al. used an isolated word recognition task that does not involve normal reading. Due to the centrality of this issue to eye movement control in reading, it is important that the phenomenon be shown to be robust across experiments. To provide a strong test of the phenomenon, we measured preview benefit for four-letter words with correct versus incorrect (visually dissimilar) previews. Foveal load was modulated by word frequency. If Henderson and Ferreira's findings are reliable, the preview benefit should be greater when four-letter words are preceded by frequent as opposed to infrequent words.

Henderson and Ferreira (1990) excluded trials in which participants were aware that a display change had taken place. In typical boundary paradigm experiments, only a small percentage of participants are aware that there has been a change. It is not clear why a few participants detect display changes but most others do not. One possibility is that individuals have varying degrees of nonfoveal visual processing (Toet & Levi, 1992) or nonfoveal awareness; those with high nonfoveal awareness may be able to detect display changes. In the present experiment, we tried to increase the percentage of participants who might be aware of a display change by using short and distinctive orthographically illegal previews (random consonant strings). Thus, the results for participants who were and who were not aware of a change were analyzed separately to determine whether similar patterns of results held for both groups of participants.

A second critical issue under consideration was whether the duration of the prior fixation modulates the influence of foveal load on preview benefit. The E-Z reader model (Reichle et al., 1998; Reichle et al., 1999, 2003) suggests that preview benefit is reduced when there is high foveal load because there is less time between the shift of attention to the next word and the subsequent eye movement to that word. For example, in Sentence 1 in Table 1, the time between the attention shift and the eye movement to word $n + 1$ (e.g., *girl*) should be shorter when word n is difficult (e.g., *agile*) than when it is easy (e.g., *happy*) to process. The timing of the attention shift and the saccade depend on linguistic processes and operate regardless of the duration of the previous fixation. Therefore, E-Z reader predicts that foveal load should modulate preview benefit regardless of the duration of the previous fixation. In contrast, Schroyens et al. (1999) suggested that when there are inappropriately short fixations, processing might continue (spill over) on the following word (word $n + 1$). Thus, there would be little preview of word $n + 1$, and spillover processing might interfere with subsequent processing of word $n + 1$. Schroyens et al. suggested that difficult words would be more likely to produce such effects than easy words because difficult words take longer to process. Accordingly, there should be reduced preview benefits for words that are difficult to process with short, but not long, prior fixations.

The E-Z reader model and Schroyens et al. (1999) provide different explanations for how foveal load modulates preview benefit. Because Schroyens et al. used an isolated word task, it is crucial to undertake similar tests for reading. The present study provides a more ecologically valid test of the relationship between prior fixation durations, foveal difficulty, and preview benefit.

METHOD

Participants

Forty-eight students at the University of Massachusetts participated in the experiment.[2] Of these, 32 were unaware of the display change (Group 1) and 16 were aware of it (Group 2).[3] All participants had normal vision and were naive regarding the purpose of the experiment.

Apparatus

The sentences were presented on an NEC 4FG monitor interfaced with a PC. The eye-contingent boundary technique was used (Rayner, 1975); the display changes occurred within 5 msec of detection of the boundary's having been crossed. Sentences were displayed at a viewing distance of 61 cm, and 3.8 characters subtended 1º of visual angle. Movements of the right eye were monitored using a Dual Purkinje eye tracker. The resolution of the eye tracker is less than 10′ of arc, and the sampling rate was every millisecond.

Materials and Design

Two variables, foveal processing difficulty[4] and parafoveal preview, were manipulated within participants and items. Word n was either easy to process (high frequency, *happy*) or difficult to process (low frequency, *agile*) (see Table 1). The preview of word $n + 1$ before it was first fixated was either correct (*girl*) or incorrect (*bstc*). The incorrect previews were always visually dissimilar consonants

Table 1
Examples of Experimental Sentences and Critical Words for Each Condition

1. Outside the school the happy/agile [bstc] girl skipped around the other children.
2. The supporters cheered when the local/inept [wtdr] team finally won the match.
3. The cook ordered the daily/bland [gkhn] food from the local market.
4. The child pestered the green/timid [jbws] fish that was hiding behind the pondweed.

Note— The high-frequency word n is to the left of each slash; the low-frequency, to the right. The incorrect preview of word $n + 1$ is shown in brackets.

in comparison with the correct preview. Word *n* was five to six letters long, and word $n + 1$ was four letters long. Word frequencies for word *n* were calculated using Francis and Kučera (1982). Frequent words ($M = 216$, $SD = 251$) were significantly more frequent than infrequent words ($M = 5$, $SD = 4$) [$t(43) = 5.59$, $p < .01$].

Four lists of 98 items were constructed, and participants were randomly allocated to each list. Each list was read by 8 participants who were not aware of the display change and 4 participants who were. Each list included 44 experimental items, of which 11 were from each of the four conditions. The sentences were no longer than one line (80 characters), and the critical words appeared approximately in the middle of the sentence. Conditions were rotated following a Latin square design. There were 54 filler items, and sentences were presented in a random order with six filler sentences at the beginning. Thirty-two of the sentences were followed by comprehension questions.

Procedure

Participants were told to read the sentences for comprehension. A bite bar minimized head movements. The accuracy of the eyetracker was checked (and recalibrated when necessary) before each trial. After each sentence, the participants pressed a button box to continue and to respond "yes"/"no" to comprehension questions. After the experiment, the participants were asked whether or not they had noticed anything strange about the appearance of the text in the experiment. The experiment lasted 35 min.

Analyses

Fixations under 80 msec within one character of the next or previous fixation were incorporated into that fixation. Remaining fixations under 80 msec and over 1,200 msec were discarded. Trials were excluded due to (1) display changes happening too early,[5] (2) tracker loss or blinks on first-pass reading of word *n* or $n + 1$, and (3) zero reading times on the first part of the sentence. For Group 1, 17% of the trials were excluded; for Group 2, 12% were excluded.

RESULTS

Infrequent words are more likely to be refixated than frequent words (Inhoff & Rayner, 1986). Therefore, in order to avoid any confound with refixation probability, the results presented here are based only on instances in which a single first-pass fixation occurred on word *n*. In addition, instances were included where there were no first-pass regressions from word *n*. Analyses across participants and items are based on participants or items only when there were sufficient data for each of the conditions.[6]

Single fixation durations were calculated for words *n* and $n + 1$. The duration of the first fixation and gaze duration (the sum of fixations on a word before leaving it) were calculated for word $n + 1$. A series of 2 (word *n* foveal load: frequent, infrequent) × 2 (word $n + 1$ preview: correct, incorrect) repeated measures analyses of variance (ANOVAs) were undertaken with participants (F_1) and items (F_2) as random variables. Group 1 answered 89% of the comprehension questions correctly. Group 2 answered 92% of them correctly.

Word *n* Reading Time

For Group 1, single fixation durations were longer on word *n* when it was infrequent than when it was frequent [$F_1(1,31) = 11.99, p < .01$; $F_2(1,40) = 18.37, p < .001$]. The preview of word $n + 1$ did not influence single fixation durations on word *n* [$F_1(1,31) = 1.16, p = .29$; $F_2 < 1$], and there was no interaction between the frequency of word *n* and the preview of word $n + 1$ [$F_1(1,31) = 1.81$, $p = .188$; $F_2(1,40) = 2.99$, $p = .092$]. Similarly, for Group 2, single fixation durations were longer on word *n* when it was infrequent than when it was frequent [$F_1(1,15) = 16.24, p < .01$; $F_2(1,37) = 13.57, p < .01$]. There was no effect of preview [$F_1(1,15) = 2.9$, $p = .109$; $F_2(1,37) = 1.53$, $p = .223$], and no interaction (Fs < 1). Therefore, for Groups 1 and 2, the modulation of foveal load was effective and reading time on word *n* was uninfluenced by the preview of word $n + 1$.

Word $n + 1$ Reading Time

Table 2 shows the mean reading times on word $n + 1$.[7] For Group 1, there was no influence of the frequency of word *n* on word $n + 1$ for first fixation durations (Fs < 1), gaze durations [$F_1(1,29) = 1.96, p = .172$; $F_2 < 1$], or single fixation durations (Fs < 1). Similarly, for Group 2,

Table 2
Mean Single First-Pass Fixation Durations on Words *n* and $n + 1$ (Single Fix), and Mean First Fixation Durations (FF) and Gaze Durations (GD) on Word $n + 1$ (in Milliseconds)

			Word *n* Single Fix		Word $n + 1$ FF		Word $n + 1$ GD		Word $n + 1$ Single Fix	
Participants	Word *n* Frequency	Word $n + 1$ Preview	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Group 1	Frequent	Correct	277	83	274	85	293	98	279	85
		Incorrect	295	103	321	112	340	132	325	113
		Benefit	–		47		47		46	
	Infrequent	Correct	321	112	304	114	329	144	311	116
		Incorrect	311	110	295	91	330	123	300	89
		Benefit	–		−9		1		−11	
Group 2	Frequent	Correct	261	76	262	93	269	104	262	94
		Incorrect	268	84	362	164	398	171	379	166
		Benefit	–		100		129		117	
	Infrequent	Correct	296	98	273	89	286	103	275	90
		Incorrect	316	132	375	152	416	161	390	155
		Benefit	–	102		130		115		

Note—Preview benefits (incorrect − correct) are calculated for word $n + 1$.

there was no effect of the frequency of word *n* on word $n + 1$ for first fixation durations [$F_1 < 1$; $F_2(1,33) = 1.42$, $p = .242$], gaze durations [$F_1 < 1$; $F_2(1,33) = 2.14$, $p = .153$], or single fixation durations (Fs < 1). Therefore, for both groups, there was no continued processing of word *n* as shown by spillover effects on reading times on word $n + 1$.

For Group 1, reading times on word $n + 1$ were longer for incorrect previews than for correct previews: first fixation durations, $F_1(1,29) = 6.51, p = .02, F_2(1,39) = 3.4$, $p = .073$; gaze durations, $F_1(1,29) = 6.24$, $p = .02$, $F_2(1,39) = 4.1$, $p = .05$; and single fixation durations, $F_1(1,28) = 5.2, p = .03, F_2(1,37) = 2.68, p = .11$. Similarly, for Group 2, reading times on word $n + 1$ were longer for incorrect previews than for correct previews: first fixation durations, $F_1(1,15) = 20.9, p < .001, F_2(1,33) = 43.3, p < .001$; gaze durations, $F_1(1,15) = 38.6, p < .001$, $F_2(1,33) = 73.73, p < .001$; and single fixation durations, $F_1(1,15) = 28.82$, $p < .001$, $F_2(1,31) = 54.81$, $p < .001$. For both groups, these results suggest that parafoveal processing of word $n + 1$ facilitated processing in such a way that reading times on word $n + 1$ were reduced. The critical question is whether this processing was limited by foveal processing load (the frequency of word *n*).

For Group 1, on word $n + 1$, there was an interaction between the frequency of word *n* and the preview of word $n + 1$ for first fixation durations [$F_1(1,29) = 8.53$, $p < .01$; $F_2(1,39) = 10.12$, $p < .01$], gaze durations [$F_1(1,29) = 5.81, p = .02; F_2(1,39) = 6.01, p = .02$], and single fixation durations [$F_1(1,28) = 10.3$, $p < .01$; $F_2(1,37) = 11.09, p < .01$]. When word *n* was infrequent, there were no effects of preview for first fixation durations (ts < 1), gaze durations (ts < 1), or single fixation durations [$t_1(29) = 1.29$, $p = .207$; $t_2 < 1$]. However, when word *n* was frequent, a preview effect did occur such that reading times were longer for incorrect than correct previews: first fixation durations, $t_1(29) = 3.88$, $p < .01, t_2(43) = 3.94, p < .001$; gaze durations, $t_1(29) = 3.23, p < .01$, $t_2(43) = 2.72, p < .01$; and single fixation durations, $t_1(29) = 3.99, p < .001, t_2(42) = 3.84, p < .001$. In contrast, for Group 2, there was no interaction between foveal load (the frequency of word *n*) and parafoveal preview (of word $n + 1$) for first fixation durations, gaze durations, or single fixation durations (Fs < 1). These reading time measures suggest that for Group 1, the frequency of word *n* modulated the preview benefit derived from word $n + 1$. However, for Group 2, preview benefit was not modulated by the difficulty of the previous word.

Effects of change awareness.The results above suggest that foveal load modulated preview benefit for participants who were not aware of display changes (Group 1), but not for participants who were aware of changes (Group 2). However, because the number of participants who were aware of changes was smaller, it is possible that this lack of an effect was due to reduced power. Consequently, we undertook a combined analysis of both data sets with awareness of display changes as a between-participants and within-items variable.

For the analyses across participants,[8] there was an interaction of display change awareness, frequency of word *n*, and preview of word $n + 1$ for first fixation durations [$F_1(1,44) = 4.83$, $p = .03$] and gaze durations [$F_1(1,4) = 3.99, p = .05$], but not for single fixation durations [$F_1(1,43) = 2.34$, $p = .134$]. This suggests that display change awareness influenced preview benefit modulation by foveal load. In addition, there were interactions of change detection and preview of word $n + 1$ for first fixation durations [$F_1(1,44) = 16.98, p < .001$; $F_2(1,30) = 15.55, p < .001$], gaze durations [$F_1(1,44) = 23.98, p < .001; F_2(1,30) = 34.97, p < .001$], and single-fixation durations [$F_1(1,43) = 29.11, p < .001; F_2(1,28) = 22.1$, $p < .001$]. The interactions were due to preview benefits' being twice as large for Group 2 as for Group 1.

Effects of previous fixation duration. Schroyens et al. (1999) suggested that reduced preview benefits occur for difficult words with short, but not long, previous fixations. For Group 1, this possibility was tested using a median split procedure. Single fixations on word *n* were classified as short or long for each participant within each condition.[9] Table 3 shows the mean single fixation durations on word *n* in each of the conditions, and also the mean first fixation, gaze, and single fixation durations on word $n + 1$.

There was no effect of whether the single fixation on word *n* was short or long for first fixation durations [$F_1(1,25) = 2.51, p = .126$], gaze durations [$F_1(1,25) = 2.43, p = .132$], or single fixation durations [$F_1(1,24) = 1.54, p = .226$]. There were no interactions between previous fixation duration and preview of word $n + 1$ (Fs < 1.2) or between previous fixation duration and word frequency (Fs < 1.7, ps $> .21$) for the three measures. These results suggest that the duration of single fixations on word *n* does not modulate preview benefit derived from word $n + 1$ or spillover processing on word $n + 1$.

Importantly, although there were interactions between word frequency and preview for first fixations [$F_1(1,25) = 5.57$, $p = .026$] and single fixations [$F_1(1,24) = 6.45$, $p = .02$], there was no three-way interaction for prior fixation duration, frequency of word *n*, and preview of word $n + 1$ for either measure ($F_1 < 1.2$). For gaze durations, there was no interaction between frequency and preview [$F_1(1,25) = 1.98$, $p = .171$] and no three-way interaction [$F_1(1,25) = 1.72$, $p = .202$]. Therefore, at least for first fixations and single fixations on word $n + 1$, the difficulty of word *n* modulates preview benefit from word $n + 1$ regardless of whether the single fixation duration on word *n* is short or long. That is, contrary to Schroyens et al.'s (1999) suggestion, previous fixation duration does not determine the degree to which preview benefit is modulated by foveal load.

Table 3
Mean Short and Long Single Fixation Durations on Word *n* and Mean First Fixation Durations, Gaze Durations, Single Fixation Durations, and Preview Benefits on Word *n* + 1 for Each Condition for Cases in Which Short and Long Single Fixation Durations Were Made on Word *n*

		Word *n* Median Split Single Fixation				Word *n* + 1 Reading Time Measures											
						First Fixation				Gaze				Single Fixation			
		Short		Long		Short		Long		Short		Long		Short		Long	
Word *n* Frequency	Word *n* + 1 Preview	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Frequent	Correct	232	61	318	84	279	94	270	75	293	102	293	95	282	96	275	73
	Incorrect	243	58	358	120	326	117	315	106	363	149	318	109	331	119	317	108
	Benefit	–		–		47		45		70		25		49		42	
Infrequent	Correct	265	60	372	117	311	123	296	104	340	171	317	110	321	126	301	105
	Incorrect	259	67	356	124	289	90	294	97	328	133	327	119	291	85	304	98
	Benefit	–		–		−22		−2		−12		10		−30		3	

Note—Results are shown for the 32 Group 1 participants. The median split was recalculated for the analyses of single fixation durations on word *n* + 1. The mean single fixation durations on word *n* were similar to those shown above. Durations were measured in milliseconds.

DISCUSSION

The present experiment replicated Henderson and Ferreira's (1990) finding that foveal load modulates parafoveal processing as shown by preview benefit. Note that the differences in preview benefits for high and low foveal load in the present experiment were larger than those reported by Henderson and Ferreira. For example for first fixations, Henderson and Ferreira found a difference of 13 msec, whereas we found a 56-msec difference in preview benefit. One possible reason for this difference is that Henderson and Ferreira's preview words were longer than those in the present experiment.[10] The present data are consistent with the claim that increased parafoveal word length reduces preview benefit.

Henderson and Ferreira (1990) specifically excluded participants who were aware of the display change. In the present study, the data were analyzed separately for participants who were and for those who were not aware of the display change. Although foveal load modulated preview benefit for the participants who were not aware of the change, there was no such effect for those who were aware of the change. In addition, preview benefits were numerically larger for participants who were aware of the display change than for those who were not. These results have three possible implications for the way in which foveal load influences parafoveal processing during reading.

First, foveal load may not modulate parafoveal processing for all readers. Second, foveal load may modulate parafoveal processing to different degrees for different readers. Perhaps foveal word frequency is insufficient to reduce parafoveal processing in some readers. The fact that participants who were aware of the display changes had much larger preview benefits suggests that their parafoveal processing may have been at ceiling regardless of the frequency of the previous word. Third, the boundary paradigm may be unsuitable for participants who are able to process the previews consciously. If some participants are able to consciously detect the difference between the preview and the fixated word, such detections would surely disrupt their eye movements. The large preview benefit effects shown by Group 2 participants may have occurred because some of them actually were aware of the difference between the preview and the target.

Although it is difficult to interpret the nature of the results for the participants who were aware of the display change, the fact that these individuals produced results that were qualitatively different from the results for those who were not aware of the display change has two important implications. First, individual differences may be contributing to parafoveal processing. Second, experimenters must record whether or not participants report noticing saccade-contingent display changes. Failure to account for these participants separately may lead to incorrect interpretations of results.

The final issue investigated in this study was whether differences in single fixation durations on the foveal word modulated the influence of foveal load on preview benefits. In contrast to the findings of Schroyens et al. (1999), our results showed that foveal load modulates preview benefit for both short and long previous fixation durations. Our results therefore suggest that the effect of foveal load on preview benefit is not due to spillover following inappropriately short fixation durations on difficult foveal words. The results are in line with the account given in the E-Z reader model (Reichle et al., 1998; Reichle et al., 1999, 2003) that foveal load modulates parafoveal processing regardless of the previous fixation duration.

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NOTES

1. They also showed comparable effects for a syntactic modulation of foveal processing difficulty. Therefore, processing difficulty at least at and beyond the level of lexical processing appears to modulate parafoveal processing.

2. In order to complete the counterbalancing scheme within the two different groups of participants, an additional 15 participants were run, some of whom were also excluded due to too much missing data.

3. Participants were categorized into Group 1 or Group 2 by their responses to the question "did you notice anything strange about the appearance of the text?" at the end of the experiment. Among the Group 2 participants, some reported noticing nonsense letter sequences, whereas others were not aware of exactly what had changed. Some reported noticing something only occasionally, whereas others reported that they often noticed something odd.

4. To ensure that the critical words were equally predictable within the context of the sentence, sentence completion norms were obtained. Ten participants were given the beginning portions of the sentence up to and including word n, and were asked to provide a single four-letter word that they felt could fit as the next word in the sentence. There was no difference in the frequency with which participants produced word $n + 1$ in the frequent word n (frequency, 26%; *SD* across items, 28%) and infrequent word n (frequency, 26%; *SD* across items, 33%) conditions (ts < 1).

5. Before analyzing the data, we removed any trials on which the eye was sufficiently close to the target word that it triggered the change prior to its direct fixation; this can occur at the end of a saccade when there is a slight overshoot and subsequent correction. This procedure ensured that only trials on which participants triggered the change by directly fixating the target word could contribute to any preview benefit effects that we obtained.

6. Due to skipping or excluded data, not all of the participants and items contributed to each analysis. The number of participants and items that did contribute to the analyses is reflected in the degrees of freedom.

7. Word $n + 1$ was skipped approximately 16% of the time (obviously with more skipping in the correct than in the incorrect condition). Given skipping and excluded data, there were five to six data points on average for participants per condition.

8. For the items analyses, there was no interaction for any measure (Fs < 1). The lack of reliable items effects for these analyses is probably due to the fact that these participants were aware of the change on only some of the trials.

9. Due to insufficient data, it was only possible to do these analyses across participants, not items.

10. The exact word lengths of the preview word in Henderson and Ferreira (1990) is not indicated in their article. However, in some cases, the preview word consisted of a short function word and a content word (e.g., *to fight*), and the examples provided consisted of seven-letter words. Given this, it must be the case that the preview words in the Henderson and Ferreira study were longer than the four-letter words we used.

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