The frequency-predictability interaction in reading:

It depends where you're coming from

Christopher J. Hand[1,2]

Sébastien Miellet[1]

Patrick J. O'Donnell[1]

Sara C. Sereno[1]*

[1]University of Glasgow

[2]University of Bedfordshire

*Address for correspondence:

Sara C. Sereno
Department of Psychology
58 Hillhead Street
University of Glasgow
Glasgow G12 8QB
Scotland, UK

phone: +44 (0)141 330-5089
fax: +44 (0)141 330-4606

email: s.sereno@psy.gla.ac.uk

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Abstract

A word's frequency of occurrence and its predictability from a prior context are key factors that determine how long the eyes remain on that word in normal reading. Past reaction-time and eye movement research can be distinguished by whether these variables, when combined, produce interactive or additive results, respectively. Our study addressed possible methodological limitations of prior experiments. Initial results showed additive effects of frequency and predictability. However, we additionally examined launch site (the distance from the pre-target fixation to the target word) to index the extent of parafoveal target processing. Analyses revealed both additive and interactive frequency × predictability effects on target fixations, with the nature of the interaction depending on the quality of the parafoveal preview. Target landing position and pre-target fixation time were also considered. Results were interpreted in terms of models of language processing and eye movement control. Our findings with respect to parafoveal preview and fixation time constraints aim to help parameterize eye movement behavior.

Keywords: reading; eye movements; word frequency; contextual predictability; launch site; landing position; parafoveal-on-foveal processing; additive; interactive; models of eye movement control

Two key variables that influence the amount of time a reader spends fixating a word in reading are its frequency of occurrence and its predictability from the prior text. Past research has been somewhat equivocal on whether these two factors are additive or interactive. Our study explores the relationship between frequency and predictability on eye movement behavior during normal reading. In contrast to prior studies, we additionally examine the effect of launch site, that is, the distance between the target word and the location of the pre-target fixation. Launch distance can determine how much information is obtained from the target parafoveally, prior to its subsequent fixation. We believe this approach provides a more dynamic account of how frequency and predictability interact as a function of the reader's initial viewing distance.

During normal reading, a series of discrete eye fixations are made through text and individual word meanings are activated and integrated on-line into a developing discourse representation. Measuring eye movements during fluent reading is an established technique that is sensitive to on-line perceptual and cognitive aspects of lexical processing (Rayner, 1998; Sereno & Rayner, 2003). As a response measure, fixation time possesses certain advantages over traditional behavioral measurements – namely, there is no secondary task involving overt decisions, and fixation times are shorter than, for example, naming or lexical decision latencies. Eye movement reading research over the past three decades has revealed that reading behavior can be accurately assessed by measuring the position, duration, and sequence of eye fixations in text (for reviews, see Rayner, 1998; Rayner, 2009).

One variable that influences fixation time is word length, with longer (and more) fixations made on longer words (e.g., Just & Carpenter, 1980; Kliegl, Olson, & Davidson, 1982; Rayner, Sereno, & Raney, 1996). After controlling for word length, however, two higher-level variables in particular have been shown to strongly influence fixation time on a word – namely, a word's frequency and its predictability from the prior context. The individual effects of word frequency and contextual predictability on eye movement behavior have been extensively documented. Numerous studies have demonstrated that readers look longer at low frequency (LF) than high frequency (HF) words (Inhoff & Rayner, 1986; Just & Carpenter, 1980; Kennison & Clifton, 1995; Kliegl, Grabner, Rolfs, & Engbert, 2004; Kliegl, Nuthmann, & Engbert, 2006; Rayner & Duffy, 1986; Rayner & Raney, 1996; Rayner et al., 1996; Rayner, Ashby, Pollatsek & Reichle, 2004; Schilling, Rayner, & Chumbley, 1998; Sereno, O'Donnell, & Rayner, 2006; Sereno, Pacht, & Rayner, 1992; Sereno & Rayner, 2000; Slattery, Pollatsek, & Rayner, 2007). Likewise, several studies have demonstrated that words which are less constrained by a prior context are read slower and skipped less often than more constrained (or predictable) words (Balota, Pollatsek & Rayner, 1985; Carroll & Slowiaczek, 1986; Ehrlich & Rayner, 1981; Kliegl et al., 2004, 2006; McDonald & Shillcock, 2003a, 2003b; Morris, 1994; Rayner et al., 2004; Rayner & Well, 1996; Zola, 1984).

The precise time-course of context effects, however, remains a topic of debate: Does context affect early, lexical processing or only later, post-lexical processing? The answer to this question has often been pursued within the lexical ambiguity literature in determining whether the contextually appropriate meaning of a homograph can be selected during its lexical access, or whether all meanings are nonetheless accessed with the appropriate meaning only selected post-lexically as a consequence of its semantic integration (see, e.g., Sereno et al., 2006). An alternative approach has gauged the temporal course of contextual predictability effects by whether such effects interact with word frequency (e.g., Sternberg, 1969). The presence of word frequency effects is generally considered an index of lexical access (e.g., Balota, 1990; Sereno & Rayner, 2003). Frequency effects have been reliably demonstrated "early" in processing both in eye movement and electrophysiological paradigms. For example, Sereno and Rayner (2000) found frequency effects in the initial fixation on words whose parafoveal preview (from the prior fixation) consisted of a nonword letter string that was visually unrelated to the subsequent target. Additionally, in measuring event-related potentials (ERPs) during single word presentations, Sereno and colleagues have consistently found frequency effects in the N1 component (i.e., first negative-going wave) beginning around 130 ms post-stimulus (Scott, O'Donnell, Leuthold, & Sereno, 2009; Sereno, Brewer, & O'Donnell, 2003; Sereno, Rayner, & Posner, 1998; see also Dien, Frishkoff, Cerbone, & Tucker, 2003; Hauk & Pulvermüller, 2004; Neville, Mills, & Lawson, 1992; Nobre & McCarthy, 1994; Pulvermüller, Assadollahi, & Elbert, 2001). An observed interaction between frequency and predictability would suggest that these variables share the same processing stage, supporting an early, lexical locus of contextual processing. Alternatively, additive effects of frequency and predictability would suggest that the temporal locus of contextual processing is relatively delayed.

Interactive findings

Early behavioral reaction-time (RT) experiments examined the joint effects of word frequency and contextual predictability. The majority of these studies typically reported an interactive pattern of effects (but cf. Schuberth & Eimas, 1977). For example, across several experiments, Stanovich and West (1981; 1983) examined context effects in pronunciation latencies on end-of-sentence HF and LF words. In addition to main effects of frequency and predictability, they reported a significant interaction, in which LF words were facilitated more by predictable contexts than HF words. West and Stanovich (1982) observed the same pattern of effects using lexical decision. Taken together, these results provide considerable evidence that context interacts with the variable (word frequency) that otherwise determines how rapidly a word can be identified. However, there are certain aspects of these studies which may limit their generalizability. First, delays often occurred between offset of the context and onset of the target. Such delays could induce strategic processing. Second, the contexts were quite short and often contained intralexical primes (e.g., Forster, 1979). Thus, it is possible to argue that the pattern of contextual facilitation may have been carried by associative priming rather than top-down effects from higher-order levels of discourse representation. Third, comparisons were often made between a contextually congruous condition that was highly predictable and an incongruous condition that was highly anomalous. A more representative contrast might be to compare high predictable with less predictable (but not anomalous) targets. Finally, as mentioned earlier, the response measures of naming and lexical decision may involve the recruitment and application of strategies not found in normal reading.

In an early eye movement reading study, Inhoff (1984) investigated frequency and predictability effects. Similar to the RT studies, Inhoff found an interaction in gaze duration (i.e., the sum of all consecutive fixations made on a word). Inhoff's results, however, represented the combined data from a normal reading condition and a degraded stimulus condition in which there was a 3-character mask that moved in synchrony with the eyes and that significantly lengthened fixation times. In addition, the experimental passages were excerpts from Alice in Wonderland; as such, target words were selected opportunistically and word length (which covaries with frequency) was not formally controlled.

In an ERP study, Sereno et al. (2003) presented sentences word-by-word and examined end-of-sentence HF and LF targets in neutral and biasing contexts. They also obtained an interactive pattern of frequency and predictability in terms of the voltage amplitude of the N1 component, from 132-192 ms post-stimulus. That is, while there was no context effect for HF words, LF words were facilitated in a biasing context. As this effect occurred in the same time window in which word frequency effects had been demonstrated, they argued that top-down processing modulated early lexical processing. However, the presentation rate was relatively slow compared to normal reading (~500 ms per word), and the predictability contrast for LF words was statistically marginal.

Additive findings

Despite the enormous amount of research into the individual effects of frequency and predictability on eye movements during reading, surprisingly few eye movement studies have included manipulations that orthogonally vary target word frequency and predictability. Four previous eye movement studies included manipulations of frequency and predictability of target words in sentences (Altaribba, Kroll, Sholl & Rayner, 1996; Ashby, Rayner, & Clifton, 2005; Lavigne, Vitu & d'Ydewalle, 2000; Rayner, Binder, Ashby, & Pollatsek, 2001). These studies consistently found main effects of frequency and predictability on fixation times, but all failed to find a significant interaction. It is important to note that the interaction between these two variables was not the principal focus of any of these studies. Lavigne et al. (2000) and Rayner et al. (2001) investigated the effects of predictability on landing positions in words, and Altaribba et al. (1996) dealt with cross-language priming. Ashby et al. (2005) compared reading behavior of highly skilled and average readers. Although they reported differential effects of frequency and predictability between participant group, they found no frequency-predictability interaction.

Three recent eye movement studies did explicitly investigate the interaction between word frequency and contextual predictability. In a study conducted in French, Miellet, Sparrow, and Sereno (2007) selected a subset of words from a passage that varied in frequency and predictability, and only differed minimally in length. They observed additive effects of frequency and predictability and were able to account for the pattern of data by modifying a version (extended, additive version 7; Rayner et al., 2004) of the E-Z Reader model of eye movement control (Reichle, Rayner, & Pollatsek, 2003). The only methodological drawback of this study was in terms of the modest number of data points acquired. There were only five items in each of the four conditions, obtained by crossing frequency (HF, LF) with predictability (high, low), that were read by a total of 15 participants.

Kliegl et al. (2004) examined the effects of word length, frequency, and contextual predictability on various measures of eye movement behavior during reading of the Potsdam Sentence Corpus (144 individual German sentences ranging from 5-11 words each, with an average length of 7.9 words). Analyses of the eye movement data revealed reliable independent effects of word length, frequency, and predictability on the probability of fixation. In fixation duration measures which did not include regressions to words (i.e., first fixation duration, single fixation duration, and gaze duration), a non-significant tendency of predictability was obtained when the effects of length and word frequency were controlled. The effect of predictability on the corpus data, however, became significant when regressions to words were included (i.e., total fixation time). Upon analyzing a subset of target words from the corpus, Kliegl et al. only found significant predictability effects in single fixation duration (i.e., the duration of first-and-only fixations) as well as gaze duration measures. They argued that *a priori* selection of target words yielded a benefit to the reliability of predictability effects in measures of first-pass reading. Kliegl et al. also examined multiplicative interactions between their variables, but in terms of frequency and predictability, the multiplicative interaction did not add significantly to the amount of variance explained by a linear expression of the effects of these variables. However, it was acknowledged by the authors that the regression lines obtained in their analyses were suggestive of higher-order terms.

Finally, an eye movement reading study that directly investigated the frequency × predictability interaction was carried out by Rayner et al. (2004). Participants read a series of single-line sentences, each containing a target word that was either HF or LF and either predictable or unpredictable from the prior context. In their design, this was achieved by switching targets across contexts. That is, for half of the sentences, HF targets were predictable while their length-matched LF targets were unpredictable; for the other half, LF targets were predictable while HF targets were unpredictable (participants only read one version of each sentence). Fixation time data showed an additive pattern, with main effects of frequency and predictability. While Rayner et al. found no statistical interaction, they stated that the numerical pattern of their effects were suggestive of an interaction with larger word frequency differences in their unpredictable condition (i.e., larger predictability effects for LF words). Rayner et al. did find a reliable interaction, however, in how often target words were skipped, with HF predictable targets skipped more often than any of the other three conditions (which did not differ from each other).

Although this study directly examined the frequency × predictability interaction, it was perceived to have certain limitations. First, there were only 8 items that each participant read in each experimental condition. It could be argued that having few items per condition may result in a pattern of effects reflecting idiosyncrasies of the stimuli used and may not be generalizable to a wider range of materials. Second, target words were embedded near the middle of a single sentence. For context effects to develop more fully, it may be more appropriate to employ longer contexts preceding target words. Another concern relates to the content of their contexts. Some materials were "anecdotal," relying upon target words fulfilling certain contextual conventions. Finally, despite their results using off-line predictability ratings, their unpredictable words seemed sometimes anomalous. As mentioned previously, comparisons between high predictable (HP) and low predictable (LP) conditions may be more representative of natural texts. Example materials from Rayner et al.'s (2004) study are shown in Table 1.

Insert Table 1 about here

<u>Interactive or additive</u>?

It is unclear why there is discrepancy between the results of the earlier RT studies and eye movement research in terms of the relationship between the effects of word frequency and contextual predictability. It may be that the frequency × predictability interaction is an elusive effect that does not manifest itself in the eye movement record. Alternatively, an interaction *may* exist, and by employing a more robust experimental design, an interactive pattern of frequency and predictability effects may be observed, not only on the probability of fixating target words, as has been reported, but also on fixation duration measures. Accurately determining the precise relationship between the effects of word frequency and contextual predictability is important for models of language processing. A modular architecture maintains that higher-order discourse context can only operate on the output of the lexical processor (e.g., Fodor, 1983; Forster, 1979). Conversely, an interactive model asserts that prior context can directly influence lexical access, itself (e.g., McClelland, 1987; Morton, 1969). The presence of additive or interactive effects would lend support to either a modular or interactive account of lexical processing, respectively.

Parafoveal effects of frequency and predictability

Previous eye movement research has demonstrated that information acquired to the right of fixation during reading (i.e., parafoveally) is not only beneficial to the reader, but is necessary for reading to occur at a normal rate (Rayner, 1998). *Parafoveal preview benefit* is defined as the fixation time advantage on a target word when the parafoveal information associated with that target (obtained from the prior fixation) is valid versus invalid. Parafoveal preview is typically manipulated by employing a gaze-contingent display change paradigm during reading. For example, in the "boundary" paradigm, participants parafoveally view either valid or invalid information of the (eventual) target, which then changes to the target when the reader crosses a pre-specified invisible boundary (Rayner, 1975). Research has demonstrated that the ability of the reader to extract information from the parafovea is influenced both by the frequency and the contextual predictability of that parafoveal word. The parafoveal preview benefit is greater for HF versus LF words (Inhoff & Rayner, 1986), and for contextually predictable versus unpredictable words (Balota et al., 1985).

It is possible that the amount of parafoveal preview obtained from the pre-target fixation may play a role in the frequency × predictability interaction. While the "boundary" paradigm does manipulate parafoveal preview, it typically does so in a binary way (i.e., valid or invalid). We have adopted an alternative approach based on the fact that visual acuity drops off as a function of retinal eccentricity. Assuming that the amount of parafoveal preview obtained is largely related to the pre-target launch distance – with greater distances giving rise to lesser previews – then target word processing as a function of launch distance should represent a more continuous, although necessarily *post-hoc*, assessment of parafoveal processing. While there is evidence that the complexity of the pre-target word influences the amount of parafoveal processing on the subsequent target (e.g., Henderson & Ferreira, 1990), such effects should also be modulated by visual acuity as gauged by launch distance.

The *perceptual span* is defined as that region of text from which useful information can be extracted (i.e., reading is slowed when text within the span is altered). The perceptual span has been functionally approximated from "moving window" studies (McConkie & Rayner, 1975; Miellet, O'Donnell, & Sereno, 2009). For English, it is estimated to extend from 3 characters to the left of fixation (approx. the beginning of the fixated word) to about 14 characters to the right of fixation. The span's asymmetry is taken to reflect attentional demands linked to reading direction (e.g., in English, new information is always located to the right). In reference to launch distance, our approach was to examine distances in which the target word would still fall within the perceptual span of the pre-target fixation.

Current study

The present experiment was carried out to investigate whether simultaneously varying the frequency and predictability of target words in short texts yielded additive or interactive effects on eye movement behavior in reading. Although this study was principally designed to address the perceived limitations of Rayner et al. (2004), it also served to accumulate a large body of eye movement data to allow for the *post-hoc* analysis of the additional effects of parafoveal preview benefit, as indexed by the distance between the beginning of the target word and the location of the prior fixation. The present study used a 2 (Frequency: HF, LF) × 2 (Predictability: HP, LP) design with 22 items per condition. Each experimental item extended over two lines of text, with longer contexts preceding target words than those used in Rayner et al. The factor of parafoveal preview was implemented *post-hoc* with three levels of launch distance: Near (1-3 characters), Middle (4-6 characters), and Far (7-9 characters). Data were analyzed across several standard eye movement measures, first in the 2 × 2 and then in the 2 × 2 × 3 designs outlined above.

We predicted that, in the 2 × 2 design, an interactive pattern of findings might emerge, with larger predictability effects for LF than HF words. We thought that the changes and augmentations we implemented, in comparison to the Rayner et al. design, would provide more advantageous circumstances for observing such effects. In the 2 × 2 × 3 design, we predicted that we would find a launch distance effect, with longer target fixations associated with greater launch distances, replicating prior research (e.g. McConkie, Kerr, Reddix, & Zola, 1988; Sereno, 1992). We were less certain of the effect that launch distance would have on the frequency × predictability interaction. Although we thought that effects would be reduced with greater launch distances, we were unsure whether the attenuation would equally affect frequency, predictability, and their interaction.

Method

Participants

Sixty-four members of the University of Glasgow community (47 females; mean age 22.2 years old) were paid £6 or given course credit for their participation. All were native English speakers with normal or corrected-to-normal vision and had not been diagnosed with any reading disorder.

Apparatus

Participants' eye movements were monitored via a Fourward Technologies (Buena Vista, VA) Dual-Purkinje Eyetracker (Generation 5.5). The eyetracker's resolution is less than 10 min of arc, and its signal was sampled every millisecond by a 386 computer. Although viewing was binocular, eye movements were recorded from the right eye. Passages were displayed over two lines on a ViewSonic 17GS CRT in a non-proportional font (light cyan on a black background) and were limited to the central 60 characters of an 80-character line. Participants were seated approximately 86 cm from the monitor, and 4 characters of text subtended 1° of visual angle. The room was dimly lit and display brightness was adjusted to a comfortable level.

Design

A 2 (Frequency: HF, LF) × 2 (Predictability: HP, LP) design was used. HF and LF targets appeared in short, two-line passages (one per passage) in which each target was considered either contextually predictable (HP) or not (LP). Each passage was designed to accommodate both an HF and LF target (one each in two versions of each passage). For half of the passages, the HF target was HP while the LF target was LP; for the other half of passages, the LF target was HP while the HF target was LP. Because there were two possible targets for each passage, the materials were divided into two sets to be read by two different participant groups. Group 1 read half of the HF/LF target pairs in HP contexts and half in LP contexts. Group 2 read the HF/LF target pairs in the opposite context conditions as Group 1. With 44 pairs of HF/LF targets appearing in either HP or LP contexts, there was a total of 176 passages. Because each participant group was only presented with half (88) of the possible passages (to avoid repetition of targets or contexts), each participant received 22 items in each of the 4 experimental conditions (HF-HP, HF-LP, LF-HP, LF-LP). All passages and corresponding targets are listed in the Appendix. Target words were always positioned near the middle of a line and were never sentence initial or final. Experimental passages were presented in a different random order to each participant.

Materials

The specifications of HF-HP, HF-LP, LF-HP, and LF-LP targets are presented in Table 2. Word frequencies were acquired from the British National Corpus (BNC), a database of 90 million written word tokens (http://www.natcorp.ox.ac.uk). Mean frequency values for HF (range: 52-512 per million) and LF (range: 0-10 per million) words are listed in Table 2. Word length was matched exactly on a pairwise basis, and average word length was 5.89 characters (range: 5-8 characters). The pre-target context length of 15.5 words on average was twice that of the 7.7 words on average used in Rayner et al.'s (2004) materials and allowed more time for a contextual representation to develop. Contextual predictability was determined on the basis of the results from two norming tasks: word predictability rating and Cloze probability.

Insert Table 2 about here

Predictability task. The materials were divided into two sets and were presented to two different participant groups (to avoid target word or context repetition). Two groups of 10 participants (none of whom participated in either the experiment or Cloze task) were presented passages with the target word presented in bold font. Participants were asked to indicate how predictable they considered the target word to be on a scale of 1 (highly unpredictable) to 7 (highly predictable). The same targets (across participants) were always rated higher in HP contexts, even when targets in LP contexts were rated above 4 (i.e., on the predictable end of the scale). It is important to note that the relatively high ratings of LP targets reflected the fact that they were designed to be *less* predictable (and not implausible or anomalous) compared to HP targets in a given context. And, although HP contexts were constructed to be predictive of their targets, they were not intended to be exclusively predictive. Finally, an effort was made to avoid intralexical priming of the target by the immediately preceding context (e.g., Forster, 1979). Mean predictability ratings are listed in Table 2 and are comparable to Rayner et al.'s (2004) values of 6.6, 4.4, 6.3, and 4.6 for their analogous HF-HP, HF-LP, LF-HP, and LF-LP conditions, respectively.

Cloze task. A single group of 20 participants (none of whom participated in either the experiment or word-rating task) were given each experimental item up to, but not including, the target word (only one set of materials was administered because the target word was absent). Participants were asked to generate the next word in the sentence (i.e., the missing target). Responses were scored as "1" if the target was correctly identified and "0" for all other guesses.

Mean Cloze probabilities (correct responses) across the experimental conditions are listed in Table 2. Rayner et al. (2004) reported Cloze values of 0.78 for HP and less than 0.01 for LP words (averaging across HF and LF conditions). In comparison, our Cloze probabilities were lower for HP (0.57) and slightly higher for LP words (0.02).

Procedure

Participants were given written and verbal instructions about the eyetracking task. A bite bar was prepared to minimize head movements. Participants were instructed to read normally for comprehension, as they would read a story. They were told that yes-no questions followed half the passages to ensure they were paying attention.

The experiment involved initial calibration of the eyetracking system, reading 10 practice passages, recalibration, and reading the 88 experimental passages. A calibration display appeared before every trial and comprised a series of calibration points extending over the maximal horizontal and vertical range in which passages were presented. During this display, the calculated position of the eye was visible, allowing the experimenter to check the accuracy of the calibration and recalibrate if necessary.

Each trial began with the calibration display. When participants were fixating the upper left-most calibration point (corresponding to the first character of text), a passage was presented. After reading each passage, participants fixated on a small box, below and to the right of the last word, and pressed a key to clear the screen. The calibration screen reappeared either immediately or after they had answered a yes-no question by pressing corresponding response keys. Participants had no difficulty in answering the questions (average over 90% correct).

Results

The target region comprised the space before the target word and the target itself. Lower and upper cutoff values for individual fixations were 100 and 750 ms, respectively. Data were additionally eliminated if there was a blink or track loss on the target, or if the fixation on the target was either the first or last fixation on a line. Overall, 6.1% of the data were excluded for these reasons. In reading, most content words are generally fixated once. Sometimes they are immediately refixated and sometimes they are skipped altogether. In this study, the percentages of data for single fixation, immediate refixation, and skipping of the target were 62.8, 12.4, and 18.7%, respectively.

The resulting data were analyzed over a number of standard fixation time measures on the target word: (a) first fixation duration (FFD; the duration of the initial fixation, regardless of whether the word was refixated); (b) single fixation duration (SFD; fixation time when the word is only fixated once); (c) gaze duration (GD; the sum of all consecutive fixations before the eyes move to another word); and (d) total fixation time (TT; the sum of all fixations, including later regressions made to that word). FFD, SFD, and GD represent first-pass, more immediate measures of processing. For reasons of comparison with Rayner et al. (2004), we also examined the probability of making a first-pass fixation (PrF) on the target in the initial analysis. Analyses of variance (ANOVAs) were conducted both by participants (F_1) and by items (F_2) and are reported below, first for the Frequency × Predictability, and then for the Frequency × Predictability × Preview design. Table 3 reports the number of data points across all conditions used in these analyses. Following these main analyses, we also report supplementary findings regarding the position of the target fixation (landing position) as well as effects on the fixation immediately preceding the target fixation (parafoveal-on-foveal effects).

Insert Table 3 about here

Frequency × Predictability analyses

The means for FFD, SFD, GD, TT, and PrF measures across experimental conditions are shown in Table 4. As SFD accounts for the majority of first-pass fixation time data on the target (83.5%), these means, including standard error bars, are displayed in Figure 1.

Insert Table 4 and Figure 1 about here

FFD, SFD, and GD. The main effect of Frequency was significant in the FFD, SFD, and GD measures [$F_1(1,63)$: F-values 82.01-104.09, *MSE*s 399-810, all ps<.001; $F_2(1,43)$: F-values 89.28-147.46, *MSE*s 190-568, all ps<.001]. HF words were fixated for less time than LF words (260 vs. 284 ms for FFD, 264 vs. 290 ms for SFD, and 279 vs. 312 ms for GD, respectively). Predictability was also significant in FFD, SFD, and GD [$F_1(1,63)$: F-values 13.76-16.87, *MSE*s 309-618, all ps<.001; $F_2(1,43)$: F-values 12.05-14.36, *MSE*s 337-626, all ps<.01]. HP words were fixated for less time than LP words (267 vs. 276 ms for FFD, 272 vs. 281 ms for SFD, and 289 vs. 302 ms for GD, respectively). The Frequency × Predictability interaction was not significant [all Fs<1].

TT. The pattern of effects was similar in the TT measure. There was a main effect of Frequency, with shorter fixation times on HF (312 ms) than on LF (357 ms) words [$F_1(1,63)=71.04$, $MSE=1793$, $p<.001$; $F_2(1,43)=51.65$, $MSE=1768$, $p<.001$]. There was also a main effect of Predictability, with shorter fixations on HP (315 ms) than on LP (354 ms) words [$F_1(1,63)=55.93$, $MSE=1675$, $p<.001$; $F_2(1,43)=37.07$, $MSE=1899$, $p<.001$]. The interaction was marginal by participants, but non-significant by items [$F_1(1,63)=2.86$, $MSE=1261$, $p=.096$; $F_2<1$].

PrF. The PrF was calculated on the basis of the whether a trial received a fixation, given that that trial was included in the analysis (i.e., PrF is based on ~94% of the data, after rejected trials were excluded). The main effect of Frequency was significant [$F_1(1,63)=9.72$, $MSE=.008$, $p<.01$; $F_2(1,43)=10.74$, $MSE=.005$, $p<.01$]. The probability of fixating HF words (.79) was less than that for LF words (.82). Unlike the fixation time data, the effect of Predictability did not reach significance [$F_1(1,63)=1.85$, $MSE=.006$, $p>.15$; $F_2(1,43)=2.54$, $MSE=.006$, $p=.118$]. Also in contrast to the fixation time data, the Frequency × Predictability interaction was significant, although this effect was marginal by items [$F_1(1,63)=7.71$, $MSE=.006$, $p<01$; $F_2(1,43)=3.63$, $MSE=.009$, $p=.064$]. Follow-up contrasts for HF words showed that HF-HP words were less likely to be fixated than HF-LP words [F_1=8.67, p<.01; F_2=4.94, p<.05]. For LF words, however, the equivalent comparison (LF-HP vs. LF-LP) was not significant [all Fs<1]. Follow-up contrasts for HP words showed that HF-HP words were less likely to be fixated than LF-HP words [F_1=20.37, p<.001; F_2=9.17, p<.01]. For LP words, however, the equivalent comparison (HF-LP vs. LF-LP words) was not significant [all Fs<1]. Overall, HF-HP words were less likely to be fixated than words in other conditions.

Summary. In general, the pattern of results from the Frequency × Predictability analyses replicated those of Rayner et al. (2004). In first-pass measures (FFD, SFD, and GD), there were significant effects of Frequency and Predictability with no interaction. Rayner et al. found an identical pattern of first-pass results. For TT in the current study, the main effects were again significant, and there was only a hint of an interaction (marginal by participants, but non-significant by items). Rayner et al. only found reliable main effects. Rayner et al., however, did find a significant interaction in the PrF measure: words in their analogous HF-HP condition were skipped more often than any of their other three conditions (analogous HF-LP, LF-HP, and LF-LP conditions). Their main effect of Frequency for PrF was only significant by items and their main effect of Predictability was not significant. Our results were quite similar. Frequency was statistically significant in both participants and items analyses, but Predictability was not. The interaction, although marginal by items, was in all other ways identical to that found in Rayner et al.: HF-HP words were skipped more often than words in the other conditions.

Frequency × Predictability × Preview analyses

The first-pass target fixation time data used in the analyses above were conditionalized *post-hoc* in terms of launch distance as a metric of parafoveal preview. We were specifically interested in assessing the first-pass data because it corresponds to the earliest measures of processing. Launch distance was measured as the distance from the beginning of the target (i.e., the space before the target) to the location of the immediately preceding pre-target fixation.

There were three levels of this Preview factor: Near (1-3 characters), Middle (4-6 characters), and Far (7-9 characters). Fixations initiated from launch sites of 10 or more characters only accounted for 14.3% of the total data (9.5% from 10-12 characters, 4.8% from 13+ characters). In addition, these fixations were spread out over an 11 character window (10-21 characters). In the conditionalized data, the percentages of the total data for each Preview condition for single fixation and immediate refixation were as follows: 15.2 and 1.1% for Near; 20.8 and 3.3% for Middle; and 17.0 and 3.6% for Far, respectively. Conditionalized fixation time data accounted for 81.0% of the initial fixation time data. The mean data for FFD, SFD, and GD measures across Frequency, Predictability, and Preview conditions are displayed in Table 5. As in the overall analysis, because SFD comprised the majority of the first-pass conditionalized data (86.9%), these means, including standard error bars, are shown in Figure 2. In the 2 × 2 × 3 analyses, FFD, SFD, and GD produced highly similar patterns of results, including levels of significance. Accordingly, we have limited our presentation of results below to the SFD data.

Insert Table 5 and Figure 2 about here

Main effects. All three main effects were significant. First, there was a main effect of Preview [$F_1(2,126)=50.03$, $MSE=1634$, $p<.001$; $F_2(2,86)=32.15$, $MSE=1303$, $p<.001$]. Follow-up contrasts, in general, revealed significant differences between target fixations launched from Near (251 ms), Middle (276 ms), and Far (285 ms) positions, with shorter fixation times associated with closer launch distances [Near vs. Middle: Fs>40, ps<.001; Near vs. Far: Fs>55, ps<.001; Middle vs. Far: $F_1=6.62$, $p<.05$, and $F_2=1.22$, $p>.25$]. Second, there was a significant main effect of Frequency [$F_1(1,63)=77.64$, $MSE=2111$, $p<.001$; $F_2(1,43)=106.46$, $MSE=1099$, $p<.001$]. As in the initial analysis, HF words (256 ms) were fixated for less time than LF words (285 ms). Finally, the main effect of Predictability was also significant [$F_1(1,63)=19.02$, $MSE=1546$, $p<.001$; $F_2(1,43)=13.68$, $MSE=2125$, $p<.001$]. As in the initial analysis, HP words (264 ms) were fixated for less time than LP words (277 ms).

Interactions. All interactions were significant except for Frequency × Predictability [all Fs<1]. Frequency × Preview was significant [$F_1(2,126)=9.36$, $MSE=1939$, $p<.001$; $F_2(2,86)=7.71$, $MSE=1905$, $p<.001$], as was Predictability × Preview [$F_1(2,126)=5.72$, $MSE=1570$, $p<.01$; $F_2(2,86)=5.57$, $MSE=1453$, $p<.01$]. Because the 3-way interaction was also significant [$F_1(2,126)=7.19$, $MSE=1425$, $p<.01$; $F_2(2,86)=7.49$, $MSE=1212$, $p<.01$], and for reasons of clarity, we performed separate Frequency × Predictability ANOVAs for Near, Middle, and Far Preview conditions. Condition means relevant to these analyses are shown in Table 5.

Near (1-3 characters) analysis. There were significant main effects of Frequency and Predictability [all Fs>15, all ps<.001]. As in the prior analyses, HF and HP words elicited shorter fixations than LF and LP words, respectively. There was also a Frequency × Predictability interaction [all Fs>4, all ps<.05]. As can be seen in Figure 2, the Predictability effect was greater for LF than HF words. The HF-HP vs. HF-LP contrast was significant by participants, but marginal by items [$F_1=4.71$, $p<.05$; $F_2=3.60$, $p=.065$]. The other three contrasts – LF-HP vs. LF-LP, HF-HP vs. LF-HP, and HF-LP vs. LF-LP – were all highly significant [all Fs>18, all ps<.001].

Middle (4-6 characters) analysis. The pattern of effects in this analysis differed somewhat from the Near analysis. As before, there was a main effect of Frequency, with HF words eliciting shorter fixations than LF words [all Fs>18, all ps<.001]. The Predictability effect, however, was only trend by participants and marginal by items [$F_1(1,63)=2.77$, $p=.101$; $F_2(1,43)=3.28$, $p=.077$]. Although the interaction was significant [all Fs>5, all ps<.05], the pattern of contrasts differed. As shown in Figure 2, unlike the Near pattern, the Predictability effect was greater for HF than LF words in the Middle condition. That is, in comparison to the Near analysis, the HF-HP vs. HF-LP contrast was significant [all Fs>7, all ps<.01], while neither the LF-HP vs. LF-LP contrast [$F_1=1.16$, $p>.25$; $F_2<1$] nor the HF-LP vs. LF-LP contrast

[F_1=2.41, p=.126; F_2=2.06, p>.15] reached significance. The HF-HP vs. LF-HP contrast, as before, was significant [all Fs>22, all ps<.001].

Far (7-9 character) analysis. The pattern of effects in this analysis differed substantially from the other two analyses. The only effect that was significant, as seen in Figure 2, was Frequency [all Fs>5, all ps<.05]. Neither Predictability nor the interaction were significant [all Fs<1].

Summary. The Frequency × Predictability × Preview analyses demonstrated several effects. First, as in the 2-way analysis, Frequency and Predictability were significant but their interaction was not. Second, the main effect of Preview was not only significant, but all interactions involving Preview were also significant (Frequency × Preview, Predictability × Preview, and Frequency × Predictability × Preview). In general, shorter launch distances led to greater parafoveal previews and, subsequently, shorter fixation times on the target. To better understand the 3-way interaction, separate 2-way analyses were performed at each level of Preview (Near, Middle, Far), each of which produced a distinct pattern of results. The Near analysis of Frequency × Predictability revealed reliable main effects and an interaction in which LF words showed a larger Predictability effect than HF words. The only main effect in the Middle analysis was Frequency; Predictability was trend by participants and marginal by items. Although the interaction was significant, the pattern was opposite to that of the Near analysis: HF words showed a larger Predictability effect than LF words. Finally, the Far analysis only showed a significant effect of Frequency. From these analyses, it appears that the original additive effects of Frequency and Predictability on fixation time (as measured without regard to launch site) was the result of a combination of three differing patterns of results, two of which were interactive.

<u>Landing position analyses</u>

One concern regarding the launch site analyses involves the location of readers' target word fixations in terms of character position. It is well-established that the landing position in a target depends on the launch distance (e.g., McConkie et al., 1988; Radach & Kempe, 1993; Radach & McConkie 1998; Rayner et al., 1996). As launch distance increases, landing position shifts further to the left within the target and becomes more variable. Moreover, target fixation time varies as a function of landing position, with longer fixation times associated with more eccentric landing positions. This U-shaped function tends not to be symmetric. The most efficient viewing position in normal reading is one situated halfway between the beginning and middle of a word ("preferred viewing location"; Rayner, 1979) and is less central than that found in single word identification ("optimal viewing position"; O'Regan & Jacobs, 1992).

As in our prior analyses with fixation duration, we examined landing position in 3-way (Frequency × Predictability × Preview) ANOVAs by participants and items. We found a significant main effect of Preview (i.e., launch distance) [$F_1(2,126)=202.08$, $MSE=1.04$, $p<.001$; $F_2(2,86)=183.75$, $MSE=.55$, $p<.001$]. Follow-up contrasts showed that the landing position from each launch distance (Near, Middle, or Far) differed significantly from every other launch distance condition [F_1s>92.40, ps<.001; F_2s>77.00, ps<.001]. That is, Near launch sites gave rise to average landing positions (4.52 characters) that were located further into the target than landing positions associated with Middle launch sites (3.57 characters), and both of these were further right than landing positions from Far launch sites (2.71 characters). It is interesting to note that, although launch sites were distributed across 9 characters, the ensuing average landing positions comprised a range of less than 2 characters.

Other effects of landing position were, overall, not significant. The main effect of Frequency, although statistically suggestive, was not reliable, with only a small numerical difference between landing position on HF versus LF words (3.65 vs. 3.54 characters, respectively) [$F_1(1,63)=3.07$, $MSE=.76$, $p=.085$; $F_2(1,43)=2.40$, $MSE=.57$, $p=.129$]. Similarly, the main effect of Predictability was not significant [$F_1<1$; $F_2(1,43)=2.80$, $MSE=.44$, $p=.102$]. Finally, none of the 2- and 3-way interactions were significant [all Fs<1.25, ps>.30].

Recall, we had found a significant main effect of Preview in SFD, with shorter fixation times associated with closer launch distances. We suggested that a closer launch distance gave rise to better parafoveal preview, reducing subsequent target fixation time. Results from the current landing position analyses, however, suggest that there might be a complex trade-off between preview benefit and landing position. That is, although close launch sites provide a clearer preview of the target, the succeeding saccade will land further into the target, hence resulting in a non-preferred or less-than-optimal viewing position which would serve to increase target recognition time. Far launch sites, in contrast, not only provide a poor preview, but also tend to undershoot the preferred viewing location, again leading to increased fixation time. Medium launch sites, which occurred most frequently in our data, may represent the "just right" situation – in which a certain degree of parafoveal preview can still be obtained without adversely affecting the subsequent preferred landing (or processing) position on the target.

To address these issues, we examined SFD *only* in cases when the landing position was on character 3 of the target. This allowed us to consider the effects of launch distance in the absence of variability in landing position. The average SFDs on character 3 of the target across Frequency, Predictability, and Preview conditions are shown in Figure 3. Unfortunately, we were not able to conduct ANOVAs on these results as there were too few cases in our dataset. The percentage of data points per condition are reported in Table 6 (average number of data points per condition = 62, range: 32-100). Overall, SFD data from character 3 represented 25% of the SFD data conditionalized on launch site, and only 13% of the total possible number of data points. The pattern of means, however, was quite similar to that obtained in the 3-way SFD design (Figure 2). For the main pattern to emerge, it must have been maintained in the remaining 75% of the conditionalized SFD data having landing positions other than character 3 (based on the average target word length of ~6 characters, there were 6 other possible landing positions – the space or character 0, and characters 1, 2, 4, 5, and 6). Taken together, this seems to tentatively demonstrate that the pattern of effects in the 3-way SFD data was not, in fact, driven by the processing consequences of systematic differences in landing position, but by differences in the amount of parafoveal preview.

Insert Figure 3 and Table 6 about here

Finally, we considered the entire pattern of SFD effects across all landing positions. We divided target words into beginning (Beg), middle (Mid), and ending (End) regions, disregarding fixations on the space before the target. For 5-, 6-, 7-, and 8-letter targets, the Beg region comprised letters 1-2, 1-2, 1-3, and 1-3, the Mid region comprised letters 3, 3-4, 4-5, and 4-5, and the End region comprised letters 4-5, 5-6, 6-7, and 6-8, respectively. The number of SFD data points in each condition as a function of launch distance and landing position is presented in Table 7. The distribution of data points was consistent with past landing position research described above. For example, a near launch site gave rise to fewer word-initial fixations and more word-final fixations, while the opposite held for a far launch site, with more word-initial fixations and fewer word-final fixations. SFD means within this 2 (Frequency) × 2 (Predictability) × 3 (Landing Position) × 3 (Preview) design are displayed in Figure 4. We did not conduct ANOVAs on these data – the additional post-hoc division of data by landing position not only reduced the number of data points per condition but also served to distribute them unevenly. A comparison of the pattern of means of all SFD data (Figure 2) and of SFD data as a function of landing position (Figure 4), however, demonstrates a high qualitative degree of similarity. Thus, the amount of parafoveal preview obtained seems to play a key role in determining the subsequent pattern of target fixation times.

Insert Table 7 and Figure 4 about here

Pre-target fixation analyses

We also examined the duration of the launch site fixation, itself, as a function of target word condition. The goal was to determine whether aspects of the target word affected the duration of the pre-target fixation. Such effects are termed “parafoveal-on-foveal” effects because the ease or difficulty of processing a target can begin to emerge on the prior fixation, when the target is located in parafoveal vision. While the mechanisms underlying parafoveal-on-foveal effects are disputed (see, e.g., Miellet et al., 2009), these effects, in general, tend to be quite small and are often difficult to demonstrate reliably (Kliegl, 2009).

Three-way (Frequency × Predictability × Preview) ANOVAs on the fixation before the target were conducted by participants and by items. Pre-target fixations were included in the analyses only if they were immediately followed by a fixation on the target. We excluded cases in which the target was skipped for several reasons. Fixations preceding skips occur only in a minority of the data and are typically inflated in duration. Additionally, skips are more likely to occur in certain conditions (Table 4). The pre-target fixation data are displayed in Figure 5. The only effect that was significant in both participants and items analyses was a main effect of Predictability [$F_1(1,63)=9.73$, $MSE=1304$, $p<.01$; $F_2(1,43)=4.81$, $MSE=1271$, $p<.05$]. Fixations occurring before HP words (256 ms) were reliably shorter than those occurring before LP words (264 ms), supporting the presence of parafoveal-on-foveal effects.

Insert Figure 5 about here

The remaining effects were either not significant or were only significant by either participants or by items (but not both). As such, our interpretations are fairly tentative. The main effect of Frequency was not significant [$F_1(1,63)=1.74$, $MSE=1731$, $p>.15$; $F_2(1,43)=1.39$, $MSE=1340$, $p>.20$]. The main effect of Preview was only significant by participants [$F_1(2,126)=3.08$, $MSE=2579$, $p<.05$; $F_2(2,86)=2.03$, $MSE=1103$, $p=.137$]. Pre-target fixation times tended to be longer with closer launch sites (265, 260, and 254 ms for Near, Middle, and

Far launch distances, respectively). Frequency × Preview was not significant by participants and only marginal by items [F_1 <1; $F_2(2,86)=2.36$, *MSE*=966, $p=.100$]. Predictability × Preview, however, was significant, but only by participants [$F_1(2,126)=3.36$, *MSE*=1817, $p<.05$; $F_2(2,86)=2.13$, *MSE*=1021, $p=.125$]. The greatest difference between HP and LP conditions (collapsed across Frequency) on the pre-target fixation arose from Near (LP–HP=19 ms) in comparison to Middle (LP–HP=6 ms) or Far (LP–HP=0 ms) launch sites. The Frequency × Predictability interaction was marginal [$F_1(1,63)=2.71$, *MSE*=1591, $p=.104$; $F_2(1,43)=3.34$, *MSE*=2525, $p=.075$]. The numerical pattern of means showed that pre-target fixations were shortest for HF-HP targets (251 ms) compared to any other target condition (264, 260, and 263 ms for HF-LP, LF-HP, and LF-LP conditions, respectively). Finally, Frequency × Predictability × Preview was not significant [F_1 <1; $F_2(2,86)=1.47$, *MSE*=1324, $p>.20$].

In sum, parafoveal-on-foveal effects did emerge, but only in limited circumstances. Pre-target fixations were speeded when the parafoveal target was HP versus LP. Although the interactions were generally of marginal significance, these showed that the parafoveal-on-foveal effect of predictability was mediated, to a degree, both by launch distance (with greater predictability differences the closer the launch site) and by frequency (with greater differences when the target was HF).

Discussion

Our study examined the interaction between word frequency and contextual predictability on target words in short passages of text while readers' eye movements were monitored. While past RT studies have generally demonstrated interactive effects of frequency and predictability, eye movement reading studies have typically reported additive effects. We suggested that several possible methodological limitations were associated with both the RT and eye movement studies. Our study attempted to address these limitations, particularly with respect to the recent reading study of Rayner et al. (2004), by using more experimental items per condition in carefully controlled, lengthier contexts, and by avoiding anomaly in conditions of low predictability. Because the processing of some level of frequency and predictability begins on the prior fixation, as evidenced by the parafoveal preview benefit associated with these variables, we additionally examined target fixation times as a function of the pre-target launch distance. In this way, the amount of parafoveal preview achieved on the prior fixation varies (from high to low) as a result of launch distance (from near to far). Prior research manipulating parafoveal preview has typically used letter strings that are visually different from target words in their "no preview" condition (e.g., Sereno & Rayner, 2000; for a review, see Balota & Rayner, 1991). When the boundary is crossed, the preview is replaced by the target. While an invalid preview ensures foveal-only processing of a target, it also introduces an incorrect stimulus, which may be perceived in greater or lesser detail depending on the location of the pre-target fixation. Analyzing target word processing as a function of launch distance should provide a more ecologically valid assessment of parafoveal processing. By testing a relatively high number of items per condition (N=22) across a high number of participants (N=64), we were able to perform reliable *post-hoc* analyses by launch distance on our data.

We first analyzed Frequency (HF, LF) × Predictability (HP, LP) effects on target words irrespective of prior launch site. Fixation time measures that reflect more immediate, first-pass processing of the target – FFD, SFD, and GD – showed reliable effects of Frequency and Predictability but no interaction, replicating the results from identical measures in Rayner et al. (2004). HF and HP words received shorter fixations than their LF and LP counterparts. Our TT results (which include later regressions made to the target) also replicated those of Rayner et al., showing main effects and no interaction (N.B. our interaction was marginal by participants). Finally, as in Rayner et al., we found a reliable interaction in the PrF measure. HF-HP words were skipped more often (i.e., had a lower probability of fixation) than the other conditions (HF-LP, LF-HP, and LF-LP). We had predicted that the "upgraded" specifications of our materials, in relation to those used in Rayner et al., might lead to interactive fixation time findings. This did not occur. The implications of these results, however, cannot be discussed without reference to our findings in which launch distance was used as an additional factor in the analysis.

We performed the Frequency × Predictability × Preview (Near, Middle, Far) analyses while maintaining a relatively high number of data points within each sub-condition (average=249 for SFD). As in the original analysis, we found reliable effects of Frequency and Predictability but no interaction of these two factors. As predicted, the main effect of Preview was also significant, with longer target fixation times associated with greater launch distances. Additionally, all interactions involving Preview were significant, including the 3-way interaction. We thus performed separate Frequency x Predictability analyses at each level of Preview (Near, Middle, and Far). Frequency was significant in all three analyses. While LF words were consistently fixated for longer durations than HF words, this difference was greater for nearer launch sites (SFD differences: 48, 25, and 14 ms for Near, Middle, and Far launch sites, respectively). Predictability was significant in the Near analysis, trend by participants and marginal by items in the Middle analysis, and non-significant in the Far analysis. Again, the advantage for HP words over LP words decreased with launch distance (SFD differences: 26, 8, and 4 ms for Near, Middle, and Far launch sites, respectively). In terms of the Frequency × Predictability interaction, three distinct patterns emerged across Preview condition. The interaction was significant in both the Near and Middle analyses, but in different ways. In the Near analysis, although both HF and LF words showed reliable Predictability effects, this effect was larger for LF words. In the Middle analysis, Predictability was only significant for HF words. Finally, in the Far analysis, the interaction was non-significant. In general, the overall pattern of launch site findings demonstrated, as predicted, an attenuation of effects with greater launch distance (i.e., less effective parafoveal preview).

We also performed two further supplementary analyses of our data. First, we examined how target landing position was affected by launch site. Past research has demonstrated that greater launch distances yield landing positions that are both further to the left within the target (word-beginning) and more variable. Moreover, landing position, itself, influences the ease or difficulty of processing of the target as reflected in fixation time, with more eccentric positions (word-beginning or word-end) giving rise to longer fixations. In line with prior research, we found that average landing position did vary systematically as a function of launch distance: fixation location moved toward the left with increased launch distance. Thus, it was possible that the pattern of fixation time results was not solely due to differences in the amount of parafoveal preview available from the prior fixation (as gauged by launch distance), but was instead due to associated differences in fixation location on the target, itself. We held fixation location constant by only considering SFDs whose landing position was character 3. While these data represented a relatively large proportion (25%) of the SFD data (i.e., assuming an even distribution, each of the 7 possible landing positions should comprise ~14% of the data), the data were too sparse to perform meaningful analyses. We also examined the pattern of SFD means as a function of landing position defined by word region (beginning, middle, or ending). In both cases, the numeric pattern of means generally mirrored that of the complete dataset. We suggested that, although landing position was influenced by launch distance, the resulting effects on fixation time were more a consequence of the relative amount of parafoveal preview of the target (i.e., launch site) rather than the location of the fixation on the target.

Our second ancillary analysis concerned the duration of the pre-target fixation, namely, whether there was any evidence of parafoveal-on-foveal processing, when target word effects begin to appear before its subsequent fixation. We found that the pre-target fixation was shorter when the parafoveal target was HP versus LP. Although the remaining effects produced a variable pattern of statistical significance, they were suggestive that the parafoveal-on-foveal effect of predictability was influenced, in part, by launch distance to the target and target frequency, with larger parafoveal-on-foveal predictability effects for closer launch sites and HF targets, respectively.

All of these additional analyses inject complexity to the initial findings of additive Frequency × Predictability target word effects and provide a more dynamic account of events. In terms of the pre-target fixation, closer launch sites tended to give rise to longer (pre-target) fixations. However, closer launch sites also led to greater parafoveal pre-processing of the target, specifically in terms of its predictability, particularly when the target was HF. Although the pre-target launch site systematically affected the subsequent location of the fixation on the target (leading to more or less preferred viewing locations), differences in target fixation location did not result in any significant target fixation time effects. For example, when saccades were made from the Near location, although the landing position was further into the target (in a less-preferred location), target fixation times were, nevertheless, shortest in this condition. Thus, it seems that the increased parafoveal pre-processing of the target acquired from a close launch site was sufficient to offset any cost associated with a non-optimal fixation location. Moreover, when landing position was limited to the third character of the target, the basic pattern of target effects remained. From these analyses, it appears that at least some portion of target word Frequency and Predictability effects begin to emerge prior to its fixation. This suggestion of lexical-level pre-processing is substantiated by the differential pattern of Frequency × Predictability effects demonstrated on the target, itself, which are dependent on launch distance (i.e., the amount of parafoveal preview). Further evidence for a degree of lexical pre-processing is derived from the pattern of target word skipping, in which HF-HP words were more likely to be skipped than words in any other condition.

Floors and ceilings

Our analyses showed that the apparent additive effects were the product of frequency effects at all launch distances and two opposing interactions related to predictability at the Middle and Near launch sites. As can be seen in Figure 2, with Middle preview, the HF predictability effect was greater than a (non-significant) LF predictability effect, while with Near preview, the LF predictability effect was greater than a (significant) HF predictability effect. At least superficially, the range of fixation times across conditions seems to suggest possible floor and ceiling effects. On the "floor" end, it can be argued that there is a lower limit for the duration of single fixations on words in reading – that is, due to oculomotor constraints, fixation times, on average, just cannot get any faster. On this view, it is possible that HF-HP words in the Near condition *should* be fixated for less time but are not. While there is evidence that first fixations of immediately refixated words are shorter than first-and-only (single) fixations (e.g., Sereno, 1992), this is often attributed to lower-level aspects of eye movement behavior (Rayner, 1979). That is, an awkward location of the initial fixation (e.g., landing on external vs. more central letters of a word) can lead to an immediate refixation in order to optimize the viewing position. In addition, first fixations of refixated words are also shorter because there is no associated cost of shifting attention to another word as would be the case with single fixations (Sereno, 1992). The most compelling evidence for a floor effect in our data, however, is demonstrated by comparing first-pass measures for HF-HP words at the Near launch site. As seen in Table 5, this condition has associated means of 218, 219, and 220 ms for FFD, SFD, and GD measures, respectively. For all three measures to be equivalent, targets would have to be fixated only once almost all of the time. Thus, a single fixation was sufficient in duration, and possibly excessive, to process such words at the closest launch site.

On the "ceiling" end, the average longest duration of single fixations was around 290 ms. As seen in Figure 2, all LF conditions, with the exception of LF-HP words at the Near launch site, received similar SFDs (means were within 9 ms of each other). The notion of a fixation deadline in reading has been previously proposed and is able to account for certain aspects of eye movement behavior (e.g., Henderson & Ferreira, 1990; Sereno, 1992). On this view, if a criterion level of processing on the current word has not been completed (reaching the criterion would normally trigger an eye movement to the next word), a deadline will be reached whereby an eye movement will nonetheless be made. The saccade target (intra- or extra-word) depends on the relative timing and progress of cognitive and oculomotor variables. If there is a fixation deadline, the question remains as to *when* the processing occurs in more difficult conditions (e.g., LF-LP words at the Far launch site). To this end, we examined the number of immediate first-pass refixations as well as the number of second-pass fixations across all Frequency, Predictability, and Preview conditions. Across these conditions, there was a total of 385 refixations and 430 second-pass fixations. This data is somewhat obscured in fixation time measures. That is, although GD includes first-pass refixations and TT includes second-pass fixations, such fixations only account for a small percentage of the data. Thus, GD is largely a function of FFD and SFD, and TT a function of GD. As noted earlier, each cell of the 3-way design attracted a different number of fixations (see Table 3). For example, there were more target fixations that originated from Middle versus Near or Far launch distances. To control for this uneven distribution, we calculated the percentage of refixations and second-pass fixations in any given cell based on the total possible number of data points in that cell. Table 8 shows these percentages. Numerically, on average, there were more of these fixations in the LF (27%) than in the HF (20%) condition, in the LP (28%) than in the HP (19%) condition, and in the Far (28%) or Middle (25%) than in the Near (18%) condition. This pattern of data lends support to the idea of a deadline, with more fixations (immediate or returning) made to those conditions which were more difficult.

Insert Table 8 about here

One further assessment of the data was performed to substantiate the occurrence of floor and ceiling effects. We calculated the variance across all conditions. If floors and ceilings were operating in certain conditions, then there should be relatively less variance in these conditions. The average standard deviations across all conditions are shown in Figure 6. The standard deviations, however, were highly variable. In addition, as some of the participant and item means in any given condition were only represented by a single data point, standard deviations could not be obtained, giving rise to missing cells. Thus, although the numerical pattern of results generally confirmed our conjectures, we could not provide any statistical proof of such effects.

Insert Figure 6 about here

In sum, our qualitative assessments of the data lend some support to the notion of a floor affecting the HF-HP/Near condition and a ceiling affecting all LF conditions except the LF-HP/Near condition. However, we cannot definitively show that such effects exist. If floor and ceiling effects were, in fact, operative, it becomes somewhat problematic to interpret the results. For example, if the HF-HP/Near condition had not been artificially slowed by a putative floor, the pattern of Frequency and Predictability effects in the Near Preview condition may have been additive. None of the HF conditions, however, were affected by a ceiling, as evidenced by reliable Frequency effects across all Predictability and Preview conditions. HF conditions also showed, when unconstrained by either a floor or ceiling, an attenuation of Predictability effects from the Middle to Far launch distances. In contrast, LF-HP/Near was the only condition *not* affected by a putative ceiling. It is possible, for example, that if fixation times in the remaining LF conditions were unimpeded, then Frequency × Predictabiliy may have been additive in the Middle Preview condition and interactive in the Far Preview conditions (with extended fixations selectively for LF-LP words). Such scenarios at this point, however, are purely speculative. Despite the limitations imposed by the possibility of such effects, we have attempted to offer plausible interpretations of these findings with respect to models of lexical processing and current models of eye movement control.

Models of lexical processing

Our approach from the outset had been to frame Frequency × Predictability within the modularity-interactive debate by determining whether the data exhibited additive or interactive effects. Within the additive-factors approach, additive or interactive statistical findings are generally used to infer either serial processing over discrete stages or multiple activations affecting each other within a common stage, respectively. Although this approach is still widely used within the literature related to mental chronometry, it has long been subjected to a variety of critical assessments (see, e.g., Townsend, 1984; Yap & Balota, 2007). Given the complex connectivity of the neural substrates associated with, for example, language processing, the notion of isolated, non-overlapping processing stages seems implausible. Nevertheless, additive-factors has provided a productive framework that has helped reveal the relative timing of lexical variables. Temporally precise techniques such as measuring electrophysiological responses can then be used to confirm the onset and duration of different aspects of processing.

Within an additive-factors framework, the original (2-way) Frequency × Predictability results, when examined in isolation, demonstrated additive effects and seem, at first glance, to support a modular account of lexical processing. That is, context does not directly affect lexical access, but influences a later, post-lexical integration stage of processing. Given that this additive pattern was maintained in all fixation time measures (FFD, SFD, GD, and TT), this view would have to assume that both lexical and post-lexical stages are reflected in the earliest FFD measure and are not modulated by additional processing that occurs in the temporally later GD or TT measures. As a corollary, it would also assume that the processing cost of integrating LF or LP meanings is equivalent to that associated with HF or HP meanings. An interactive account, on the other hand, would have to posit that the apparent additive pattern of effects was a consequence of differential access and integration processes that happen to offset each other. During lexical access, a biasing context would confer greater benefit to LF than HF words. In terms of semantic integration, however, an interactive account would have to assume that an initial advantage gained during access is offset by a cost in integration (depending on the specific frequency-predictability activation profile), masking underlying interactive lexical effects. These opposing effects would begin in FFD and continue into later measures. Because additional suppositions are required from both models to explain why the pattern of fixation times does not differ across measures, at present, neither account seems wholly tenable. The issue remains of how to account for the different Frequency × Predictability sub-patterns when Preview is included as a factor.

It is clear from our 3-way analysis that past eye movement findings (including our initial analysis) demonstrating additive effects of frequency and predictability conceal sub-patterns (some interactive) which vary with launch distance. Analyses across the different launch sites in the present study indicated a dynamic complexity – the nature of the interaction reversed from Near to Middle sites and became insignificant at Far sites. The potential presence of apparent floor and ceiling effects, however, severely constrains our attempts to offer a definitive interpretation. At a superficial level, at least, there is clear evidence that the additive pattern of results does not hold when launch site is considered. Given these circumstances, it does not seem prudent to speculate about what modular and interactive models might suggest in order to account for the additional factors of launch distance and fixation time limits. We think that a more productive approach is to discuss the present findings in relation to current models of eye movement control.

Models of eye movement control

Recently, several models of eye movement control in reading have emerged which attempt to capture the temporal dynamics of reading by parameterizing lower-level, perceptual to higher-level, cognitive contingencies of reading behavior. The assumption that on-going cognitive processing is the main determinant of eye movement control (Rayner et al., 1996) is a key feature of such models. Specifically, fixation time (i.e., when to move the eyes) is mainly determined by the status of on-line language processing, while fixation position (i.e., where to move the eyes) depends on the combined influence of linguistic, visual, and oculomotor factors. There are two main categories of eye movement control models that differ in how visual attention is thought to be allocated in reading. In "sequential attention shift" models, parafoveal preview benefit is due to a covert, serial movement of attention towards the parafoveal word preceding the eye movement to that word (e.g., Morrison, 1984; E-Z Reader of Reichle et al., 2003). In "guidance by attentional gradient" models, the preview benefit is explained by parallel processing of several words within the perceptual span (e.g., SWIFT of Engbert, Nuthmann, Richter, & Kliegl, 2005; Mr. Chips of Legge, Hooven, Klitz, Mansfield, & Tjan, 2002; Glenmore of Reilly & Radach, 2003). Our discussion will be limited to E-Z Reader and SWIFT as these are the most prominent models.

In E-Z Reader (e.g., Reichle et al, 2003), lexical access occurs over two stages. Completion of the first stage of lexical access ("familiarity check") signals saccadic programming to begin, and completion of the second ("completion of lexical access") signals the attentional "spotlight" to shift to the next word. The main factors affecting both stages of access are word frequency and contextual predictability. The model can and has simulated either an additive or a multiplicative interaction of frequency and predictability. In its original instantiation, E-Z Reader adopted a multiplicative function (Reichle et al., 2003). To accommodate the data of Rayner et al. (2004), this function was changed to an additive one (detailed in the same paper).

The SWIFT model (e.g., Engbert et al., 2005) assumes that processing is spatially distributed within an "activation field" which decreases with the distance from fixation location.

The activation on a given word increases with the degree of lexical access, but then rapidly declines when the word is fully comprehended. Consequently, most words to the left of the foveal target will have minimal activation unless they have not been fully accessed. Words to the right generally have a higher level of activation, although this decreases with degree of eccentricity. Lexical access time is a function of both frequency and predictability. The parallel processing of words leads to predictions regarding the processing difficulty of target word *n* both on word *n+1* and word *n-1* (Kliegl et al., 2006).

E-Z Reader and SWIFT can be discriminated by the absence or presence, respectively, of pervasive parafoveal-on-foveal effects, in which lexical characteristics of the parafoveal word are reflected in fixation time on the foveal word. Recently, proponents of E-Z Reader have suggested that parafoveal-on-foveal effects can arise from "mislocated" fixations – that is, ones resulting from saccadic undershoots of the parafoveal word which land, instead, on the foveal word (Drieghe, Rayner, & Pollatsek, 2008). This claim, however, has been challenged by those who argue for parallel processing of adjacent words (e.g., Kennedy, 2008). Our data on the pre-target fixation are somewhat equivocal on this issue. On one hand, we show a significant main effect of Predictability (i.e., collapsed across Near, Middle, and Far pre-target fixation locations), supporting a parallel processing approach. On the other, we also show statistically weaker effects in which the pre-target Predictability effect is modulated by proximity of the pre-target fixation to the target, supporting a serial account in conjunction with mislocated fixations. Of more relevance to the current findings, however, is each model's theoretical stance on how frequency and predictability interact. E-Z Reader is theoretically silent on the additive versus multiplicative nature of the interaction. SWIFT identifies a different temporal profile for each function. That is, frequency only becomes relevant when the word comes into view. Word predictability is independent of visual input and can, therefore, occur earlier than frequency.

This process dissociation in SWIFT, however, produces neither a strictly additive nor multiplicative interaction.

Our data show both additive and multiplicative patterns of frequency and predictability. The nature of the interaction seems to depend not only on launch site, but also on possible floor and ceiling effects. If these conjectures are valid, then it becomes a computationally empirical question whether implementing a preview function along with certain fixation ranges in E-Z Reader (additive or multiplicative versions) or SWIFT would generate simulated data replicating our findings. Both models discuss launch site, but only in relation to its effect on the accuracy and distribution of landing sites. In both models, landing sites can influence fixation duration. For example, close and far launch sites to short and long words, respectively, can give rise to non-optimal landing positions (overshoots and undershoots, respectively), and increase fixation duration. As such, launch distance is potentially confounded with a word's optimal viewing location as a function of its length. Although word length and frequency in general tend to be negatively correlated, these variables were manipulated orthogonally in our experiment. In any case, the quality of the preview is not directly addressed in either model. In terms of fixation limits, Reichle et al. (2003) specifically argued against the concept of a deadline. They reasoned that if it were present, then first fixations of refixated words should always be longer than single-and-only fixations (i.e., the deadline would always be reached if a word required a second fixation). This account, however, fails to recognize the additional demands in single fixations associated with shifting attention to a new word versus, in refixations, simply maintaining attention on the current word (Sereno, 1992). A benefit of implementing a preview function and fixation limits might be that a single rule could be used to characterize the activation functions of frequency and predictability. Thus, an additive or interactive pattern of effects would not be hard-wired into the model, but instead emerge as a consequence of other constraints

Conclusion

Our experiment explored the nature of the interaction between word frequency and contextual predictability in fixation times on words during normal reading. In general, RT research has found interactive effects of these variables while eye movement research has found additive effects. Our design attempted to improve on various methodological aspects of previous studies. We also examined the role of parafoveal preview, indexed by launch distance. When only frequency and predictability were considered, our results replicated past eye movement research demonstrating additive effects. When launch distance was taken into account, however, we found interactive as well as additive patterns within the data. These patterns were suggestive of the operation of concurrent floor and ceiling effects. A methodological drawback of our study was that, although there was a relatively large amount of data points per condition within the post-hoc analysis of launch distance, it was not enough to definitively demonstrate the existence of fixation time limits. As a result, the interpretation of our findings in terms of models of language processing can only be speculative. The data, however, do have implications for current models of eye movement control. The quality of parafoveal preview and the notion of fixation time limits are factors that, if incorporated into eye movement models, could provide insight into the underlying processing that occurs while reading. In sum, we believe our experiment provides a worthwhile approach to validate models of word recognition and eye movement control in reading.

References

Altaribba, J., Kroll, J.F., Sholl, A., & Rayner, K. (1996). The influence of lexical and conceptual constraints on reading mixed language sentences: Evidence from eye fixation and naming times. Memory & Cognition, 24, 477-492.

Ashby, J., Rayner, K., & Clifton, C., Jr. (2005). Eye movements of highly skilled and average readers: Differential effects of frequency and predictability. Quarterly Journal of Experimental Psychology, 58A, 1065-1086.

Balota, D.A. (1990). The role of meaning in word recognition. In D.A. Balota, G.B. Flores d'Arcais, & K. Rayner (Eds.), Comprehension processes in reading (pp. 143-164). Hillsdale, NJ: Erlbaum.

Balota, D.A., Pollatsek, A., & Rayner, K. (1985). The interaction of contextual constraints and parafoveal visual information in reading. Cognitive Psychology, 17, 364-390.

Balota, D.A., & Rayner, K. (1991). Word recognition processes in foveal and parafoveal vision: The range of influence of lexical variables. In D. Besner & G.W. Humphreys (Eds.), Basic processes in reading: Visual word recognition (pp. 198-232). Hillsdale, NJ: Erlbaum.

Carroll, P., & Slowiaczek, M.L. (1986). Constraints on semantic priming in reading: A fixation time analysis. Memory & Cognition, 14, 509-522.

Dien, J., Frishkoff, G.A., Cerbone, A., & Tucker, D. (2003). Parametric analysis of event-related potentials in semantic comprehension: Evidence for parallel brain mechanisms. Cognitive Brain Research, 15, 137-153.

Drieghe, D., Rayner, K., & Pollatsek, A. (2008). Mislocated fixations can account for parafoveal-on-foveal effects in eye movements during reading. Quarterly Journal of Experimental Psychology, 61, 1239-1249.

Engbert, R., Nuthmann, A., Richter, E.M., & Kliegl, R. (2005). A dynamical model of saccade generation during reading. Psychological Review, 112, 777-813.

Ehrlich, S.F., & Rayner, K. (1981). Contextual effects on word perception and eye movements during reading. Journal of Verbal Learning and Verbal Behavior, 20, 641-655.

Fodor, J.A. (1983). Modularity of mind. Cambridge, MA: MIT Press.

Forster, K.I. (1979). Levels of processing and the structure of the language processor. In W.E. Cooper & E. Walker (Eds.), Sentence processing: Psycholinguistic studies presented to Merrill Garrett (pp. 27-85). Hillsdale, NJ: Erlbaum.

Hauk, O., & Pulvermüller, F. (2004). Effects of word length and frequency on the human event-related potential. Clinical Neurophysiology, 115, 1090-1103.

Henderson, J.M., & Ferreira, F. (1990). Effects of foveal processing difficulty on the perceptual span in reading: Implications for attention and eye movement control. Journal of Experimental Psychology: Learning, Memory, and Cognition, 16, 417-429.

Inhoff, A.W. (1984). Two stages of word processing during eye fixations in the reading of prose. Journal of Verbal Learning and Verbal Behavior, 23, 612-624.

Inhoff, A.W., & Rayner, K. (1986). Parafoveal word processing during eye fixations in reading: Effects of word frequency. Perception & Psychophysics, 40, 431-439.

Just, M.A., & Carpenter, P.A. (1980). A theory of reading: From eye fixations to comprehension. Psychological Review, 87, 329-354.

Kennedy, A. (2008). Parafoveal-on-foveal effects are not an artifact of mis-located saccades. Journal of Eye Movement Research, 2, 1-10.

Kennison, S.M., Clifton, C., Jr. (1995). Determinants of parafoveal preview benefit in high and low working memory capacity readers: Implications for eye movement control. Journal of Experimental Psychology: Learning, Memory, and Cognition, 21, 68-81.

Kliegl, R. (2009, August). Distributed processing during reading fixations. Keynote presentation, European Conference on Eye Movements (ECEM) 15 meeting, Southampton, UK.

Kliegl, R., Grabner, E., Rolfs, M., & Engbert, R. (2004). Length, frequency, and predictability effects of words on eye movements in reading. European Journal of Cognitive Psychology, 16, 262-284.

Kliegl, R., Nuthmann, A., & Engbert, R. (2006). Tracking the mind during reading: The influence of past, present, and future words on fixation durations. Journal of Experimental Psychology: General, 135, 12-35.

Kliegl, R., Olson, R. K., & Davidson, B. J. (1982). Regression analyses as a tool for studying reading processes: Comments on Just and Carpenter's eye fixation theory. Memory & Cognition, 10, 287-296.

Lavigne, F., Vitu, F., & d'Ydewalle, G. (2000). The influence of semantic context on initial landing sites in words. Acta Psychologica, 104, 191-214.

Legge, G.E., Hooven, T.A., Klitz, T.S., Mansfield, J.S., & Tjan, B.S. (2002). Mr. Chips 2002: New insights from an ideal-observer model of reading. Vision Research, 42, 2219-2234.

McClelland, J.L. (1987). The case for interactionism in language processing. In M.Coltheart (Ed.), Attention and performance: Vol.12. The psychology of reading (pp. 363-383). Hillsdale, NJ: Erlbaum.

McConkie, G.W, Kerr, P.W., Reddix, M D., & Zola, D. (1988). Eye movement control during reading: I. The location of initial eye fixations in words. Vision Research, 28, 1107-1118.

McConkie, G.W., & Rayner, K. (1975). The span of the effective stimulus during a fixation in reading. Perception & Psychophysics, 17, 578-586.

McDonald, S.A., & Shillcock, R.C. (2003a). Eye movements reveal the on-line computations of lexical probabilities during reading. Psychological Science, 14, 648-652.

McDonald, S.A., & Shillcock, R.C. (2003b). Low-level predictive inference in reading: The influence of transitional probabilities on eye movements. Vision Research, 43, 1735-1751.

Miellet, S., O'Donnell, P.J., & Sereno, S.C. (2009). Parafoveal magnification: Visual acuity does not modulate the perceptual span in reading. Psychological Science, 20, 721-728.

Miellet, S., Sparrow, L., & Sereno, S.C. (2007). Word frequency and predictability effects in reading French: An evaluation of the E-Z Reader model. Psychonomic Bulletin & Review, 14, 762-769.

Morris, R.K. (1994). Lexical and message-level sentence context effects on fixation times in reading. Journal of Experimental Psychology: Learning, Memory, and Cognition, 20, 92-103.

Morrison, R.E. (1984). Manipulation of stimulus onset delay in reading: Evidence for parallel programming of saccades. Journal of Experimental Psychology: Human Perception and Performance, 10, 667-682.

Morton, J. (1969). Interaction of information in word recognition. Psychological Review, 76, 165-178.

Neville, H.J., Mills, D.L. & Lawson, D.S. (1992). Fractionating language: Different neural subsystems with different sensitive periods. Cerebral Cortex, 2, 244-258.

Nobre, A.C., & McCarthy, G. (1994). Language-related ERPs: Scalp distributions and modulation by word type and semantic priming. Journal of Cognitive Neuroscience, 6, 233-255.

O'Regan, J. K., & Jacobs, A. M. (1992). The optimal viewing position effect in word recognition: A challenge to current theory. Journal of Experimental Psychology: Human Perception and Performance, 18, 185-197.

Pulvermüller, F., Assadollahi, R., & Elbert, T. (2001). Neuromagnetic evidence for early semantic access in word recognition. European Journal of Neuroscience, 13, 201-205.

Radach, R., & Kempe, V. (1993) An individual analysis of initial fixation positions in reading. In G. d'Ydewalle & J. Van Rensbergen (Eds.), Perception and cognition: Advances in eye movement research (pp. 213-226). Amsterdam: North Holland.

Radach, R., & McConkie, G. W. (1998). Determinants of fixation positions in words during reading. In G. Underwood (Ed.), Eye guidance in reading and scene perception (pp. 77-101). Oxford: Elsevier.

Rayner, K. (1975). Parafoveal identification during a fixation in reading. Acta Psychologica, 39, 271-282.

Rayner, K. (1979). Eye guidance in reading: Fixation locations within words. Perception, 8, 21-30.

Rayner, K. (1998). Eye movements in reading and information processing: 20 years of research. Psychological Bulletin, 124, 372-422.

Rayner, K. (2009). Eye movements and attention in reading, scene perception, and visual search. Quarterly Journal of Experimental Psychology, 62, 1457-1506.

Rayner, K., Ashby, J., Pollatsek, A., & Reichle, E.D. (2004). The effects of frequency and predictability on eye fixations in reading: Implications for the E-Z Reader model. Journal of Experimental Psychology: Human Perception and Performance, 30, 720-730.

Rayner, K., Binder, K.S, Ashby, J., & Pollatsek, A. (2001). Eye movement control in reading: Word predictability has little effect on initial landing positions in words. Vision Research, 41, 943-954.

Rayner, K., & Duffy, S.A. (1986). Lexical complexity and fixation times in reading: Effects of word frequency, verb complexity, and lexical ambiguity. Memory & Cognition, 14, 191-201.

Rayner, K, & Raney, G.E. (1996). Eye movement control in reading and visual search: Effects of word frequency. Psychonomic Bulletin & Review, 3, 238-244.

Rayner, K., Sereno, S.C., & Raney, G.E. (1996). Eye movement control in reading: A comparison of two types of models. Journal of Experimental Psychology: Human Perception and Performance, 22, 1188-1200.

Rayner, K., & Well, A.D. (1996). Effects of contextual constraint on eye movements in reading: A further examination. Psychonomic Bulletin & Review, 3, 504-509.

Reichle, E.D., Rayner, K., & Pollatsek, A. (2003). The E-Z Reader model of eye movement control in reading: Comparisons to other models. Behavioral and Brain Sciences, 26, 445-476.

Reilly, R.G. & Radach, R. (2003). Foundations of an interactive activation model of eye movement control in reading. In J. Hyönä, R. Radach & H. Deubel (Eds.), The mind's eye: Cognitive and applied aspects of eye movement research (pp. 429-455). Amsterdam: Elsevier.

Schilling, H.E.H., Rayner, K., & Chumbley, J.I. (1998). Comparing naming, lexical decision, and eye fixation times: Word frequency effects and individual differences. Memory & Cognition, 26, 1270-1281.

Schuberth, R.E., & Eimas, P.D. (1977). Effects of context on the classification of words and nonwords. Journal of Experimental Psychology: Human Perception and Performance, 3, 27-36.

Scott, G.G., O'Donnell, P.J., Leuthold, H., & Sereno, S.C. (2009). Early emotion word processing: Evidence from event-related potentials. Biological Psychology, 80, 95-104.

Sereno, S.C. (1992). Early lexical effects when fixating a word in reading. In K. Rayner (Ed.), Eye movements and visual cognition: Scene perception and reading (pp. 304-316). New York: Springer-Verlag.

Sereno, S.C., Brewer, C.C., & O'Donnell, P.J. (2003). Context effects in word recognition: Evidence for early interactive processing. Psychological Science, 14, 328-333.

Sereno, S.C., O'Donnell, P.J., & Rayner, K. (2006). Eye movements and lexical ambiguity resolution: Investigating the subordinate bias effect. Journal of Experimental Psychology: Human Perception and Performance, 32, 335-350.

Sereno, S.C., Pacht, J.M., & Rayner, K. (1992). The effect of meaning frequency on processing lexically ambiguous words: Evidence from eye fixations. Psychological Science, 3, 296-300.

Sereno, S.C., & Rayner, K. (2000). Spelling-sound regularity effects on eye fixations in reading. Perception & Psychophysics, 62, 402-409.

Sereno, S.C. & Rayner, K. (2003). Measuring word recognition in reading: eye movements and event-related potentials. Trends in Cognitive Sciences, 7, 489-493.

Sereno, S.C., Rayner, K., & Posner, M.I. (1998). Establishing a time-line of word recognition: Evidence from eye movements and event-related potentials. NeuroReport, 9, 2195-2200.

Slattery, T.J., Pollatsek, A., & Rayner, K. (2007). The effect of the frequencies of three consecutive content words on eye movements during reading. Memory & Cognition, 35, 1283-1292.

Stanovich, K.E., & West, R.F. (1981). The effect of sentence context on ongoing word recognition: Tests of a two-process theory. Journal of Experimental Psychology: Human Perception and Performance, 7, 658-672.

Stanovich, K.E., & West, R.F. (1983). On priming by sentence context. Journal of Experimental Psychology: General, 112, 1-36.

Sternberg, S. (1969). Memory-scanning: Mental processes revealed by reaction-time experiments. American Scientist, 57, 421-457.

Townsend, J.T. (1984). Uncovering mental processes with factorial experiments. Journal of Mathematical Psychology, 28, 363-400.

West, R.F, & Stanovich K.E. (1982). Source of inhibition in experiments on the effect of sentence context on word recognition. Journal of Experimental Psychology: Learning, Memory, and Cognition, 8, 385-399.

Yap, M.J., & Balota, D.A. (2007). Additive and interactive effects on response time distributions in visual word recognition. Journal of Experimental Psychology: Learning, Memory, and Cognition, 33, 274-296.

Zola, D. (1984). Redundancy and word perception during reading. Perception & Psychophysics, 36, 277-284.

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Appendix: Experimental Materials

Experimental materials comprised 44 sets of short passages extending over two lines of the display as indicated. Corresponding high- and low-frequency (HF, LF) targets appear to the right. In the A-version of each set, HF targets were high predictable (HP) and LF targets were low predictable (LP); in the B-version, LF targets were HP while HF targets were LP. One participant group read HF-HP and LF-HP targets for odd-numbered item sets and HF-LP and LF-LP targets for even-numbered item sets, while the other participant group read the converse.

			HF	LF
1	A.	On holiday for a week, Jill and Harry decided to redecorate some rooms in their ______ that they felt needed making over.	house	motel
	B.	Exhausted from driving, and lost on the dusty highway, Tony decided to stop at the first ______ to get directions.		
2	A.	The gifted students were selected to receive extra lessons at the local ______ during weekends and holidays.	school	circus
	B.	All the children were thoroughly amused by the clowns that came once a year to the ______ in their village.		
3	A.	Denise was inconsolable after her friend’s death. At the funeral, she wore a sombre ______ dress and cried throughout.	black	satin
	B.	In preparation for her luxury spa weekend trip, Lucy treated herself to some fancy, new ______ pyjamas from the boutique.		
4	A.	Helena enjoyed literature and writing essays. She was going to university to study ______ and hoped to teach one day.	English	Zoology
	B.	Paul was sure he’d be made curator of exotic animals at the nature park. He had a degree in ______ and vast experience.		
5	A.	Construction work was now complete, and everyone was excited about the opening of the new ______ in the city centre.	building	monument
	B.	Many locals had died in the battle. In their memory, the community erected a ______ in the town square.		
6	A.	When Ann served against a superior tennis opponent, she always expected that the ball would ______ even faster.	return	bounce
	B.	Robbie enjoyed playing football. He spent hours kicking the ball against a wall and having it ______ back to him.		
7	A.	A problem with the cattle was that they would occasionally wander into the nearby ______ that belonged to Farmer Smith.	field	swamp
	B.	When crossing the marshlands, it was possible to become trapped in a muddy ______ if there had been heavy rainfall.		
8	A.	Rinsing hadn’t stopped the bleach from burning his eyes. He needed emergency attention from the ______ immediately.	hospital	optician
	B.	As he had grown older, his eyesight had deteriorated. He thought he should visit the o______ and get new glasses.		
9	A.	Guests were arriving and Jen’s flat was a sty. She picked up her clothes from the ______ and quickly cleaned the bathroom.	floor	couch
	B.	Clare had been on her feet all day. Armed with a pizza and a video, she laid down on the ______ for a relaxing evening.		

10	A.	None of the baker's plans for the wedding cake had satisfied the bride. He had completely run out of ______ and was irate.	ideas	yeast
	B.	Amy's bread dough for the dinner wouldn't rise and the shops were now closed. She had run out of ______ and was panicking.		
11	A.	Before her big date tonight, Natalie brushed her teeth until she was sure they were thoroughly ______ before meeting Luke.	clean	shiny
	B.	Wanting to make a good impression at the interview, Albert polished his nicest shoes to make them as ______ as possible.		
12	A.	They could have spent a week at the castle, but their train was leaving. They rushed to the s______ before time ran out.	station	dungeon
	B.	Hearing about torture in the castle made Debbie squeamish. She left the tour group in the ______ and went for a smoke.		
13	A.	The dentist carelessly let the extracted tooth slip from his tweezers into the patient's ______ to their mutual surprise.	mouth	beard
	B.	As the scruffy professor struggled for inspiration, he would pace his office and stroke his ______ hoping to find answers.		
14	A.	Frank was going to call the police. He was fed up with kids throwing stones at his ______ as damage could be done.	windows	chimney
	B.	The real coal fire was wonderful, but every month we had to have the sooty ______ cleaned, to our great inconvenience.		
15	A.	Arriving late, Penelope thought the birthday cake would be finished, but there was still a small ______ left in the box.	piece	crumb
	B.	Roger loved eating biscuits in bed. However, he was very careful not to drop a single ______ as his wife would be mad.		
16	A.	Because of heavy congestion on the roads, most of the freight was transported by ______ whenever possible.	train	barge
	B.	The gypsies travelled along the canal by hiding in the cargo of a slow moving ______ in the middle of the night.		
17	A.	While Linda was away on holiday, she arranged for her friend to come by and water all the ______ in her window boxes.	plants	tulips
	B.	Our photos from Holland were mostly of museums, windmills, and well-kept parks full of ______ of all different colours.		
18	A.	The Boy Scouts' weekend trip was a good way to teach them how to set up camp in the ______ should they ever have to.	forest	jungle
	B.	Their plane went down miles from any village. Injured and lost, they had to survive the ______ to make it back alive.		
19	A.	At her favourite band's concert, Melissa pushed to the front and was so close that she could almost ______ the singer.	touch	grope
	B.	The boss would lose his job. His secretary had reported him after he had tried to ______ her in the stationary cupboard.		
20	A.	After dessert, they ordered some ______ and took it through to the bar so that Jean could have a cigarette.	coffee	brandy
	B.	Dinner in the Paris bistro was superb. They agreed to finish their meal with a luxury ______ as they were on holiday.		
21	A.	Kyle knew he would go to prison. He had been caught outside the club selling ecstasy-laced ______ to undercover police.	drugs	mints
	B.	The smell of garlic was on his breath. Before going out, he thought he should take some ______ in case he met a girl.		

22	A.	John's bank manager would not give him the loan because he hadn't brought a valid ______ for identification.	document	passport
	B.	The immigrant was sure he would be deported. He had been caught with a fake ______ by customs officers at the port.		
23	A.	Dave's birthday was usually an event to remember. This year he and his friends were having a huge ______ to celebrate.	party	disco
	B.	My parents met in the Seventies, when every Saturday night they would go into town to a ______ and dance the night away.		
24	A.	Gillian was on the last mile of the women's marathon. She grabbed a bottle of ______ from a spectator and drank it.	water	lager
	B.	Although a rugby player, Clive struggled through the crowd at the bar carrying glasses of ______ and bags of crisps.		
25	A.	George had been raised to be kind to everyone in his life and was undoubtedly the nicest ______ Angela had ever met.	person	waiter
	B.	The starters had not yet arrived. Annoyed, Peter decided to stop the next ______ he saw and complain about the service.		
26	A.	When Colin needed refuge from the pressures of everyday life, he would go to the ______ to sit alone and reflect.	church	quarry
	B.	The children were warned about throwing stones and playing in the abandoned ______ as they could get seriously injured.		
27	A.	The boss and foreman argued. Feeling awkward, the workers thought it was best to ______ and let them argue in private.	leave	drill
	B.	They knew the other area had much more oil, but their bosses wouldn't allow them to ______ until the current job was done.		
28	A.	At school, Nigel enjoyed painting with wild brush strokes. He covered every inch of his ______ with untidy smears.	paper	easel
	B.	In art class, the first thing that Phillipa did was ensure that she had correctly set up her ______ before painting.		
29	A.	The noise from next door was outrageous. No one could get any sleep because of the loud ______ that went on all night.	music	siren
	B.	The civil defence drill had been a great success. Everyone had been able to hear the ______ that would signal an attack.		
30	A.	Simon was stressed. His had to e-mail his coursework to his tutor but his ______ had broken and he couldn't fix it.	computer	keyboard
	B.	Rachael was finishing typing in the report when she spilled her tea, getting her desk and ______ completely soaked.		
31	A.	Sheila's son had been involved in a fight at school. Before deciding what to do, she would talk to her ______ tonight.	husband	nephews
	B.	Mary loved toyshops at Christmas. Although she did not have children, she would buy gifts for her ______ instead.		
32	A.	The storm had come unexpectedly. The tarpaulin would have to be stretched to provide a ______ for everyone caught out.	cover	quilt
	B.	After purchasing a new mattress and pillows, it made sense to buy a new ______ and cotton sheets for their new bedroom.		
33	A.	Mr. Bain had the flu. Being a busy man, he made an emergency appointment with his ______ before rushing to the office.	doctor	banker
	B.	Fiona was interested in finance. After obtaining a degree in Accounting, she hoped to become a ______ and live in London.		

34	A.	Gardening is a very rewarding hobby. I enjoy being able to feel the ______ between my fingers when planting bulbs.	earth	filth
	B.	The youth hostel hadn't been cleaned in months. Maria had never seen so much ______ on one floor in her whole life.		
35	A.	Jamming all my laundry into the washer, I ignored the fact that it could ______ because I had overloaded its capacity.	break	erupt
	B.	The geologists hurried to get away from the volcano. Their measurements suggested that it could ______ at any moment.		
36	A.	Their day at the zoo was certain to be good. The children looked forward to seeing the ______ and having a picnic.	animals	giraffe
	B.	On safari, we witnessed the upper leaves of the acacia tree being eaten by the hungry ______ and we took a picture.		
37	A.	Callum was having trouble with his homework. He asked his uncle who was a ______ to help him with the assignment.	teacher	plumber
	B.	Ingrid's boiler had suddenly broken down. Fortunately, her neighbour's father was a ______ and would be able to help.		
38	A.	Little Joey loved the story his father told about the cowboy and his faithful ______ and the adventures they had together.	horse	puppy
	B.	Emma prayed for a cute pet every Christmas. Her heart leapt when she saw a beautiful ______ waiting outside in the pen.		
39	A.	Sitting outside at his barbecue, Brian got so drunk that he almost fell off his ______ and was very embarrassed indeed.	chair	patio
	B.	As a kid, when summer came, I spent my days playing in the park and my nights out on my Grandad's ______ reading comics.		
40	A.	Arranging tables in the cafe was difficult. Some were oblong and others were ______ and they differed in height as well.	square	chrome
	B.	The tenants liked the look of their new bathroom. All the fixtures were ______ and fit the modern design of the house.		
41	A.	Nowhere was safe for the prime suspect. A national manhunt was underway as the ______ had caused public outcry.	murder	thefts
	B.	Locals were advised to lock all doors and especially their windows. There had been reports of ______ in the town.		
42	A.	Unusually, the children weren't home yet. Their parents hoped they would be home for ______ as they were worried.	dinner	sunset
	B.	Living on the coast meant that Jane and Dan could enjoy a beautiful ______ before going for a stroll along the beach.		
43	A.	The police had been on Wayne's tail for a long time. He was well known to be a ______ but they had little evidence.	criminal	hooligan
	B.	Sid was not allowed into Austria to watch his favourite football team. He was a known ______ and troublemaker.		
44	A.	After the war, there was much rebuilding to do. To maintain order, British ______ had visible presence as peacekeepers.	troops	cadets
	B.	The young men all wanted to be in the army. Until they were old enough, they would serve as ______ in local forces.		

Table 1

Example Materials from Rayner et al. (2004)

HF-P or LF-U

Most cowboys know how to ride a *horse*|*camel* if necessary.
June Cleaver always serves meat and *potatoes*|*carrots* for dinner.
He scraped the cold food from his dinner *plate*|*spoon* before washing it.
Wanting children, the newlyweds moved into their first *house*|*igloo* and were excited.

LF-P or HF-U

In the desert, many Arabs ride a *camel*|*horse* to get around.
Bugs Bunny eats lots of *carrots*|*potatoes* to stay healthy.
John stirred the hot soup with the broken *spoon*|*plate* until it was ready to eat.
The traditional Eskimo family lived in the *igloo*|*house* built from snow and ice.

Note. HF = high frequency; LF = low frequency; P = predictable; U = unpredictable. Target words are in italics. Each sentence can accommodate either an HF-P or LF-U target (upper set of materials) or an LF-P or HF-U target (lower set of materials).

Table 2

Specifications of Target Stimuli

Condition	Length	Frequency	Predictability	Cloze
HF-HP	5.89 (1)	144 (104)	6.20 (0.42)	0.60 (0.31)
HF-LP	5.89 (1)	144 (104)	4.07 (1.17)	0.02 (0.06)
LF-HP	5.89 (1)	5 (3)	6.05 (0.51)	0.53 (0.31)
LF-LP	5.89 (1)	5 (3)	3.69 (1.16)	0.02 (0.06)

Note. Mean values are shown with standard deviations in parentheses. Units of measurement are as follows: Length in number of letters; Frequency in occurrences per million; Predictability rating range is 1 (highly unpredictable) to 7 (highly predictable). HF = high frequency, LF = low frequency, HP = high predictable, and LP = low predictable.

Table 3

Number of Data Points for Analyses

		Launch Distance (characters)						
		1-3	4-6	7-9	10+	Skip	Reject	Total
FFD								
	HF-HP	220	323	262	200	318	85	1408
	HF-LP	219	347	331	180	262	69	1408
	LF-HP	222	358	314	201	232	81	1408
	LF-LP	255	331	250	223	242	107	1408
SFD								
	HF-HP	212	288	220	155			
	HF-LP	203	309	278	118			
	LF-HP	206	299	261	136			
	LF-LP	233	276	198	146			

Note: The total number of data points across the experiment is 5632, resulting from 64 participants with 22 items in each of 4 conditions. FFD = first fixation duration; SFD = single fixation duration; HF = high frequency; LF = low frequency; HP = high predictable; LP = low predictable.

Table 4

Average Fixation Time (ms) and Fixation Probability across Target Measures

	HF		LF	
	HP	LP	HP	LP
FFD	256	264	279	289
SFD	259	269	285	294
GD	273	286	306	318
TT	297	328	334	380
PrF	0.77	0.81	0.83	0.82

Note: HF = high frequency; LF = low frequency; HP = high predictable; LP = low predictable; FFD = first fixation duration; SFD = single fixation duration; GD = gaze duration; TT = total fixation time; PrF = probability of fixation.

Table 5

Average Fixation Time (ms) as a Function of Launch Distance (characters) across Target Measures

	HF		LF	
	HP	LP	HP	LP
Near: 1-3 characters				
FFD	218	233	256	295
SFD	219	234	256	293
GD	220	244	264	315
Middle: 4-6 characters				
FFD	250	269	282	280
SFD	252	274	292	285
GD	265	286	308	308
Far: 7-9 characters				
FFD	268	273	283	283
SFD	276	280	291	294
GD	297	305	317	318

Note: HF = high frequency; LF = low frequency; HP = high predictable; LP = low predictable; FFD = first fixation duration; SFD = single fixation duration; GD = gaze duration.

Table 6

Percentage of SFD Data Points on Character 3 as a Function of Launch Distance

	HF		LF	
	HP	LP	HP	LP
Near: 1-3 characters	18	30	30	28
Middle: 4-6 characters	15	20	20	36
Far: 7-9 characters	32	35	18	16

Note: SFD = single fixation duration; HF = high frequency; LF = low frequency; HP = high predictable; LP = low predictable.

Table 7

Number of SFD Data Points for each Target Landing Position as a Function of Launch Distance and Condition

	Target Landing Position			
Launch Distance	Space	Beginning	Middle	Ending
Near: 1-3 characters				
HF-HP	11	32	74	83
HF-LP	12	18	72	88
LF-HP	9	36	60	92
LF-LP	6	30	68	121
Middle: 4-6 characters				
HF-HP	5	100	97	77
HF-LP	5	88	105	102
LF-HP	3	104	98	88
LF-LP	3	108	83	76
Far: 7-9 characters				
HF-HP	20	96	49	31
HF-LP	13	135	58	49
LF-HP	15	133	58	32
LF-LP	16	90	48	28

Note: SFD = single fixation duration; HF = high frequency; LF = low frequency; HP = high predictable; LP = low predictable.

Table 8

Percentage of Refixations and Second-Pass Fixations as a Function of Launch Distance (characters) across Conditions

	HF		LF	
	HP	LP	HP	LP
Near: 1-3 characters	9	18	15	28
Middle: 4-6 characters	18	23	23	34
Far: 7-9 characters	23	30	23	35

Note: HF = high frequency; LF = low frequency; HP = high predictable; LP = low predictable.

Figure 1. Average single fixation duration (SFD) on target words (with standard error bars) as a function of word frequency and contextual predictability. Note: HF = high frequency; LF = low frequency; HP = high predictability; LP = low predictability.

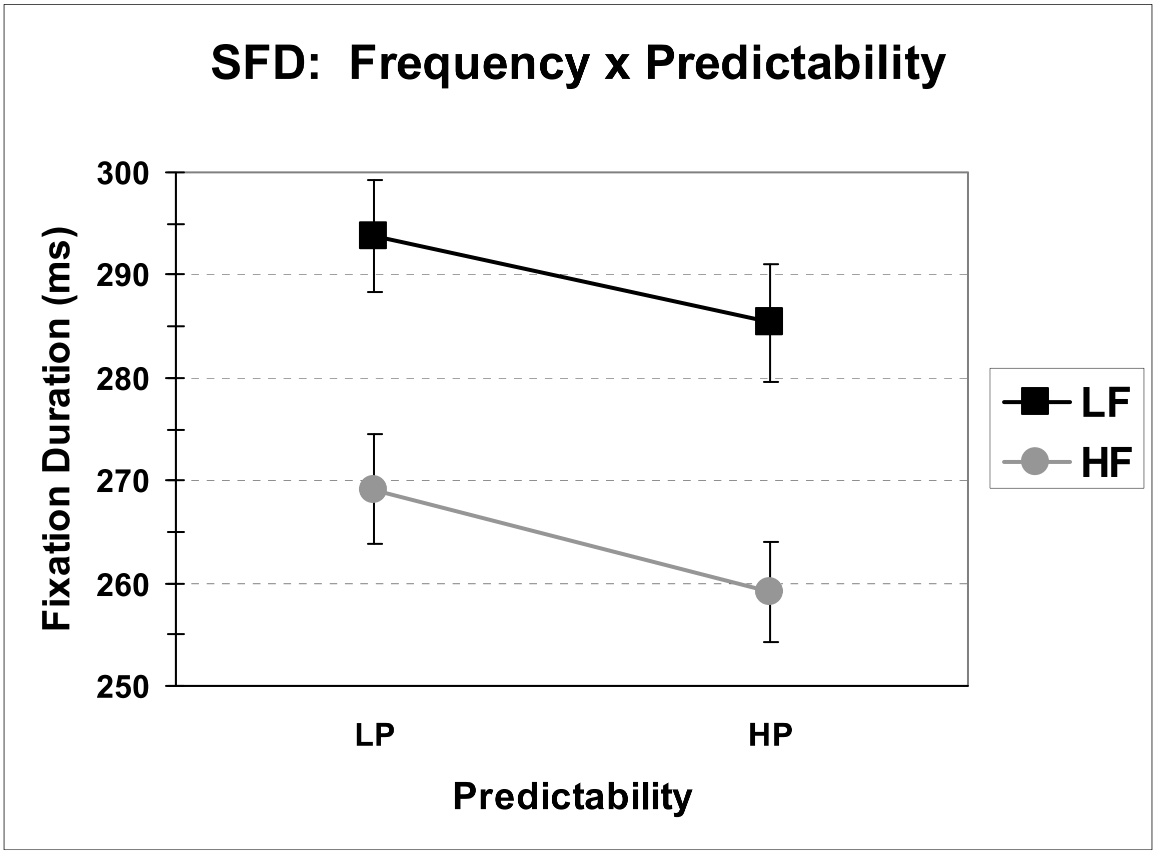

Figure 2. Average single fixation duration (SFD) on target words (with standard error bars) as a function of word frequency, contextual predictability, and parafoveal preview as indexed by launch distance. Note: HF = high frequency; LF = low frequency; HP = high predictability; LP = low predictability.

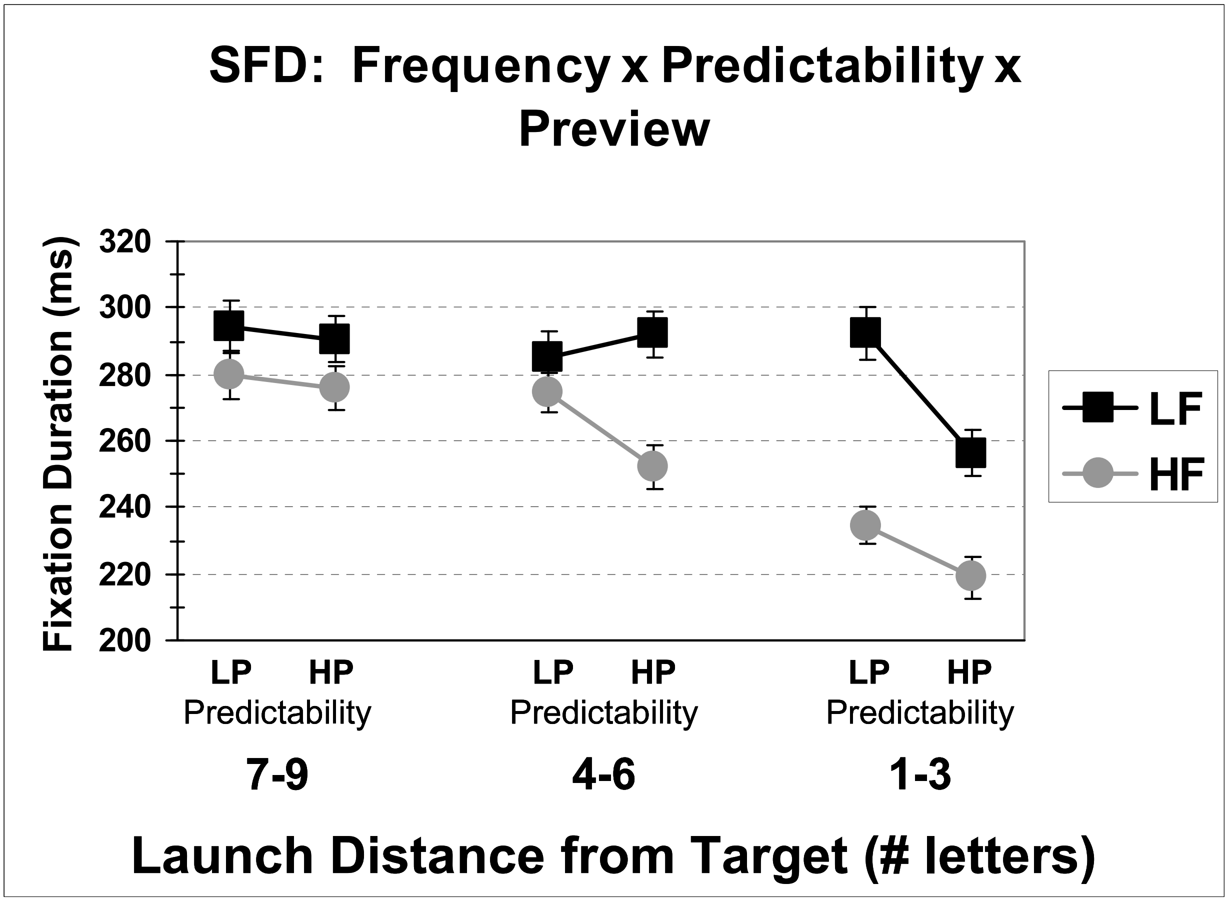

Figure 3. Average single fixation duration (SFD) on character 3 of target words as a function of word frequency, contextual predictability, and parafoveal preview as indexed by launch distance. Note: HF = high frequency; LF = low frequency; HP = high predictability; LP = low predictability.

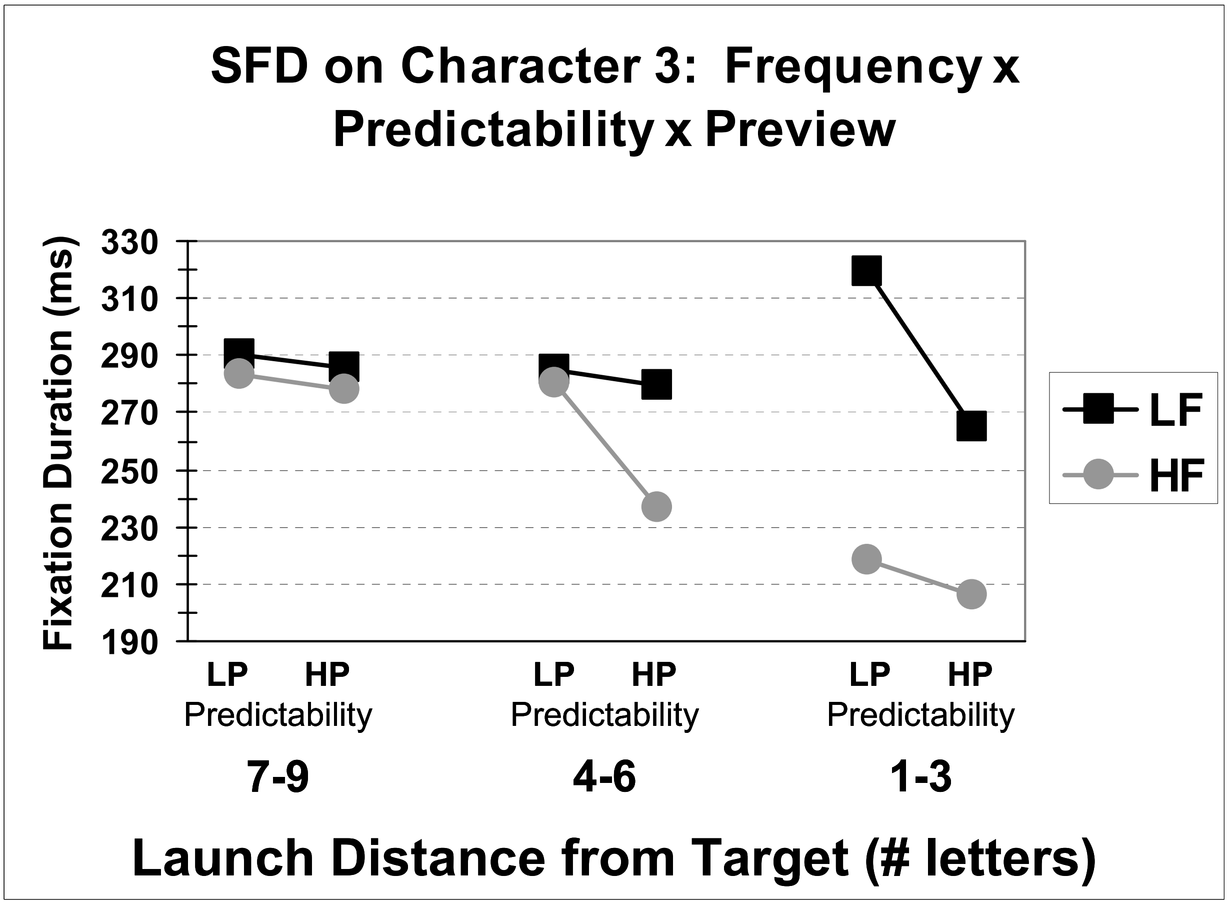

Figure 4. Average single fixation duration (SFD) on beginning (Beg), middle (Mid), and end (End) of target words as a function of word frequency, contextual predictability, target landing position, and parafoveal preview as indexed by launch distance. Note: HF = high frequency; LF = low frequency; HP = high predictability; LP = low predictability; Beg, Mid, and End = landing position of beginning, middle, and ending target letters.

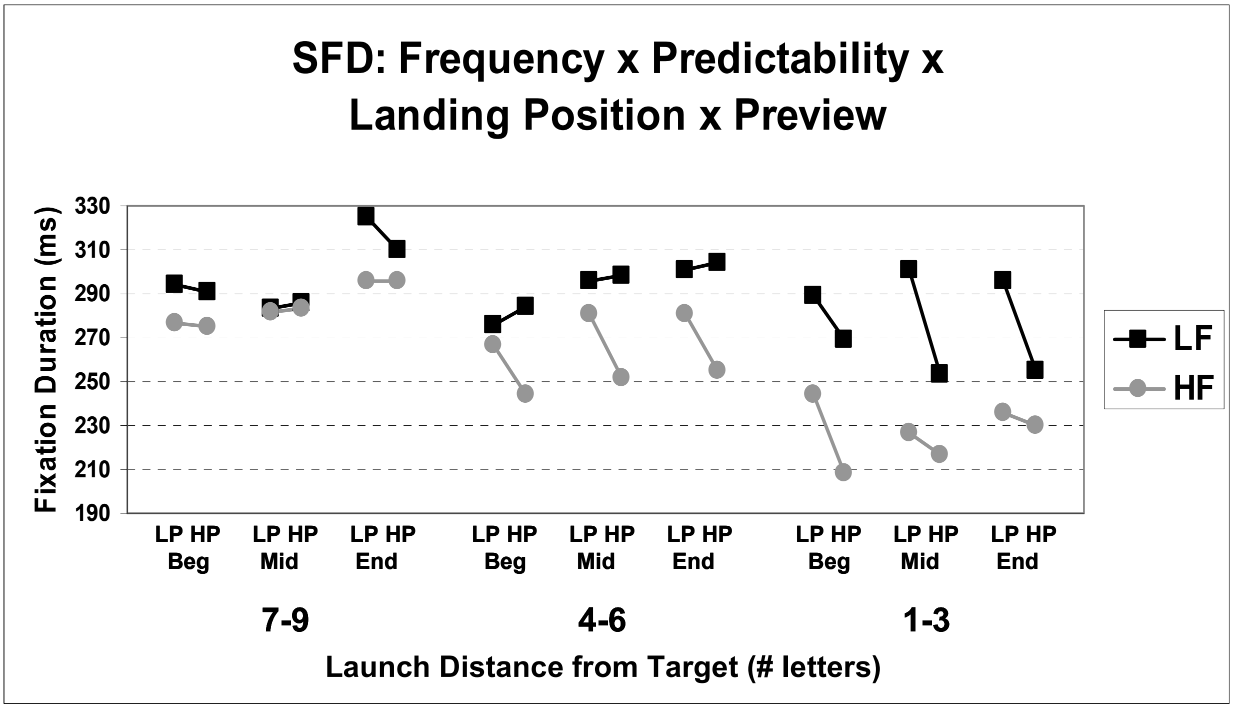

Figure 5. Average pre-target fixation duration (with standard error bars) as a function of word frequency, contextual predictability, and parafoveal preview as indexed by launch distance. Note: HF = high frequency; LF = low frequency; HP = high predictability; LP = low predictability.

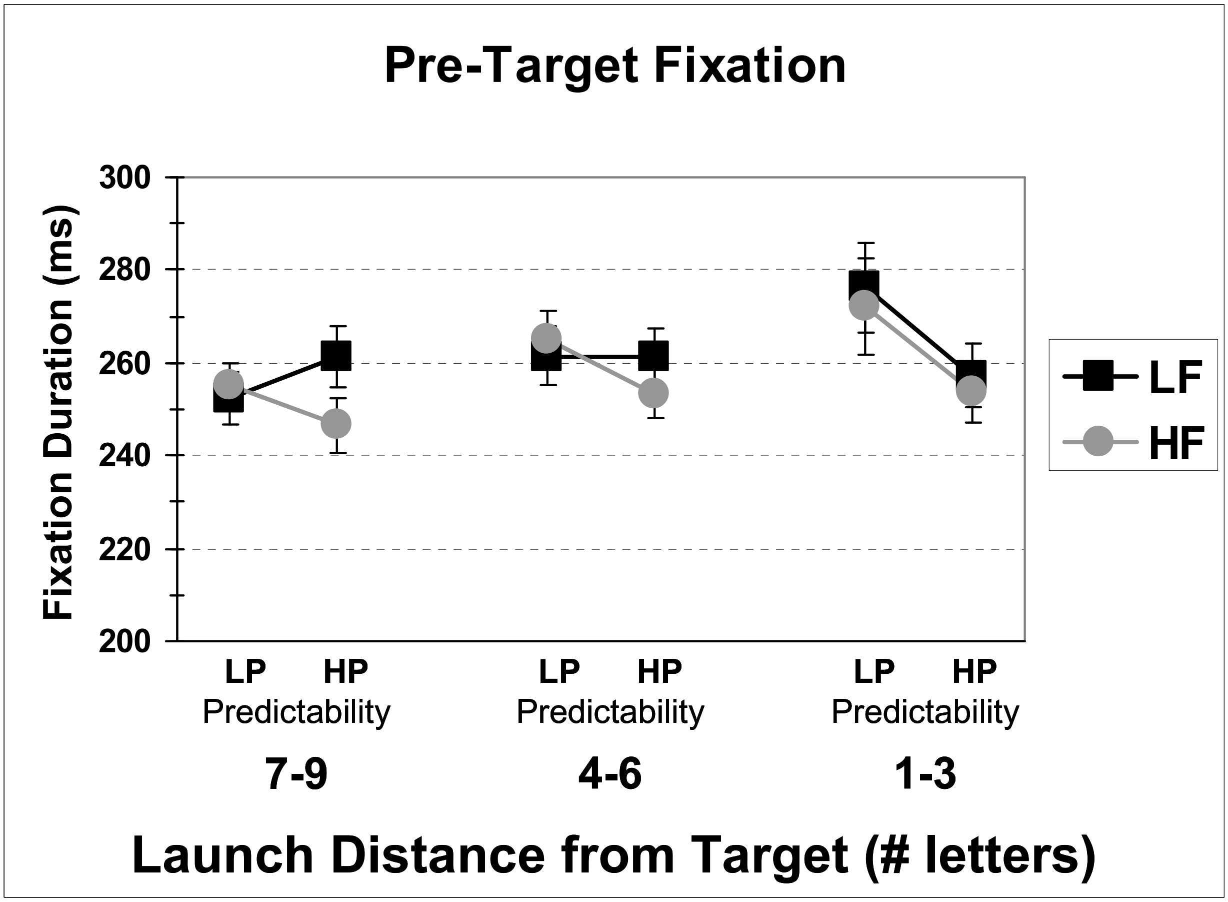

Figure 6. Average single fixation duration (SFD) variance on target words as a function of word frequency, contextual predictability, and parafoveal preview as indexed by launch distance. Note: HF = high frequency; LF = low frequency; HP = high predictability; LP = low predictability.