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The influence of parafoveal word length and contextual constraint on fixation durations and word skipping in reading

SARAH J. WHITE
University of Durham, Durham, England

KEITH RAYNER
University of Massachusetts, Amherst, Massachusetts

and

SIMON P. LIVERSEDGE
University of Durham, Durham, England

The present study examined the relationship between the predictability of words within a sentence and the availability of parafoveal word length information, on when and where the eyes move in reading. Predictability influenced first-pass reading times when parafoveal word length preview information was correct, but not when it was incorrect. Similarly, for saccades launched from near the target word (word n), predictability influenced the probability with which it was skipped only when the word length preview was correct. By contrast, for saccades launched farther away from word n, predictability influenced word skipping regardless of the parafoveal word length preview. Taken together, the data suggest that parafoveal word length preview and predictability can act as a joint constraint on the decision of when and where to move the eyes.

Much research has demonstrated that predictable words are read more quickly and are more likely to be skipped than unpredictable words (Balota, Pollatsek, & Rayner, 1985; Ehrlich & Rayner, 1981; Rayner & Well, 1996; for a review, see Brysbaert & Vitu, 1998). Word length is also an important factor in determining word skipping (Brysbaert & Vitu, 1998; Rayner & McConkie, 1976), and where within a word a fixation is made (Rayner, 1979). Furthermore, Inhoff, Starr, Liu, and Wang (1998) showed that disruption to processing occurs for incorrect parafoveal word length previews.

In the present study, we sought to determine whether parafoveal word length information modulates the effects of predictability and influences eye-movement behavior. It is quite conceivable that parafoveal word length information is an important constraint on potential lexical candidates for the upcoming word (Clark & O'Regan, 1999; Hochberg, 1975; O'Regan, 1979). Thus, when word length preview rules out particular lexical candidates, predictability effects may be nullified. Thus, predictability and parafoveal word length information might jointly influence eye movements during reading.

However, two recent studies have suggested that parafoveal word length information does not constrain potential lexical candidates for the upcoming word (or subsequent foveal lexical processing of that word when it is directly fixated). Inhoff, Radach, Eiter, and Juhasz (2003) used the eye-contingent display change paradigm (Rayner, 1975) to investigate the influence of parafoveal orthography and word length information on *preview benefit* (Rayner, 1998), which is the reduction in reading time, given a correct versus an incorrect parafoveal preview. Thus, for a target word like *subject*, orthographically incorrect and correct previews were either the correct length (*mivtirp* and *subject*) or incorrect length (*miv irp* and *sub ect*). Fixation times were shorter when the orthographic and word length previews were correct compared with incorrect, with no interaction between the two.

Drieghe, Brysbaert, Desmet, and De Baecke (2004) tested whether contextual constraint influences word skipping probability on the basis of length. Participants

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read sentences in which a parafoveal word did not agree with the length of an expected word in a sentence. Thus, the sentence may have been highly constraining for a particular four-letter word, but an acceptable two-letter word was present instead (or vice versa). Drieghe et al. showed that expected word length does not influence word skipping probability.

Although the results of Inhoff et al. (2003) and Drieghe et al. (2004) suggest that word length does not constrain lexical candidates, their studies do not preclude this possibility altogether. Inhoff et al.'s (2003) manipulations may not have been optimal to obtain interactive effects of parafoveal word length and orthography. Furthermore, Drieghe et al.'s use of unexpected orthography may have prevented influences of contextual constraint.[1] In our study, we wanted to examine whether word length constrains the influence of predictability, given a correct orthographic preview. Unlike Inhoff et al.'s (2003) study, in our study the orthographic preview of the target word *n* was always correct. Also, unlike Drieghe et al.'s manipulation, the orthography of the expected parafoveal word is always consistent with the lexical candidate favored by context. Hence, perhaps when a correct orthographic preview is available, both word length and predictability jointly constrain lexical processing, producing interactive effects.

In our experiment, like Inhoff et al. (2003), we provided correct or incorrect word length previews. However, we did this by adding, rather than removing, a letter prior to fixation, because we wished to investigate the influence of predictability on both reading times and word skipping. By adding a letter, the word length cue is removed, but the orthography is maintained for a short word that could be parafoveally processed and/or skipped. In addition, the long parafoveal letter strings in the incorrect preview condition ensure a healthy base skipping rate for word *n* (since readers target saccades to the midpoint of the parafoveal string). Thus, we can investigate whether predictability effects on word skipping are modulated when parafoveal orthographic information facilitates identification of a predictable word, whereas parafoveal word length provides a strong cue against its identity. We anticipated that if parafoveal word length information is necessary for contextual constraint to influence preprocessing, an interaction between word length preview and predictability should occur. Thus, we predicted that reading times would be shorter and more word skipping would occur for predictable than for unpredictable words when parafoveal word length preview was correct, but that there would be no such benefit when word length preview was incorrect.

METHOD

Participants

Forty-four University of Massachusetts students with normal or corrected-to-normal vision participated in the experiment. All were naive as to the purpose of the experiment.

Apparatus

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

Materials and Design

We manipulated two variables—predictability and word length preview—within participants and items. Word *n* was predictable or unpredictable (see Table 1). The preview of words *n* and $n + 1$ before word *n* was first fixated was correct (e.g., *bomb under*) or with "s" between the two words (e.g., *bombsunder*).

To ensure that word *n* was predictable or unpredictable, sentence-completion norms were obtained. Twenty participants were given the beginning portions of the sentence up to word *n* and asked to provide a word that they felt would fit as the next word in the sentence. Ten participants were instructed that the word should be four letters long, and for the remainder of the participants word length was unspecified. When word length was specified, the participants produced predictable words more often (frequency: 82%; *SD* across items: 14%) than unpredictable words (frequency: 0%). Similarly, when word length was unspecified, the participants produced predictable words more often (frequency: 55%; *SD* across items: 27%) than unpredictable words (frequency: 0.2%; *SD* across items: 1%). When word length was specified, the predictable words were produced at least 60% of the time for every item, and when it was unspecified they were produced at least 10% of the time for every item.

There were 48 sentence frames with 48 predictable and 48 unpredictable words. Word frequencies[2] were calculated from Francis and Kučera (1982), with no differences in frequency between predictable ($M = 116$, $SD = 124$) and unpredictable ($M = 113$, $SD = 107$) conditions ($t < 1$). Word *n* in each condition was placed in an identical sentence frame. Each sentence was one line of text (80 characters), and word *n* appeared in the middle of the sentence. There were four lists of 54 sentences, and conditions were rotated following a Latin-square design so each participant read 12 sentences in each condition. The sentences were presented in a random order with six filler sentences at the beginning. A comprehension question followed 16 of the experimental sentences.

Table 1
Example Sentence in Each of the Experimental Conditions

Context	Word Length Preview	Example
Predictable	Correct	The explosives expert planted the large/ *bomb* under the old tree.
	Incorrect	The explosives expert planted the large/ *bomb*sunder the old tree.
Unpredictable	Correct	The explosives expert planted the large/ *rose* under the old tree.
	Incorrect	The explosives expert planted the large/ *rose*sunder the old tree.

Note—When the eye crossed the boundary at the very end of word $n - 1$ (marked by /), the display changed such that there was always a space between words *n* and $n + 1$. Word *n* is shown in italics.

Procedure

The participants were told to read the sentences for comprehension. A bite bar minimized head movements. Before each trial, the accuracy of the eyetracker was checked and recalibrated if necessary. After each sentence, the participants pressed a button to continue or to respond yes/no to comprehension questions (which were answered correctly 93% of the time). The experiment lasted 25 min.

Analyses

Fixations under 80 msec within one letter of the next or previous fixation were incorporated into that fixation. Any remaining fixations under 80 msec and over 1,200 msec were discarded. Thirteen percent of the trials were excluded due to (1) display changes happening too early,[3] (2) tracker loss or blinks on first-pass reading of words $n - 1$, n, or $n + 1$, and (3) zero reading times on the first part of the sentence.

RESULTS

Fixation times were computed for words n and $n + 1$. The probability of skipping word n was computed for all of the data, as well as for near and far launch sites. Regressions from words n and $n + 1$, along with regressions into word n were also computed. A series of 2 (contextual constraint: predictable, unpredictable) × 2 (word length preview: correct, incorrect) repeated measures analyses of variance (ANOVAs) were undertaken with participants (F_1) and items (F_2) as random variables.

Word *n* Reading Times

Table 2 shows the mean first fixation duration (the first fixation on a word), gaze duration (the sum of fixations on a word prior to fixating another word), and total time (the sum of all fixations on a word) on word n. Given that first fixation and gaze duration are similar and that total time is not a first-pass measure (due to the inclusion of regressions), we will focus on the gaze duration data.

Gaze durations were shorter when word length preview information was correct than when it was not [$F_1(1,43) = 33.19$, $p < .001$; $F_2(1,47) = 73.1$, $p < .001$] and when word n was predictable than when it was unpredictable [$F_1(1,43) = 8.69$, $p < .05$; $F_2(1,47) = 2.92$, $p = .094$]. These main effects were qualified by an interaction [$F_1(1,43) = 7.62$, $p < .01$; $F_2(1,47) = 3.7$, $p = .06$], which was due to an effect of predictability when the word length preview was correct [$t_1(43) = 5.19$, $p < .001$; $t_2(47) = 3.09$, $p < .01$], but not when the preview was incorrect (ts < 1).

The reading time measures show that a correct, compared with an incorrect, word length preview reduced reading times on word n, indicating that correct parafoveal word length preview facilitates word processing on subsequent fixations. However, the predictability effect was modulated by the word length preview such that a predictability effect occurred when the word length preview was correct, but not when it was incorrect. Thus, for the correct word length preview, the reading time data for word n suggest that it was easier to process when it was predictable than when it was unpredictable. These results replicate research showing that reading times are longer on unpredictable than on predictable words (Balota et al., 1985; Ehrlich & Rayner, 1981; Rayner & Well, 1996).

Word *n* + 1 Reading Times

Gaze durations on word $n + 1$ were shorter for correct than for incorrect word length previews [$F_1(1,43) = 8.1$, $p < .01$; $F_2(1,47) = 6.51$, $p = .01$] and when word n was predictable than when it was unpredictable [$F_1(1,43) = 6.66$, $p = .01$; $F_2(1,47) = 8.95$, $p < .01$]. Although the interaction was only marginal [$F_1(1,43) = 3.31$, $p = .076$; $F_2(1,47) = 3.22$, $p = .079$], the data pattern was the same for all three measures of fixation time (with a significant interaction in total time; ps $< .05$). For gaze durations, when the word length preview was correct, there was no effect of predictability (ts < 1). However, when the word length preview was incorrect, predictability did have an effect [$t_1(43) = 2.74$, $p < .01$; $t_2(47) = 2.88$, $p < .01$]. Predictability may influence reading times on word $n + 1$ for incorrect previews for two reasons. First, after fixating word n, given that no predictability effect occurred on this word, a delayed effect occurred on word $n + 1$. Such a delayed effect of predictability suggests that identification of word n may have been delayed until fixating word $n + 1$ when there was an incorrect preview. Second, after skipping word n, less disruption occurs for predictable than for unpredictable skipped words.

Skipping Probability

As seen in Table 3, word n was more likely to be skipped for incorrect than for correct word length previews

Table 2
Mean First Fixation, Gaze Duration, and Total Time on Words *n* and *n* + 1 for Each of the Conditions (in Milliseconds)

		Word *n*						Word *n* + 1					
		FF		GD		TT		FF		GD		TT	
Word Length	Context	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Correct	Predictable	263	90	276	109	309	151	271	99	300	139	371	211
	Unpredictable	289	97	310	123	358	175	276	98	309	149	369	205
	Difference	*26*		*34*		*49*		*5*		*9*		*−2*	
Incorrect	Predictable	327	117	356	121	347	142	279	102	310	154	389	209
	Unpredictable	330	127	359	143	398	183	297	113	352	184	435	226
	Difference	*3*		*3*		*51*		*18*		*42*		*46*	

Note—FF, first fixation; GD, gaze duration; TT, total time.

[$F_1(1,43) = 36.23$, $p < .001$; $F_2(1,47) = 49.85$, $p < .001$]. This result indicates that the spaces between words are used to target saccades such that most fixations land just left of the word center (Rayner, 1979). Consequently, saccades move farther into 10-letter than into 4-letter parafoveal strings. Word *n* was also more likely to be skipped if it was predictable than if it was unpredictable [$F_1(1,43) = 14.49$, $p < .001$; $F_2(1,47) = 5.87$, $p = .02$]. Although there was no interaction [$F_1(1,43) = 1.56$, $p = .219$; $F_2 < 1$], there was a numerical difference such that for correct word length previews the magnitude of the predictability effect (8%) was twice that for the incorrect previews (4%).

Due to reduced acuity at eccentricities farther from fixation, launch site influences parafoveal preview quality. Perhaps preview information might be utilized to a greater extent for saccades launched from near, in comparison with farther away from, the parafoveal word. We therefore separated the word skipping data to examine the probability of skipping word *n* for cases in which saccades were launched from near (three or fewer characters) or far from (four or more characters) word *n* (see Table 3). Of the total data set, 36% of saccades were launched near word *n* and 64% from farther away. Skipping rates were substantially higher for saccades launched from near (46% of the 36%) than from far sites (17% of the 64%). Thus, overall, the number of trials on which participants skipped the target word when launching from near and far sites were comparable.

We conducted a three-way ANOVA with launch site, preview, and predictability as the variables. There was a significant three-way interaction across participants [$F_1(1,37) = 5.81$, $p = .02$] but not items ($F_2 < 1$).[4] Consequently, separate analyses were undertaken for near and far launch sites for effects of predictability and length.[5] For both near and far launch sites, and consistent with the overall data set, word *n* was skipped more often for incorrect than for correct word length previews (Fs > 14.4, ps $< .01$). For saccades launched from near sites, although there was a predictability effect on skipping [$F_1(1,37) = 6.35$, $p = .02$], more important, we found an interaction between word length preview and predictability [$F_1(1,37) = 6.62$, $p = .01$]. Mean comparisons indicate that, for correct word length preview, there was a predictability effect on skipping [$t_1(40) = 3.35$, $p < .01$], but there was no such effect for incorrect word length previews ($t_1 < 1$). The numerical pattern for all of the word skipping data and those saccades launched from near sites complements the reliable effects observed for the gaze duration data on word *n*. In both cases, a space between words *n* and *n* + 1 caused contextual constraint to influence eye-movement behavior. In contrast, for saccades from far sites, predictable words were more likely to be skipped than were unpredictable words [$F_1(1,43) = 5.87$, $p = .02$; $F_2(1,47) = 3.62$, $p = .06$]. However, no interaction between predictability and word length preview (Fs < 1) occurred for these data. In fact, the magnitude of the predictability effect for word skipping was identical in the correct and incorrect preview conditions for saccades launched from far away.

Regressions

Finally, we analyzed patterns of regressions from words *n* and *n* + 1, as well as regressions into word *n* (see Table 3). First pass regressions from word *n* showed a marginal effect of predictability [$F_1(1,43) = 2.83$, $p = .1$; $F_2(1,47) = 4.77$, $p = .03$]. Readers were more likely to regress from word *n* when it was unpredictable than when it was predictable. No other effects were reliable (all Fs < 1.46, ps $> .23$). This effect complements the gaze duration data for this word and indicates less processing difficulty for predictable than for unpredictable words.

First-pass regressions from word *n* + 1 and into word *n* both showed a highly reliable preview effect [from word *n* + 1: $F_1(1,43) = 37.21$, $p < .001$; $F_2(1,47) = 42.42$, $p < .001$; into word *n*: $F_1(1,43) = 27.41$, $p < .001$; $F_2(1,47) = 31.82$, $p < .001$], with readers more likely to make a regression from word *n* + 1 and make a regression into word *n*, when the preview was incorrect than when it was correct. No other effects were reliable (Fs < 1). Taken together, these data suggest that often when parafoveal word length information was incorrect (and perhaps readers skipped word *n*), immediately after

Table 3
Probability of Skipping Word *n* During First Pass for All Data, Saccades Launched From Three or Fewer Characters (36% of Data), and Saccades Launched From Four or More Characters (64% of Data); Probability of Making First-Pass Regressions From Word *n* and Word *n* + 1 for Cases in Which Word *n* or Word *n* + 1 Was Fixated on First Pass Respectively; Probability of Making Regressions Into Word *n*

		Skip Word *n*						First-Pass Regressions From				Regressions Into Word *n*	
Word		All		≤3		≥4		Word *n*		Word *n* + 1			
Length	Context	*p*	*SD*	*p*	*SD*	*p*	*SD*	*p*	*SD*	*p*	*SD*	*p*	*SD*
Correct	Predictable	.24	.18	.42	.39	.13	.15	.08	.13	.09	.11	.11	.12
	Unpredictable	.16	.16	.28	.34	.09	.13	.09	.12	.09	.12	.11	.12
	Difference	*.08*		*.14*		*.04*		–		–		–	
Incorrect	Predictable	.37	.22	.58	.38	.25	.23	.08	.12	.22	.21	.21	.18
	Unpredictable	.33	.17	.55	.33	.21	.19	.13	.17	.24	.18	.24	.18
	Difference	*.04*		*.03*		*.04*		–		–		–	

Note—All, all of the data. Standard deviations are calculated across the probabilities for each participant.

fixating word $n + 1$ they made a regression to directly fixate word n.

DISCUSSION

The results show that the type of eye-movement measure (when or where the eyes move) and the quality of the parafoveal preview (near or far launch site) determine whether predictability effects are modulated by parafoveal word length information. The fixation time data show that for correct word length preview, contextual constraint immediately influences reading times, but when the word length preview is incorrect there is no effect of predictability on reading times for word n.

The numerical patterns obtained for all the word skipping data and those data for saccades launched from three or fewer characters away from word n are in line with the fixation time data. Both data sets showed that, numerically, more skipping occurred for predictable than for unpredictable words for correct as compared with incorrect parafoveal word length previews. Taken together, the fixation time data and the word skipping data, particularly for near launch sites, indicate that parafoveal word length preview information clearly influenced whether or not there was a predictability effect. These data suggest that word length preview information can constrain potential lexical candidates to which the parafoveal word may correspond. Since word length does not normally change from fixation to fixation, it provides a highly reliable source of information that may be used during preprocessing of the parafoveal word. Whereas predictability might also be a useful source of constraining information, it is probabilistic, not categorical. Consequently, it is perhaps not surprising that no predictability effect occurred when the parafoveal word length information was inconsistent with contextual cues to potential candidate words.

These results can be interpreted in the context of an interactive threshold logogen type of framework (Balota et al., 1985; McClelland & O'Regan, 1981) in which there is greater parafoveal preview benefit when logogen activation for the parafoveal word is also facilitated by contextual constraint. The fixation time measures on word n show an interaction such that the benefit derived from a correct preview, compared with an incorrect preview, is greater when the word is predictable than when it is unpredictable. A similar interactive pattern holds for the probability of skipping word n for saccades launched from near launch sites. An alternative explanation of these effects is that the spaces between words may facilitate parafoveal lexical processing—for example, by reducing visual interference between letters.

Although the basic pattern of effects that we obtained is quite clear, it is worth noting that the skipping data for far launch sites did not show the interactive pattern of effects described above. Instead, skipping data for far launch sites only showed main effects of predictability and word length preview.[6] It is likely that these data reflect readers' tendencies to target saccades from distant launch sites farther into a parafoveal letter string on the basis of predictable orthographic information at the beginning of that string, regardless of word length.

The present results are not consistent with the findings of Inhoff et al. (2003), who showed independent effects of parafoveal orthography and word length on preview benefits. The different effects obtained here, as compared with those of Inhoff et al. (2003), may be due to differences in experimental manipulations. We used sentence contexts that induced a strong expectation for a particular lexical candidate. Also, for our parafoveal word length manipulation we added a letter between words n and $n + 1$ to produce a 10-letter parafoveal preview string. Thus, prior to fixating word n, readers had a strong contextual cue concerning the identity of the target word (via appropriate parafoveal orthographic information and parafoveal word length).

By contrast, in the Inhoff et al. (2003) study, parafoveal word length was manipulated by deleting the fourth letter of a word (and replacement of this upon fixation). Also, orthographic previews were either consistent or inconsistent with the target word. Thus, in their study, prior to fixation, readers had two, not three, sources of information to constrain potential lexical candidates, and those sources were only available from nonfoveal locations. In addition, in their study the target word was ultimately a 5- to 10-letter unpredictable word, whereas in the present study it was a 4-letter predictable word. Thus, perhaps the interactive effects in the present study occurred because the reader had contextual cues in addition to nonfoveal orthographic and word length cues to constrain the selection of potential lexical candidates for a short parafoveal word.

It is also worth considering the present findings in relation to those obtained by Drieghe et al. (2004), who used contexts that induced an expectation for either a two- or a four-letter target word, and these either were or were not consistent with this expectation. Drieghe et al. showed that expected word length does not influence the probability of word skipping. However, in Drieghe et al.'s experiment, although the critical words had the expected word length, orthographic preview information was not expected. And, unlike the present study, in the Drieghe et al. experiment readers had only two sources of constraint over potential lexical candidates: sentential context and parafoveal word length. Again, perhaps the interactive effects observed in the present study occurred due to the availability of the additional constraint provided by parafoveal orthography. Furthermore, the primary focus for Drieghe et al.'s study was the word skipping data, whereas the most robust effects obtained in the present study were for the gaze duration data (measures for which in the Drieghe et al. study no meaningful comparisons were possible since target words were always different lengths in the critical conditions and were often so short as to be infrequently fixated). Thus, there appear to be principled reasons why the effects obtained in the present study differ in nature from those obtained in both the Inhoff et al. (2003) and the Drieghe et al. studies.

To summarize, we have shown that word predictability and parafoveal word length information exert an interactive influence on first-pass reading times and word skipping, particularly when saccades are targeted from locations near a critical string. The present data suggest that these two variables help to constrain potential lexical candidates for the upcoming word and that this in turn can influence decisions concerning both when and where to move the eyes.

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NOTES

1. Importantly, the sources of constraint on the identity of the parafoveal word prior to its fixation are qualitatively different in the Inhoff et al. (2003) study, the Drieghe et al. (2004) study, and the present study. In the Inhoff et al. (2003) study, all sources of constraint on the identity of the parafoveal word were exclusively available from the parafovea. Furthermore, because Inhoff et al. (2003) did not manipulate context to constrain the identity of the parafoveal word, the particular parafoveal orthographic information was not expected. Thus, such manipulations might not represent the strongest sources of constraint on the identity of the parafoveal word, and this in turn may have been why Inhoff et al. (2003) failed to obtain interactive effects. Similarly, in the Drieghe et al. study, orthographic information from the parafoveal word was inconsistent with that of the word that was expected on the basis of context. Again, this manipulation could have worked against the possibility of obtaining interactive effects. We will consider these questions in more detail in the Discussion section.

2. There were also no differences in type frequency [$t(47) = 1.16$, $p = .25$] or token frequency [$t(47) = 1.49$, $p = .14$] of the initial trigrams between predictable (type: $M = 51$, $SD = 66$; token: $M = 767$, $SD = 847$) and unpredictable (type: $M = 64$, $SD = 71$; token: $M = 1{,}023$, $SD = 1{,}128$) conditions.

3. Prior to the analysis of 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 the effects.

4. For the interaction between predictability, word length, and launch site, and for the analysis of saccades launched from near launch sites, the analyses of participants were based on 38 participants and the analyses of items were based on 44 items because not all participants and items launched saccades from near launch sites in all of the conditions. The lack of reliable items effects for these analyses is probably due to the fact that these participants only skipped word *n* on some of the trials, and therefore the proportion of trials under consideration is small.

5. Similar analyses based on launch site distance were also conducted on the reading time measures. Importantly, the three-way interaction between launch site, preview, and predictability was not significant by either participants or items (Fs < 1.22). Therefore, we will not discuss fixation times separated by launch site.

6. It is possible that the predictability of word-initial orthography influences word skipping, regardless of parafoveal word length for near launch sites as well as far ones. Such an interpretation is consistent with the main effect of predictability on word skipping shown for all of the data and the numerical (3%–4%) effect of predictability for both near and far launch site data.

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