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SHORT REPORT

Influences on and consequences of parafoveal preview in reading

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Abstract

During reading, information is extracted from upcoming words to the right of the currently fixated word, which facilitates recognition of those words when they are later fixated. According to the foveal load hypothesis (Henderson & Ferreira, 1990), this *parafoveal preview benefit* depends on how difficult the currently fixated word is to recognize. Furthermore, there is evidence that the influence of lexical variables (frequency and predictability) on word processing changes when no preview of that word is available. The present study reports two moving-window experiments in which the upcoming word to the right of fixation was either included in or excluded from the window. Through this manipulation, accurate parafoveal information was either available or not for each word in the paragraph. Two critical interactions between preview condition and lexical variables were observed. First, the word frequency at word *N* was found to be the primary influence on the amount of preview benefit obtained at word *N*+1, consistent with the foveal load hypothesis. Second, denial of preview eliminated the word predictability effect. These findings have implications for models of eye movement control in reading.

Keywords Reading · Eye movements · Reading · Parafoveal preview · Predictability · Frequency

When we read, we can extract information about words to the right of the word we are currently looking at. This is referred to as *parafoveal preview*. Studies using the gaze-contingent display change paradigm (Rayner, 1975), in which an unrelated word or letter string is presented in the parafovea but is changed to the target word once the eyes cross an invisible boundary, have shown that when parafoveal preview is available, reading is faster and more efficient (for a review, see Schotter, Angele, & Rayner, 2012).

According to the foveal load hypothesis (Henderson & Ferreira, 1990), increased processing difficulty at the currently fixated word (word *N*) reduces the amount of information extracted from the upcoming word (word *N*+1). Henderson and Ferreira (Exp. 1) manipulated word frequency, with low-frequency words creating more foveal processing difficulty than high-frequency words, and thus reducing parafoveal preview. Subsequent studies supported this finding that word frequency influences parafoveal processing (Kennison & Clifton, 1995; Schroyens, Vitu, Brysbaert, & d'Ydewalle, 1999; White, Rayner, & Liversedge, 2005). Furthermore, there is evidence that semantic and syntactic processing of the current word may also influence parafoveal preview of the next word (Henderson & Ferreira, 1990; Payne, Stites, & Federmeier, 2016).

Not all foveal loads are created equal; some types of processing difficulty do not influence parafoveal preview. Reingold and Rayner (2006) showed that manipulations that exclusively influence earlier stages of foveal word processing (e.g., making letters faint) have minimal impact on processing of the next word, whereas other manipulations (e.g., letter case alternations) do influence the processing of the next word (see also Angele, Slattery, & Rayner, 2016; Reingold, Reichle, Glaholt, & Sheridan, 2012). Together, these studies suggest that some foveal word properties will influence processing of the subsequent word, but others will not. However, not all studies have supported the foveal load hypothesis (Drieghe, Fitzsimmons, & Liversedge, 2017; Drieghe, Rayner, & Pollatsek, 2005; Marx, Hawelka, Schuster, & Hutzler, 2017), and most studies have focused on word frequency to the exclusion of other variables (Payne et al., 2016), making further exploration and refinement of the foveal load hypothesis important.

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When parafoveal processing is disrupted, the words for which preview was unavailable are processed differently than normal once they are fixated. For example, the influence of word frequency on reading is pervasive (Rayner, 2009), but this frequency effect is influenced by parafoveal preview availability. Reingold et al. (2012) found that the onset of the word frequency effect was delayed when preview was unavailable. Word predictability is also a significant influence on reading (Luke & Christianson, 2016; Staub, 2015), but this effect, too, changes when preview is unavailable. Recently, Staub and Goddard (in press) showed that the word predictability effect disappears when parafoveal preview is denied. In contrast, frequency effects remained. In sum, when parafoveal preview is denied, word frequency should have a delayed effect in the absence of preview, and the effect of word predictability should disappear. These effects need to be replicated before they can be incorporated into models of eye-movement control in reading.

The present experiments

The present study explores parafoveal processing in reading. In most previous studies of parafoveal processing, the availability of preview was manipulated for a single word in a sentence. The present study is novel in two important ways. First, the stimuli come from a corpus of paragraphs that have been normed for predictability (Luke & Christianson, 2016, 2018). Also, preview was manipulated for every word in the paragraph; participants either had a preview of each upcoming word in the paragraph or they did not. This manipulation made it possible to address two significant questions. First, what are the influences on parafoveal preview? In other words, which lexical properties actually create foveal load that reduces the preview benefit? It was predicted that frequency (Henderson & Ferreira, 1990) and possibly predictability would influence preview benefit. Second, what are the consequences of denial of preview? In other words, how do the influences of different lexical properties on word reading times change when a preview of that word was not available versus when it was available? It was expected that the predictability effect would be eliminated when preview was unavailable (Staub & Goddard, in press). The word frequency effect might also be weaker or absent in first fixation durations when preview is unavailable, which would be consistent with the findings of Reingold et al. (2012).

Two experiments are reported. Experiment 2 was a replication of Experiment 1 with different participants and an overlapping but more restricted stimulus set, so these two experiments are reported together. In both experiments, participants read paragraphs with a moving window around the currently fixated word. This moving window was either restricted to the currently fixated word *N* (no preview condition) or also included word *N*+1 (preview condition).

Method

Participants Fifty-two participants from Brigham Young University completed Experiment 1. Fifty-five different participants completed Experiment 2. Four of the participants were excluded from Experiment 1, and seven from Experiment 2, due to calibration or tracking issues, leaving 48 total in each experiment. All participants were native English speakers with 20/20 corrected or uncorrected vision.

Materials Forty-eight short texts (40–60 words) were taken from the Provo Corpus (Luke & Christianson, 2016, 2018). Word frequencies were taken from the SUBTLEX frequency database (Brysbaert & New, 2009). For each word in each paragraph, except the first word, cloze probabilities were obtained as described in Luke and Christianson (2016, 2018). In Experiment 1, four words from each paragraph contained a letter transposition manipulation that was part of another experiment. In Experiment 2, this manipulation was retained, and an additional four words from each paragraph contained a frequency manipulation that was part of another experiment. These words were excluded from the analysis.

Apparatus Eye movements were recorded via an SR Research EyeLink 1000+ eyetracker (spatial resolution of 0.01°) sampling at 1000 Hz. Participants sat 60 cm away from a 24-in. LCD monitor with display resolution set to 1,600 × 900 (refresh rate 120 Hz). Text was displayed in Courier New 15-point font, so that ~ 3 characters subtended 1° of visual angle. Head movements were minimized with a chin/head rest. Although viewing was binocular, eye movements were recorded from the right eye. The experiment was controlled with the SR Research Experiment Builder software.

Procedure Participants completed a 9-point calibration procedure at the start of an experiment and after every 12 paragraphs. Participants were told that they would be reading short paragraphs on a computer screen while their eye movements were recorded. They were further told that they might encounter misspelled words while reading, and that they should read normally and try to understand what they were reading. After a practice trial, the experiment began. Each trial began with a gaze trigger, a black circle presented in the position of the first character in the text. Once a stable fixation was detected on the gaze trigger, the text was presented.

The text was covered by a moving window, so that participants either were provided a preview of the upcoming word (a single word to the right of fixation) or were not (no words to the right were visible). Two words were always visible to the left of fixation. Words outside this window were replaced by random letter strings of similar shape to the original word. Only the current line was visible; words on the lines above and below were also replaced by random letter strings. The two different preview conditions were counterbalanced across different lists, so that equal numbers of paragraphs were read in each condition by every participant, and the different versions of each paragraph were seen equal numbers of times in each condition across participants.

Each participant read the text, pressing a button when finished. A comprehension question appeared, which participants answered by pressing buttons. Then a new gaze trigger appeared, and the next trial began. The order of text presentation was randomized for each participant. Participants were offered a break before each calibration procedure. The session lasted 30 min.

Results

Prior to the data analysis, words < 5 and > 9 letters long were excluded, as were function words, words without frequency values or cloze probabilities, words that were skipped in first-pass reading, and words fixated after the previous word had been skipped in first-pass reading. The final Experiment 1 data set consisted of 12,643 unique data points (word tokens), representing 483 separate words. The final Experiment 2 data set consisted of 8,917 unique data points (word tokens), representing 339 separate words. Comprehension question response accuracies were 84% (Exp. 1) and 79% (Exp. 2).

Table 1 shows descriptive statistics for standard reading variables. Fixations less that 80 ms and greater than 800 ms were excluded from the data prior to computation of these descriptive statistics (~ 3% of fixations). Of these variables, first fixation duration, gaze duration, and total time were analyzed. The data were analyzed using linear mixed-effects models (Bates, Mächler, Bolker, & Walker, 2015) in R (R Core Team, 2015). Dependent variables were log-transformed prior to analysis. The fixed effects (predictors) included preview condition (preview vs. no preview), as well as the frequency, predictability, and length of the current word and of the previous word in the text (previous frequency, previous predictability, and previous length). All these lexical variables were centered and log-transformed (except length) prior to analysis. Interactions between preview condition and all six lexical variables were tested. Interactions and fixed effects were retained in the final models only if significant. Initially, random effects in all models included by-participant, by-word intercepts and random by-participant slopes for all predictors and interactions, in order to avoid Type I errors that could be associated with incomplete random-effects structures (Barr, Levy, Scheepers, & Tily, 2013). The random-effects structures of the final models was simplified in order to allow for model convergence, but no random effect was removed if its removal would change a fixed effect from nonsignificance to significance. The full model structures and outputs for all models can be found in the appendix.

The pattern of results for first fixation duration[1] was the same for both experiments. There were significant effects of preview condition, in which first fixations were longer when preview was denied (both *t*s > 18.18, both *p*s < .0001). The frequencies of both the previous and current words were also significant predictors; as these frequencies went up, first fixation durations went down (both *t*s < – 4.39, both *p*s < .0001). The predictability of the current word was also significant; as predictability went up, first fixation durations went down (both *t*s < – 2.23, both *p*s < .027). Two significant interactions also emerged. First, previous frequency interacted with preview condition, indicating that the influence of the previous word's frequency on processing of the current word was eliminated when preview was denied (both *t*s > 6.82, both *p*s < .0001; see Fig. 1). Second, there was a significant interaction of predictability and preview condition, indicating that the predictability effect went away when preview was denied (both *t*s > 2.43, both *p*s < .018; see Fig. 2). The pattern of results for gaze duration was the same as that for first fixation durations in both experiments, with one addition: The effect of word length was significant in these analyses (both *t*s > 2.4, both *p*s < .017). The pattern of results for total time was the same as that observed for gaze durations in both experiments, except that in Experiment 2 previous word length was significant (t = – 2.38, p = .0018).

Discussion

The present study investigated parafoveal processing in reading, and explored two questions specifically. The first was which lexical properties of word *N* influence the preview obtained from word *N*+1. Only the frequency of word *N* influenced the preview benefit on word *N*+1. In all analyses, this influence was facilitative: When the previous word was more frequent, the current word was read more quickly. However, this influence disappeared when no preview of the previous word was available (see Fig. 1). This finding is consistent with the foveal load hypothesis (Henderson & Ferreira, 1990) and with eye movement models that incorporate foveal load

[1] This same pattern was also observed for single fixation durations.

Table 1 Means (and standard deviations) for reading variables as a function of experiment and preview condition

	Experiment 1		Experiment 2	
	Preview	No Preview	Preview	No Preview
Skipping probability	.08 (.27)	.05 (.23)	.09 (.29)	.08 (.25)
First fixation location (proportion of word)	.479 (.24)	.438 (.22)	.448 (.24)	.395 (.22)
Single fixation duration (ms)	221 (85)	275 (90)	216 (84)	276 (94)
First fixation duration[1] (ms)	219 (86)	258 (94)	214 (85)	261 (97)
Refixation probability	.2 (.4)	.31 (.46)	.21 (.41)	.30 (.46)
Gaze duration[1] (ms)	266 (144)	332 (161)	264 (152)	335 (172)
Regression probability	.15 (.36)	.15 (.36)	.16 (.37)	.15 (.36)
Total time[1] (ms)	384 (286)	476 (343)	385 (295)	481 (395)

[1] Analyzed variable.

(Engbert, Longtin, & Kliegl, 2002; Engbert, Nuthmann, Richter, & Kliegl, 2005; Reichle, Pollatsek, Fisher, & Rayner, 1998; Reichle, Rayner, & Pollatsek, 2003). For example, according to the E-Z Reader model (Reichle et al., 2003), attention is focused on the current word (word *N*) until that word is recognized. Then, if the planned saccade has not yet been executed, attention is shifted to word *N*+1. When word *N* recognition is faster, as it would be when word *N* is more frequent, more time is available to preview word *N*+1, so word *N*+1 is then recognized faster. However, when preview for word *N*+1 is not available, recognizing word *N* faster produces no benefit on word *N*+1 recognition. This is exactly what was observed in the present experiments.

However, Veldre and Andrews (2018) have recently shown that the interaction of word *N* frequency and the word *N*+1 preview benefit only appears when the parafoveal mask is an orthographically illegal nonword, as it has been in many studies, including the present one. They suggest that this interaction thus does not reflect the influence of foveal load on parafoveal processing, but rather reflects a preview cost arising from the parafoveal mask. The present results are consistent with this interpretation, as well; a spillover frequency effect was observed when preview was available, but not when it was denied (see Fig. 1). Because the foveal load hypothesis has been incorporated into models of reading, it is imperative that more research be conducted to define when, and if, foveal load does indeed influence parafoveal processing.

It is noteworthy that the predictability of the previous word did not affect preview, contrary to some previous work (Payne et al., 2016). This finding suggests that word *N* frequency is indeed the primary determinant of word *N*+1 preview. However, it could be that predictability does have an influence on preview in normal reading, but the experimental manipulation eliminated this effect (see Fig. 2), so that the influence of predictability on parafoveal processing was not observed in the present study. More research will be needed to explore this possibility.

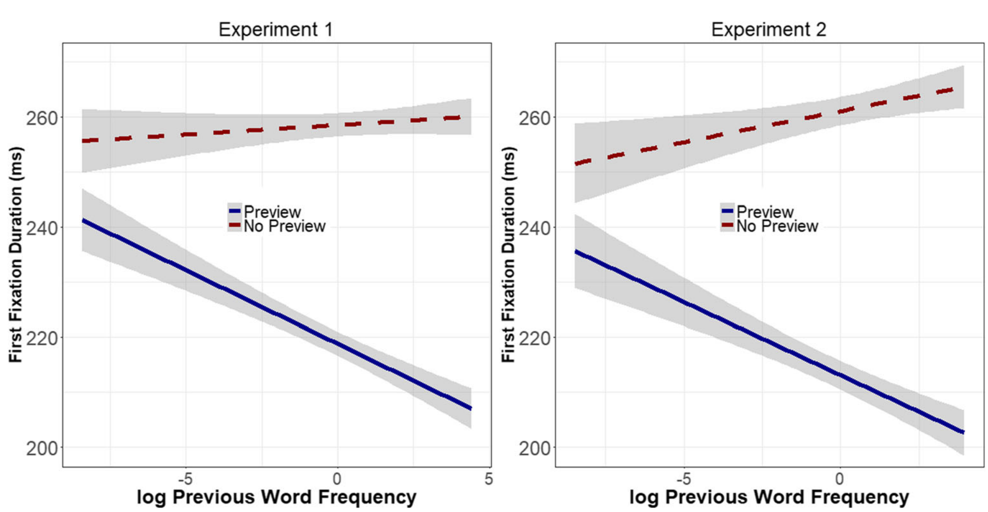

Fig. 1 Interactions of previous word frequency and preview condition in Experiments 1 (left) and 2 (right). Gray bands represent 95% confidence intervals.

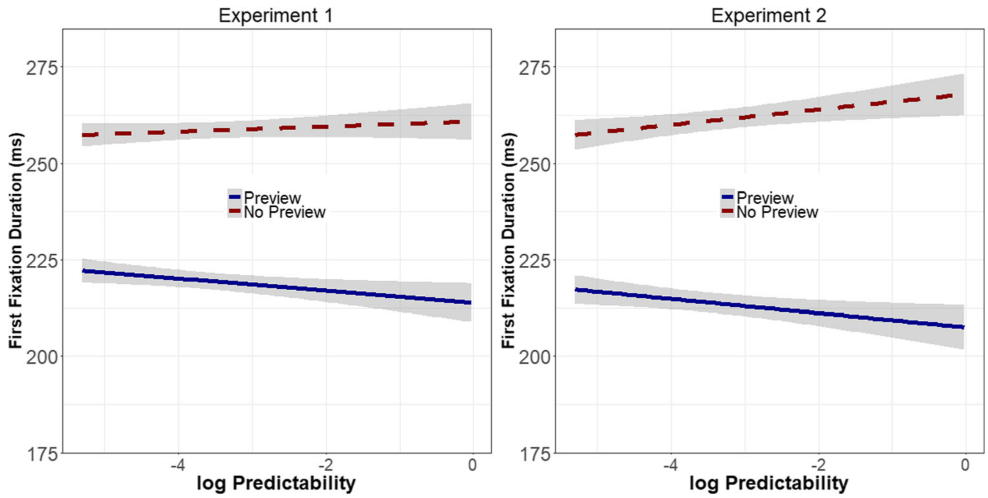

Fig. 2 Interactions of word predictability and preview condition in Experiments 1 (left) and 2 (right). Gray bands represent 95% confidence intervals.

The second question addressed in the present study was how denial of preview influences processing of the word once it is fixated. The denial of preview had no discernable influence on frequency effects at the fixated word (i.e., frequency and preview condition did not interact). This is in contrast to the findings of Reingold et al. (2012), who observed that denial of preview delayed the word frequency effect. It is possible that the nature of the present manipulation, in which preview was denied for all words, and not just for one word in the sentence, negated this delay. It is also possible that the frequency effect was indeed somewhat delayed, but not enough to eliminate or reduce the frequency effect in first fixation durations. The word predictability effect, on the other hand, was strongly affected by the preview manipulation; without preview, there was no predictability effect. This finding is highly consistent with the findings of Staub and Goddard (in press). As an explanation for their findings, Staub and Goddard suggested that predictability effects arise when contextual information is used to assist in orthographic processing. However, when no (correct) preview of the word is available, orthographic processing occurs exclusively in the fovea, and the bottom-up input is so clear that contextual support is not needed. Thus, predictability effects disappear. If this is the case, this also has implications for models of reading. For example, E-Z Reader assumes that frequency and predictability affect lexical processing at the same stages. The present data, along with the data of Staub and Goddard, suggest otherwise. Clearly, more research is needed on the timing of the predictability effect in reading.

A few limitations of the present study should be mentioned. First, in normal reading it is sometimes possible to obtain preview from word *N*+2 (Vasilev & Angele, 2017). This was not possible in the present study, so that even in the preview condition some normally available parafoveal information was denied. Second, in the no-preview condition, the parafoveal word was replaced by a nonword. There is some evidence that different types of parafoveal masks have different effects on the preview benefits observed (Vasilev & Angele, 2017; Veldre & Andrews, 2018), so that future work should employ different types of masks. However, Staub and Goddard (in press) specifically manipulated parafoveal mask type and found that the predictability effect disappeared regardless of mask type. Finally, because here preview was manipulated for each word in the paragraph, participants were more likely to become aware of the manipulation. In other boundary-change studies, this awareness has influenced the results (Angele et al., 2016). However, in these studies preview was manipulated for only one word in each sentence, making the change both more salient and more interesting. Manipulating preview for all words in the paragraph reduces the bottom-up and top-down attraction of each individual manipulation (see Luke & Christianson, 2012, 2013).

Conclusion

The present study investigated parafoveal preview in reading using a moving window. Word frequency was the primary influence on the amount of preview obtained from upcoming words, consistent with the foveal load hypothesis. However, preview costs arising from orthographically illegal previews could account for this effect, as well. Furthermore, denial of preview eliminated the predictability effect, suggesting that word predictability primarily influences early orthographic stages of processing.

Appendix: Full model output for analyses reported in "influences on and consequences of parafoveal preview in reading"

Table 2 Analyses of first fixation durations

Fixed Effect	*b*	*SE*	*t* Value	*p* Value
Experiment 1 Model: log(FIRST_FIXATION_DURATION) ~ 1 + Preview × Previous Frequency + Preview × Predictability + Frequency + (1 + Preview + Previous Frequency + Preview × Predictability | Participant)				
(Intercept)	5.34	0.015	350.93	<.0001
Preview Condition = No Preview	0.23	0.011	21.23	<.0001
Previous Frequency	– 0.014	0.0016	– 8.91	<.0001
Predictability	– 0.011	0.003	– 3.58	.00078
Frequency	– 0.014	0.0014	– 9.81	<.0001
Preview Condition = No Preview × Previous Frequency	0.017	0.0019	9.041	<.0001
Preview Condition = No Preview × Predictability	0.0097	0.004	2.43	.018
Experiment 2 Model: log(FIRST_FIXATION_DURATION) ~ 1 + Preview × Previous Frequency + Preview × Predictability + Frequency + (1 + Preview × Previous Frequency + Preview × Predictability | Participant) + (1 | Item)				
(Intercept)	5.3	0.016	339.19	<.0001
Preview Condition = No Preview	0.21	0.012	18.18	<.0001
Previous Frequency	– 0.011	0.0023	– 4.79	<.0001
Frequency	– 0.01	0.0024	– 4.39	<.0001
Predictability	– 0.0089	0.0040	– 2.23	.027
Preview Condition = No Preview × Previous Frequency	0.015	0.0021	6.82	<.0001
Preview Condition = No Preview × Predictability	0.02	0.0039	5.027	<.0001

Table 3 Analyses of gaze durations

Fixed Effect	*b*	*SE*	*t* Value	*p* Value
Experiment 1 Model: log(GAZE_DURATION) ~ 1 + Preview × Previous Frequency + Preview × Predictability + Frequency + Length + (1 + Preview × Previous Frequency + Preview × Predictability | Participant) + (1 | Item)				
(Intercept)	5.47	0.019	282.47	<.0001
Preview Condition = No Preview	0.25	0.014	18.3	<.0001
Previous Frequency	– 0.014	0.0025	– 5.5	<.0001
Frequency	– 0.02	0.0029	– 6.82	<.0001
Predictability	– 0.012	0.0044	– 2.72	.0069
Length	0.012	0.0048	2.4	.017
Preview Condition = No Preview × Previous Frequency	0.019	0.0023	8.21	<.0001
Preview Condition = No Preview × Predictability	0.01	0.004	2.55	.012
Experiment 2 Model: log(GAZE_DURATION) ~ 1 + Preview × Previous Frequency + Preview × Predictability + Frequency + Length + (1 + Preview × Previous Frequency + Preview × Predictability | Participant) + (1 | Item)				
(Intercept)	5.44	0.021	257.78	<.0001
Preview Condition = No Preview	0.28	0.014	19.42	<.0001
Previous Frequency	– 0.017	0.0028	– 6.18	<.0001
Frequency	– 0.024	0.0034	– 6.97	<.0001
Predictability	– 0.025	0.0059	– 4.15	<.0001
Length	0.016	0.0056	2.83	.0049
Preview Condition = No Preview × Previous Frequency	0.022	0.0025	8.6	<.0001
Preview Condition = No Preview × Predictability	0.021	0.0061	3.37	.0015

Table 4 Analyses of total times

Fixed Effect	*b*	*SE*	*t* Value	*p* Value
Experiment 1 Model: log(TOTAL_TIME) ~ 1 + Preview × Previous Frequency + Preview × Predictability + Frequency + Length + (1 + Preview × Previous Frequency + Preview × Predictability | Participant)				
(Intercept)	5.74	0.026	221.91	<.0001
Preview Condition = No Preview	0.25	0.018	13.99	<.0001
Previous Frequency	– 0.013	0.0025	– 5.24	<.0001
Frequency	– 0.016	0.0022	– 7.14	<.0001
Predictability	– 0.04	0.0052	– 7.56	<.0001
Length	0.021	0.0036	5.8	<.0001
Preview Condition = No Preview × Previous Frequency	0.014	0.0030	4.61	<.0001
Preview Condition = No Preview × Predictability	0.014	0.0059	2.38	.02
Experiment 2 Model: log(TOTAL_TIME) ~ 1 + Preview × Previous Frequency + Previous Length + Preview × Predictability + Frequency + Length + (1 + Preview × Previous Frequency + Preview × Predictability | Participant) + (1 | Item)				
(Intercept)	5.71	0.033	172.29	<.0001
Preview Condition = No Preview	0.27	0.018	14.63	<.0001
Previous Frequency	– 0.025	0.0061	– 4.015	<.0001
Previous Length	– 0.019	0.008	– 2.38	.0018
Frequency	– 0.024	0.005	– 4.83	<.0001
Predictability	– 0.035	0.0078	– 4.5	<.0001
Length	0.026	0.0085	3.046	.0025
Preview Condition = No Preview × Previous Frequency	0.016	0.0034	4.894	<.0001
Preview Condition = No Preview × Predictability	0.022	0.0073	3.052	.0038

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