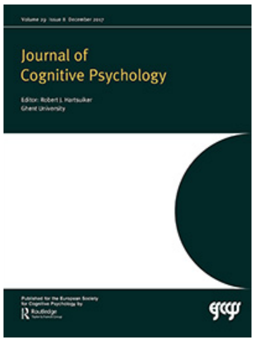

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Predictability effects during reading in the absence of parafoveal preview

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ABSTRACT
The predictability of upcoming words facilitates both spoken and written language comprehension. One interesting difference between these language modalities is that readers' routinely have access to upcoming words in parafoveal vision while listeners must wait for each fleeting word from a speaker. Despite readers' potential glimpse into the future, it is not clear if and how this bottom-up information aids top-down prediction. The current study manipulated the predictability of target words and their location on a line of text. Targets were located in the middle of the line (preview available) or as the first word on a new line (preview unavailable). This represents an innovative method for manipulating parafoveal preview which utilises return sweeps to deny access to parafoveal preview of target words without the use of invalid previews. The study is the first to demonstrate gaze duration word predictability effects in the absence of parafoveal preview.

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Language prediction; reading; parafoveal preview; eye movements; return sweeps

Introduction

When we listen to a speaker or read a text, there is strong evidence that the predictability of upcoming words influences our speed and accuracy in identifying them (for reviews see Kuperberg & Jaeger, 2016; Staub, 2015). For instance, one important task during spoken language comprehension is understanding when to take your turn in a conversation, which has been shown to rely on prediction (Garrod & Pickering, 2015; Magyari & de Rutier, 2012). There are also facilitative effects of word predictability within written language comprehension. For instance, visual word recognition processes are influenced by sentence context; words that are predictable from the beginning sentence context are processed faster than words presented in a neutral context. However, there are some important differences between spoken and written language comprehension. When we listen to a speaker, we must wait for them to utter each new word. Additionally, the auditory encoding of words is under time pressure. When reading, upcoming words are routinely available in parafoveal vision (see Schotter, Angele, & Rayner, 2012 for a review), and the words remain available on the page for re-inspection. Despite this potential glimpse into the future provided to readers, we do not yet understand if and how the bottom up information from words in the parafovea is used to aid top-down predictive processing. This is the focus of the current research.

Eye movement studies of reading have found that words that are predictable from a prior context receive shorter fixations and are skipped more than words that are unpredictable (Altarriba, Kroll, Sholl, & Rayner, 1996; Balota, Pollatsek, & Rayner, 1985; Drieghe, Rayner, & Pollatsek, 2005; Gollan et al., 2011; Rayner, Slattery, Drieghe, & Liversedge, 2011; Rayner & Well, 1996; Slattery & Yates, 2017). These empirical findings are critical benchmarks for computational models of eye movements during reading. As such, word predictability is an important input variable for both the EZ Reader (Reichle, Pollatsek, Fisher, & Rayner, 1998; Reichle, Rayner, & Pollatsek, 2003; Reichle & Sheridan, 2015) and SWIFT (Engbert, Nuthmann, Richter, & Kliegl, 2005; Laubrock, Kliegl, & Engbert, 2006; Richter, Engbert, & Kliegl, 2006) models of eye movements during reading. Both models use word predictabilities determined by the cloze task which involves

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participants guessing upcoming words of a text, given the preceding context, with a word's cloze probability being the proportion of responses which match the word (Taylor, 1953). While there are important differences between these models, both are capable of simulating the increased skipping rates and shorter gaze durations associated with high predictable words. Additionally, both of these models assume that a word's predictability can influence its processing prior to the word receiving a direct fixation.

A recent study by Rayner et al. (2011), established that predictability information can be used to modulate word skipping behaviour in the presence of impoverished bottom up information. They had participants read sentences with target words which varied from 4 to 12 letters in length. Additionally, each target appeared in either a high (0.72) or low (0.15) cloze probability sentence frame. Unsurprisingly, predictable words received shorter gaze durations than unpredictable ones, and short words received shorter gaze durations than long words; however, the interaction between length and predictability failed to reach significance. Crucially, predictable targets were more likely to be skipped than unpredictable targets, regardless of whether the target was short (36% vs. 28%), medium (22% vs. 18%), or long (18% vs. 10%). The skipping of long words, which extended beyond the word identification span, suggests that the oculomotor system can initiate a skip based on partial parafoveal orthographic information about the upcoming word which is aided by predictability.

While word predictability information can be useful when bottom up parafoveal information about upcoming words is impoverished or incomplete, there is a lack of evidence that predictability benefits can be obtained when parafoveal previews are not at least visually similar to the predictable target word (see Staub, 2015, pp. 321–322 for a discussion). Eye movement studies of reading that want to examine parafoveal preview before now always used the boundary change technique (Rayner, 1975). The technique involves placing an invisible boundary within the text just prior to a target word. When a reader's eye is fixating to the left of this boundary, various previews can be displayed to the right of the boundary. Then when the reader saccades across the boundary these previews are changed into the target. Balota et al. (1985) used this technique to manipulate the parafoveal preview of a high- or low-cloze probability target word. They found that the facilitative effects associated with highly predictable words (i.e. high skipping rates and short fixation durations) were only apparent when the preview was identical or visually similar to the target. Similar conclusions can be drawn from other studies using the boundary paradigm to investigate predictability and preview (Juhasz, White, Liversedge, & Rayner, 2008; White, Rayner, & Liversedge, 2005). More recently, Schotter, Lee, Reiderman, and Rayner (2015) reported that predictability effects were absent under conditions with invalid previews of an unrelated word. However, they did report predictability effects with invalid previews that were synonyms of the predictable target word. We will return to this latter effect of synonym previews shortly. Based on this pattern of effects, Staub (2015) proposed that predictability may influence early processing of a word by pre-activating its visual features and letters. Therefore, in the absence of these visual features in the parafovea, no predictability effect should be observed.

We propose an alternative account; that the elimination of predictability effects in past preview studies derives from the presence of invalid previews rather than from the absence of valid previews. It is now well established that there are various costs associated with processing invalid previews (Angele, Slattery, & Rayner, 2016; Gagl, Hawelka, Richlan, Schuster, & Hutzler, 2014; Marx, Hawelka, Schuster, & Hutzler, 2015; Slattery, Angele, & Rayner, 2011; Vasilev, Slattery, Kirkby, & Angele, in press; White et al., 2005). We assume Levy's (2008) parsing model (or one similar) where readers maintain multiple hypotheses about the underlying meaning of a sentence which are updated according to Bayes' rule as each new word is encountered. When a new word is encountered that was unexpected given the readers' prior beliefs, it results in a greater amount of belief updating relative to an expected word. Furthermore, processing times for a word are a function of the amount of belief updating required. We propose that in reading belief updating can begin as soon as attention is directed to them in the parafovea. Since these invalid previews nearly always represent highly unexpected input, beliefs would begin to shift away from those hypotheses where the target word is expected—essentially removing its predictability. However, in the case of the synonym previews used in Schotter et al. (2015), the relationship between the preview and target is so close that encountering the synonym would not be expected to require belief updating that moves expectation away from the predictable target.

Method

We tested our hypothesis with an innovative yet simple method for manipulating parafoveal preview to be either present or absent that relies not on the boundary change technique, but on return sweeps. The return sweep saccade brings a reader's fixation from the end of one line of text to the start of the next and is a common eye movement during normal reading (Hofmeister, Heller, & Radach, 1999; Parker & Slattery, 2017). In our preview present conditions, the target word occurred in the middle of a line of text and therefore this word was available for parafoveal preview when fixating the prior few words in the sentence. In our preview absent condition, the target word occurred as the first word on a new line and was therefore unavailable for preview when fixating the prior few words in the sentence. If valid parafoveal preview is required for predictability effects to manifest, then we should fail to find predictability effects in our preview absent condition. However, if predictability effects arise due to belief updating once information about the next word is available, then predictability effects should still be found even if previews are absent.

Due to the nature of our manipulation, it is important to consider past research findings on line position effects and return sweeps. For instance, return sweeps require extensive planning (Abrams & Zuber, 1972) but are subject to saccadic range error just like normal left to right reading saccades. Becker (1972) reported that approximately 10% of return sweeps landed short of their intended target. These undershoot saccades often result in short "undersweep" fixations which are then followed by a corrective saccade toward the start of the line (Hofmeister et al., 1999). While undersweep fixations tend to be shorter than typical reading fixations (Heller, 1982), fixations that accurately reach their target following a return sweep tend to be longer than typical reading fixations (Kuperman, Dambacher, Nuthmann, & Kliegl, 2010). Explanations for the increased duration of these line initial fixations include: Extra time for establishing a mode of grouped or strategic saccade programming over the line (Kuperman et al., 2010; Rayner, 1978), and vergence movements with a period of reorientation (Stern, 1981). We would add to these explanations the possibility that at least some of this effect is due to the absence of parafoveal preview for line initial words during the fixation prior to the return sweep, as it is widely accepted that accurate parafoveal preview of an upcoming word reduces fixation time on that word (Schotter et al., 2012; Rayner, 1998, 2009). So, we can expect to find longer fixation duration measures for line initial targets than for line central targets. However, our chief question remains how the lack of parafoveal preview for the line initial targets will influence the effect of word predictability.

Participants

Fifty-three participants from the Bournemouth University community participated in the study. All had normal or corrected-to-normal vision, were native English speakers, naive to the purpose of the experiment, and indicated that they had no history of reading impairment. Five participants were excluded due to blinks and tracking loss. This left 48 participants (42 female), with a mean age of 26.48 years ($SD = 14.83$).

Apparatus

Gaze positions were sampled at 1000 Hz using an SR research EyeLink 1000 system. Although reading was binocular, monocular data was recorded. For 44 participants, eye movements were recorded for the right eye for the remaining 4 participants the left eye was recorded.[1] Stimuli were presented in a black fixed-width 20-point Consolas font, on a white background, on a BenQ XL2410 T LCD monitor with a 1920, 1080 resolution. Participants were seated 80 cm from the monitor, and 3.57 letters equalled 1° of visual angle. Responses were recorded via a VPixx five button response box.

Materials

The stimuli consisted of 40 passages of text, where 32 were adapted from Rayner et al. (2011) for British English. Each experimental item consisted of two-to-four sentences with either a high- or low-cloze probability target word in the final sentence. Target words were positioned either at the start or

[1]Participant's left eye was tracked only if there was a problem calibrating their right eye due to issues such as glare from glasses.

middle of a line of text, where parafoveal information was absent or present respectively (see Figure 1). This led to a 2 (predictability) by 2 (location) design. Each participant viewed 10 items per experimental condition with items being counterbalanced over participants. The target words varied from 4 to 12 letters in length (mean= 7.85) and had an average log Hyperspace Analogue to Language frequency (Burgess, 1998; Burgess & Livesay, 1998) of 9.01 (range: 5.66–11.62). While there more words prior to the target in the mid-line condition[2], data from a separate Cloze norming study ($n = 51$) confirmed the appropriateness of our stimuli for the current study (see Table 1). A repeated-measures ANOVA, with predictability (2 levels) and location (2 levels) as factors, revealed cloze accuracy was higher in the predictable conditions, $F(1,39) = 976.24$, $\eta_p^2 = .96$, MSE = 19.56, $p < .001$. There was no main effect of arget word position on cloze accuracy, $F(1,39) = .18$, MSE < .01, $\eta_p^2 < .01$, $p > .250$, nor was there an interaction between these two factors, $F(1,39) = .65$, MSE < .01, $\eta_p^2 < .02$, $p > .250$.

Procedure

After providing informed consent and being familiarised with the equipment, participants were seated comfortably in front of the tracker and completed a 9-point calibration procedure. Validation errors greater than 0.4° of visual angle resulted in recalibration. At the start of each trial, a black square (100 by 100 pixels) appeared on the left side of the computer screen, which coincided with the left side of the first letter in the passage. Once a stable fixation was detected within this area, the passage replaced it on the screen. The 40 experimental stimuli and 20 stimuli from a separate experiment were presented in random order and participants were instructed to read silently for comprehension. Comprehension (yes/no) questions appeared after a third of items and required participants to respond by pressing one of two buttons on the response box.

Results

Comprehension rates were high (92%). Trials in which there was a blink or track loss on the target word or during an immediately adjacent fixation were removed prior to analysis. Trials in which there were five or more blinks during passage reading were also removed[3], as were trials in which fixation durations for target words were greater than 800 ms. In total, 3.59% of trials were removed. Fixations shorter than 80 ms, which were within 1 character of a previous or subsequent fixation, were combined with that fixation, all other fixations less than 80 ms were excluded. Additionally, for gaze duration, trials in which the return sweep from the end of the prior line to the beginning of the current line fell short of the first word on the line and were followed by a corrective regression to the target word (undersweeps), were excluded from analysis (27.8% of trials). This exclusion was necessary as fixations which land short of the first word on the line would provide a preview of the target word in the preview absent condition (start of the line). Moreover, undersweeps landing on the target word in the preview available condition (middle of the line) would not have had a valid preview on the prior fixation. In total 465 observations were included for target words at the start of the line (223 predictable) and 850 for target words occurring at the middle of the line (418 predictable)[4].

Two standard eye movement measures (Rayner, 1998, 2009) were examined: gaze duration (the sum of all first-pass fixations on the target word before moving to another word) and skipping probability (the probability that the target word was skipped on first-pass reading), see Table 2. The data were analysed with linear mixed effects models, using the lme4 package (version 1.1-12; Bates et al., 2016) in R (R Development Core Team, 2013). For all models we initially adopted a full random structure, treating both subjects and items as random factors, with random intercepts and slopes (Barr, Levy, Scheepers,

[2]The number of words occurring prior to the target word was 20.5 in the line initial condition and 23.7 in the mid-line condition. While this difference was significant, $t(79) = -14.83$, $p < .001$, $d = .42$, a generalised linear mixed effects model fit to cloze accuracy data, using subjects and items as random factors, revealed that number of words occurring prior to the target did not significantly influence cloze accuracy, $b = 1.09\text{e}{-2}$, $SE = 6.39\text{e}{-3}$, $z = 1.71$.

[3]We originally intended to remove trials where two or more blinks occurred in any sentence. This criterion, based upon single sentence reading experiments, proved too stringent. If implemented, most participants would have had at least 30% data exclusion in at least one experimental condition.

[4]To ensure that predictability did not influence the exclusion of data, we fit a GLMM to all data points prior to data exclusion. This model included fixed effects for preview availability, predictability and their interaction; subjects and items were treated as random factors. While data exclusion was increased at the start of the line, $b = -1.24$, $SE = .331$, $z = -3.75$, neither predictability, $b = .118$, $SE = .451$, $z = .262$, nor its interaction with preview availability, $b = -1.27$, $SE = .906$, $z = -1.40$, influenced data exclusion.

```
Thomas was going to ask Tanya to marry him. He decided they needed to talk about their
relationship before making such a large commitment. (Predictable, start).

Thomas and Tanya required a loan for a house. He decided they needed to talk about their
relationship before making such a large commitment. (Unpredictable, start).

Thomas was thinking about asking Tanya to marry him next month. He decided they needed to
talk about their relationship before making such a large commitment. (Predictable, middle).

Thomas and Tanya required a mortgage to buy their dream home. He decided they needed to
talk about their relationship before making such a large commitment. (Unpredictable,
middle).
```

Figure 1. Example stimuli with the target word "relationship" shown in bold.

& Tily, 2013). However, if models failed to converge, random slopes were pruned accordingly.

Word skipping

To assess target word skipping, we fit two generalised linear mixed effects models to word skipping data using the Glmer function from the lme4 package. We chose to fit a separate model to each preview condition due to the inclusion of launch site data. Launch site is an important variable for predicting word skipping during normal left to right reading (Rayner, 2009). However, as launch sites came from different directions in the two target word locations used to manipulate preview availability, centring launch site across the two conditions would be inappropriate. In the preview available conditions, the launch site was to the left of the target word yielding positive values (mean = 6.53, *SD* = 3.71). However, in the preview unavailable conditions, the launch site was far to the right of the target word yielding mostly large negative values (mean = −73.44, *SD* = 4.88).

In the preview available model, predictability (cloze probability), word length and launch site were used as centred numerical predictors. The interaction between predictability and launch site was also included in the model (Table 3).

For words occurring in the presence of parafoveal information, word skipping increased with increasing predictability. Furthermore, word skipping probability decreased with increasing word length and decreased with increasing launch site. Interestingly, the interaction between predictability and launch site significantly influenced target word skipping. As launch site decreased, the magnitude of the predictability effect decreased until word skipping was at ceiling (Figure 2).

In the preview absent condition, fixed effects were included for predictability, word length and their interaction. A fixed effect of launch site was not included as launch site was always greater than 40 characters away. Such distant launch sites can be taken as verification that parafoveal preview of the target word was not available to readers in this condition. Here a word skip was coded as any trial in which the return sweep landed short of the first word on the line and was not followed by an immediate regression to the target word. Thus, word skipping in this context differs to word skipping in the presence of parafoveal preview (Table 4).

Target word skipping probability in the absence of parafoveal information was not significantly influenced by predictability. However, word skipping was influenced by word length, where shorter words were more likely skipped. The interaction between predictability and word length did not significantly influence skipping probability.

Table 1. Cloze predictabilities for each of the four experimental conditions.

Experimental condition		
Predictability	Target word location	Cloze probability
Predictable	Start	.72
	Middle	.74
Unpredictable	Start	.03
	Middle	.03

Gaze duration

For log transformed gaze duration, the model included fixed effects for preview availability, predictability, and their interaction. Data for 1167 trials were analysed using the lmer function from lme4 package. The successfully converged model included the full random effects structure for subjects and items (Table 5).

When preview was present, gaze durations were 79 ms shorter than when preview was absent. There was also a significant effect of predictability, where gaze duration decreased with increasing word

Table 2 . Reading eye movement measures.

	Start of the line		Middle of the line	
	Predictable	Unpredictable	Predictable	Unpredictable
Gaze duration	289 (49.1)	332 (118.6)	232 (40.2)	233 (52.4)
Skipping rate	9 (15.7)	9 (14.3)	22 (17.8)	18 (14.3)

Note: Gaze durations are in milliseconds and skipping rates are in percentages. Standard deviations appear in parentheses.

Table 3. GLMM results for target word skipping in the presence of parafoveal preview.

	Skipping likelihood		
	Estimate	Standard error	*z* Value
Predictor (intercept)	−2.56	.301	**−8.42**
Cloze probability	1.15	.362	**3.16**
Word length	−.185	7.75e−2	**−2.38**
Launch site	−.407	4.78e−2	**−8.51**
Cloze probability × launch site	.246	.111	**2.20**

Note: Significant *z* values ($|z| \geq 1.96$) are printed in bold.

predictability. The numerical interaction showing larger predictability effects at the start of the line was not significant (Figure 3).

Discussion

The findings from the current study are clear: word predictability effects can be obtained in the

Table 4. GLMM results for target word skipping in the absence of parafoveal preview.

	Skipping likelihood		
	Estimate	Standard error	*z* Value
Predictor (intercept)	−11.37	4.22	**−2.70**
Cloze probability	4.06	2.30	1.76
Word length	−3.04	1.05	**−2.91**
Cloze probability × word length	.888	.742	1.20

Note: Significant *z* values ($|z| \geq 1.96$) are printed in bold.

Table 5. Linear mixed effects models for gaze duration.

	Log GD		
	Estimate	Standard error	*t* Value
Predictor (intercept)	2.47	1.29	**191.62**
Parafoveal preview (PP)	−.141	1.32e−2	**−10.64**
Cloze probability (CP)	−5.16e−2	1.80e−2	**−2.86**
PP × CP	4.14e−2	2.31e−2	1.79

Note: Significant *t* values ($|t| \geq 1.96$) are printed in bold.

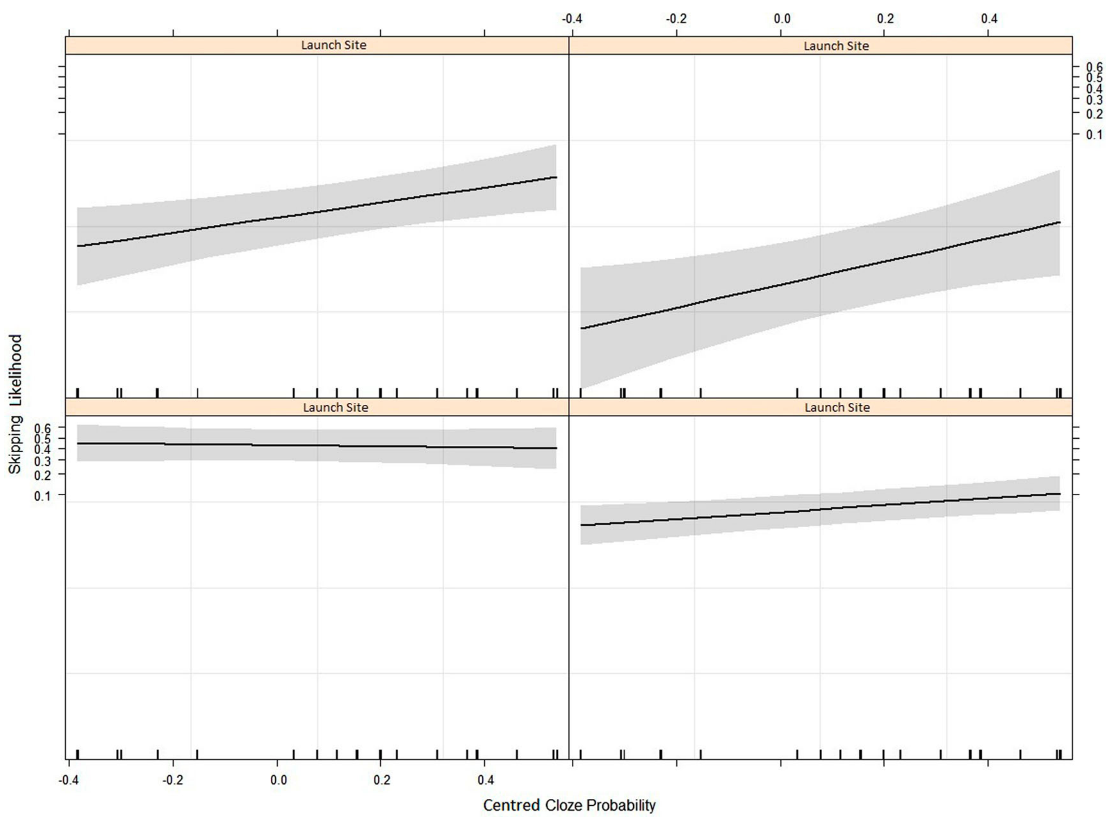

Figure 2. Word skipping likelihood: predictability by launch site.

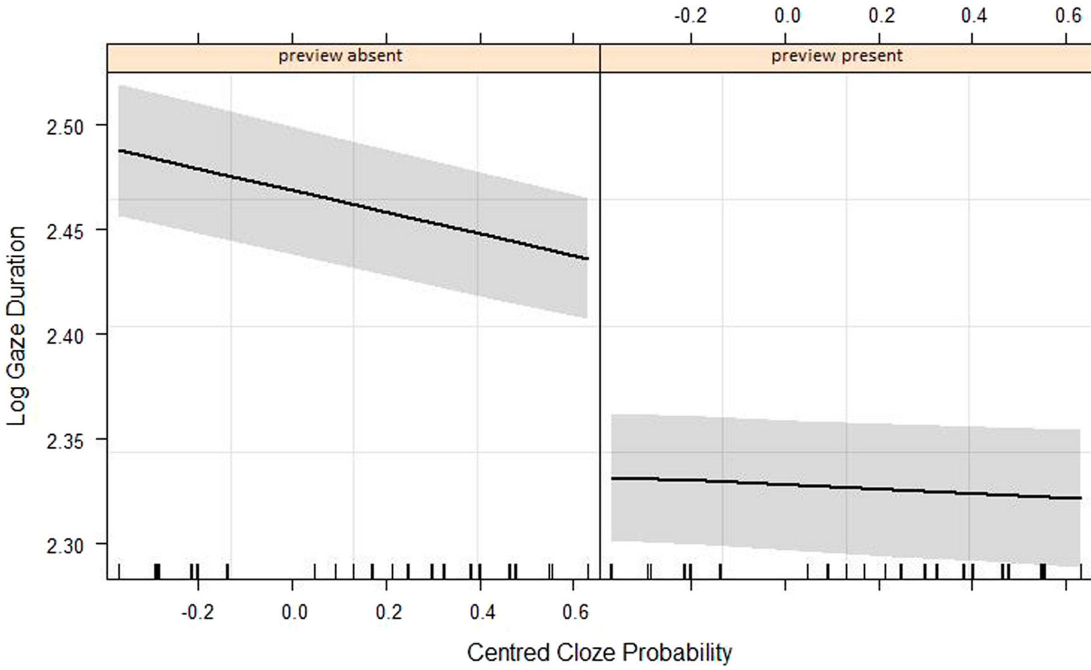

Figure 3. Gaze duration: predictability by preview availability.

absence of parafoveal preview. This stands in stark contrast to studies which manipulate parafoveal previews to be either valid or invalid and points to costs associated with processing of invalid previews as the culprit in the case of the vanishing predictability effect. We believe the most parsimonious explanation for the findings from the current study and the prior studies which have manipulated parafoveal preview and target word predictability is one based on Bayesian belief updating (Hale, 2003; Levy, 2008). When readers are provided with a glimpse of future words in parafoveal vision, they make use of the available information right away. Because such a modelling framework explains predictability effects as arising in a graded, probabilistic manner based on prior belief of the likely underlying meaning of a sentence, when the parser is provided with an invalid preview that requires shifting beliefs in a different direction, the target word will become less "predictable" in that readers will have less belief in their hypotheses that made the target word "predictable" in the first place.

There was also some indication that predictability effects were actually larger for target words in the absence than in the presence of preview though this interaction was not significant. This is of interest because in preview absent condition, the saccade to the target word took considerably more time than in the preview present condition due to the relative distances traversed by these saccades and lexical processing does not stop during saccades (Irwin, 1998). So, the larger numerical effects, if reliable, may have been the result of the additional time that readers had to engage in top-down predictive lexical processing. It is also possible that this non-significant numerical trend was due to the additional words that occurred prior to the target when it occurred in the middle of the line compared to the start of the line. However, we think this is unlikely as the offline cloze norming study found the same effect of predictability in both locations despite these extra words.

The current study was the first to investigate how word predictability modulates eye movement behaviour for line initial words and has also established the usefulness of a simple new method for investigating parafoveal preview effects during reading. Moreover, it allows researchers to examine processing of target words in the absence of preview rather than in the presence of invalid preview. However, it is admittedly not as powerful or flexible a methodology as the boundary change technique. Still, it should be seen as yet another tool for investigating eye movements during reading. A recently published Bayesian meta-analysis of the preview benefit effect in reading (Vasilev & Angele, 2016) estimated the effect to be 45 ms which is smaller than the 79 ms benefit we obtained with our new method in the current study. As mentioned earlier, the absence of parafoveal preview is not the only explanation for increased fixation durations for accurate line initial fixations. The lack of parafoveal preview may only be part of the effect we see on line initial target words in the current study with the true size of preview benefit being less than 79 ms, which in the current study may reflect a combination of preview benefit and line initial start-up effects. Additionally, the Bayesian meta-analysis estimate of 45 ms for preview effects represents both the benefits of valid previews and the costs of invalid previews (Kliegl, Hohenstein, Yan, & McDonald, 2013). If a pure benefit could be obtained it would likely be smaller than 45 ms.

Additionally, it is possible that the timings involved in the mechanisms underlying eye movement control may account for these findings. For instance, within the framework of E-Z Reader model (Reichle et al., 1998; Reichle et al., 2003; Reichle & Sheridan, 2015), if the link between lexical processing and saccade planning were moved to a later point within lexical processing (i.e. the end of L2) for line initial fixations, their durations would increase[5]. It is not clear that such a modification would be needed as the model would likely be capable of replicating this line initial fixation effect via absence of preview, and additional time from this added modification would result in an overestimation of the line initial effect. Moving the saccade trigger to a later point in lexical processing for line initial words would also result in an increase in parafoveal preview for the second word on a line. Under normal circumstances, saccade preparation happens in parallel with lexical completion, and preview benefit for the upcoming word only accumulates between the end of lexical processing and the completion of the saccade. If saccade planning is delayed relative to lexical completion the period for preview accumulation increases. Additional research is needed to explore the relationship between lexical and oculomotor programming after a return sweep in order for models of eye movement control to be extended beyond single line reading.

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