Word frequency in fast priming:

Evidence for immediate cognitive control of eye-movements during reading

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Abstract

Numerous studies have demonstrated effects of word frequency on eye movements during reading, but the precise timing of this influence has remained unclear. The fast priming paradigm (Sereno & Rayner, 1992) was previously used to study influences of related versus unrelated primes on the target word. Here, we used this procedure to investigate whether the frequency of the prime word has a direct influence on eye movements during reading when the prime-target relation is not manipulated. We found that with average prime intervals of 32 ms readers made longer single fixation durations on the target word in the low than in the high frequency prime condition. Distributional analyses demonstrated that the effect of prime frequency on single fixation durations occurred very early, supporting theories of immediate cognitive control of eye movements. Finding prime frequency effects only 207 ms after visibility of the prime and for prime durations of 32 ms yields new time constraints for cognitive processes controlling eye movements during reading. Our variant of the fast priming paradigm provides a new approach to test early influences of word processing on eye movement control during reading.

Keywords: Eye movements, Reading, Fast-priming, Word frequency, Distributional Analyses

Word Frequency in Fast Priming: Evidence for Immediate Cognitive Control of Eye Movements during Reading

The understanding of the processes that control eye movements during reading is continuously advancing. Eye-tracking experiments and computational modeling studies test assumptions about reading processes that occur in light of often very strict time constraints in an increasingly quantitative manner (e.g., Risse, Hohenstein, Kliegl, & Engbert, 2014; Schad & Engbert, 2012; Schotter, Reichle, & Rayner, 2014). Major temporal constraints in reading are imposed by the consistent observation that fixation times are influenced by the currently fixated word and saccades are programmed during ongoing reading fixations which last an average of about 250 ms (see Rayner, 1998, 2009). Given this rather short duration, only a brief time window is available for word processing to influence the programming of the upcoming saccade.

Nevertheless, it has been shown that even higher-level lexical word-processing – which is assumed to be slow compared to low-level visual word analyses – can lead to fixation-by-fixation adjustments of saccade size (e.g., O'Regan, 1979) and fixation duration (e.g., Rayner, 1975) in reading. One of the most robust findings in this respect is that, with word length controlled, low frequency words (i.e., words that occur only rarely in a given language) are fixated longer than high frequency words (Inhoff & Rayner, 1986; Just & Carpenter, 1980; Rayner & Duffy, 1986, for the original demonstrations of the frequency effect). The word-frequency effect is interpreted as reflecting the additional influence of lexical processing on fixation durations and suggests that cognition is at least partly controlling the eye movements during reading. Thus, lexical properties must be available early enough during a fixation to be able to influence the decision of when to make the next saccade, and thereby modulate the duration of the ongoing fixation. Most likely, such influences occur at an early and partial lexical processing level.

Numerous studies have investigated the time course of the word-frequency effect during reading. Here, we report a paradigm to investigate how long a word has to be processed at minimum for lexical processing of that word to affect eye movements. In our experiment, we used a variant of the fast priming paradigm (Sereno & Rayner, 1992) as subjects read sentences in which a critical word of high or low frequency (i.e., “word1” or “prime”) was briefly presented at the beginning of fixation, and quickly replaced with an unrelated word (i.e., “word2” or “target”). The goal was to experimentally constrain the availability of frequency information to a short time window at the beginning of fixation. We thus aimed to test whether lexical processing is fast enough to control the oculomotor decision of “when” to initiate the next saccade program. If lexical processing is slow, fixation durations should not differ as a function of prime word frequency in the present paradigm.

Moreover, based on the tight time constraints during reading we reasoned that if early influences of word frequency are based on a shallow and incomplete level of lexical processing, then it should be possible to trick the system into prematurely responding to improper text material. To test this hypothesis, we used critical high- and low-frequency prime words that did not fit into the sentence context. If early eye-movement responses are actually guided by lexical processing at an incomplete level as expected, then high-frequency primes which do not fit into the sentence frame should nevertheless shorten early fixation durations and low-frequency primes should prolong fixation durations in a regular manner. However, eye guidance based on later and more complete lexical prime processing stages should result in irregular eye-movement patterns indicating detection of the semantic mismatch. Last, we were also interested in investigating the time course of early frequency processing and in tracing its influence across several subsequent fixation durations. Thus, the present experiment offers insight not only into how early frequency information is obtained but also shows how long-lasting and persistent its effect can be in modulating the saccadic decisions downstream.

Time constraints challenge theories on the control of eye movements during reading

The physiological time window in which word-recognition processes in reading can affect eye movements is rather narrow and major constraints are imposed on eye-movement control by the substantial processing times for visual perception, cognitive processing, and saccadic programming. The average fixation in reading is about 225-250 ms long and – compared with fixation durations in scene perception or visual search – comparably short (for reviews see Rayner, 1998, 2009). During the first 35 ms of a fixation, visual perception is reduced due to saccadic suppression (Volkmann, Schick, & Riggs, 1968) and visual input takes at least 50 ms to bridge the eye-mind gap, travelling from the retina to the cortex (Foxe & Simpson, 2002; Lamme & Roelfsema, 2000; Poghosyan & Ioannides, 2007). When adding an estimated 150-175 ms needed for programming the next saccade (e.g., Abrams & Jonides, 1988; Rayner, Slowiaczek, Clifton, & Bertera, 1983) of which the last 80-100 ms are insensitive to any changes in visual input (i.e., the saccadic dead time; Becker & Jürgens, 1979), very little time is left for cognitive processing of the fixated word to affect fixation durations. These estimates suggest that on average word processing can modulate the upcoming saccade only if it occurs roughly within 90 ms after the onset of a fixation.

Based on these tight time constraints, there have been intriguing attempts to explain eye movements during reading purely by fast low-level, non-lexical oculomotor strategies (O'Regan, 1990; Reilly & O'Regan, 1998; Yang, 2006; Yang & McConkie, 2001). However, the majority of reading models also consider higher-level lexical processes to have an impact on eye-movement control (for overview of models see Reichle, Rayner, & Pollatsek, 2003). As such, they provide explanations for the increasing number of findings of lexical effects on eye movements such as the modulation of fixation durations based on the word’s frequency (see Rayner, 2009, for review). Nevertheless, these models strongly differ in their assumptions about how lexical processing influences eye movements during reading, and the question of how cognition is linked or “coupled” to oculomotor control to conform to the strict time constraints has been the topic of much debate (e.g., Staub, White, Drieghe, Hollway, & Rayner, 2010; Yang & McConkie, 2001).

Reingold, Reichle, Glaholt, and Sheridan (2012) recently suggested a classification of control mechanisms according to which models of eye-movement control in reading can be characterized. For example, they distinguished the information type used by the control mechanisms, that is lexical (high-level cognitive) or non-lexical (low-level visual) information. Investigating the influence of word frequency during reading the present study will focus on the lexical information type only. More importantly, Reingold et al. (2012) discerned direct and indirect control types with respect to the temporal immediacy of the coupling between word processing and oculomotor control (see also Dambacher, Slattery, Yang, Kliegl, & Rayner, 2013; Rayner & Pollatsek, 1981). They suggested a definition of direct control that emphasizes the immediate fixation-by-fixation adjustment of the eye movements towards the local processing difficulties at fixation. In other words, direct control is based on the assumption that the duration of a given fixation is determined by word-recognition processes of the currently fixated word (i.e., by properties of word *n*). In contrast, mechanisms of the indirect control type are associated with delayed adjustments. Following the assumption that cognition is relatively slow, the coupling between particularly lexical processing and oculomotor control is assumed to be time shifted. As a consequence, fixation durations should rather show non-local or global influences of the lexical processing of previously fixated words (e.g., the average text difficulty). The present experiment investigated how fast cognition can act during reading and how immediate it is in modulating fixation durations.

Time course of lexical frequency effects in reading

Despite the tight physiological time constraints, empirical evidence supports early and efficient cognitive word processing during reading. In the fast-priming paradigm (Sereno & Rayner, 1992) a briefly presented prime word is quickly followed by a target word, which is either related or unrelated to the prime in some respect. Several fast-priming studies have demonstrated that briefly presented words are processed at various levels during reading, including orthographic, homophone/phonological, vocal/vowel, and semantic processing (Frisson, Belanger, & Rayner, 2014; H. W. Lee, Rayner, & Pollatsek, 1999, 2002; Y. A. Lee, Binder, Kim, Pollatsek, & Rayner, 1999; Rayner, Sereno, Lesch, & Pollatsek, 1995; Sereno, 1995; Sereno & Rayner, 1992). Interestingly, prime words were found to be effective only during very specific time windows. While low-level orthographic primes showed an effect at a relatively wide range of prime durations (e.g., in all conditions ranging from 29 to 41 ms in H. W. Lee et al., 1999), higher-level processing effects were specific to prime durations around 30 ms, including homophone priming (29 to 35 ms; H. W. Lee et al., 1999) and semantic priming (30 and 32 ms; H. W. Lee et al., 1999; Sereno & Rayner, 1992). But how early may the effects of the frequency information as manipulated in the present experiment be evident?

Electrophysiological studies (e.g., Sereno, Rayner, & Posner, 1998) were among the first to show that brain signals respond to the lexical frequency of a target word quite fast within 132 ms when words are presented in serial order (for reviews see Reichle & Reingold, 2013; Reingold et al., 2012). More recent studies commenced to establish the temporal link between event-related brain potentials and the oculomotor response and suggested that lexical effects might even be earlier in situations of normal reading in which upcoming words can be previewed parafoveally during previous fixations (e.g., Dambacher & Kliegl, 2007; Dimigen, Sommer, Hohlfeld, Jacobs, & Kliegl, 2011). Support for an early frequency effect also comes from eye-movement studies in which words disappeared (or were masked) as early as 60 ms after fixation onset and readers were afterwards looking at a blank space (Liversedge et al., 2004; Rayner, Inhoff, Morrison, Slowiaczek, & Bertera, 1981; Rayner, Liversedge, & White, 2006; Rayner, Liversedge, White, & Vergilino-Perez, 2003). If parafoveal preview of the word was available during previous fixations, 60 ms foveal presentation time was sufficient to establish a reliable frequency effect in fixation durations even after the removal of the word. However, if the preview of the word was also time constrained, this had detrimental effects on reading.

Other studies have examined the timeline of cognitive processing by analyzing the distribution of fixation durations during reading. Studies based on Vincentile analyses have investigated the differential influence of lexical variables (like word frequency or predictability) on short and long fixation durations (Staub, 2011; Staub et al., 2010). The results from these studies suggest that lexical processing is fast enough to influence the shortest 10% of fixation durations, and that this influence increases for longer fixation durations. Very recently, survival analyses, quantifying when fixations "die" due to the onset of the next saccade, have been used to test the limits of such immediate control by searching for the first point in time when cognitive influences on eye movements can be observed (Reingold et al., 2012). Reingold et al. found the earliest word frequency effect in the distribution of first fixation durations at 145 ms after readers fixated on the target word. Importantly, however, in this experimental condition, and in the studies employing the Vincentile-analyses, the timing of frequency effects was not tightly controlled as readers had preview for the target word prior to fixating on it. What may look like highly immediate effects of word frequency may represent, at least partly, delayed effects from previewing the target word during the previous fixation (Risse & Kliegl, 2012, 2014). To investigate the role of such preview effects and to control for their influence, Reingold et al. (2012) also used a condition where no preview for the target word was provided; without preview word frequency effects occurred as late as 256 ms after presentation of the target word. This finding suggests that 256 ms may be the total time needed for a word signal to travel the complete loop from sensory input via lexical processing to eye behavior. If parafoveal preview is available, part of the processing can be accomplished prior to fixation onset thus reducing the time needed to show lexical effects when the word is then fixated.

Consistent with empirical findings and the tight physiological time constraints, major computational models of eye-movement control during reading (of the direct cognitive control type; cf. Reingold et al., 2012) assume that cognition influences saccade programming at a very early, shallow, and incomplete level of lexical processing. In the E-Z Reader model (Reichle, Pollatsek, Fisher, & Rayner, 1998; Reichle, Pollatsek, & Rayner, 2012; Reichle et al., 2003) new saccade programs are triggered by the completion of an early first stage of lexical processing (labeled L_1; Reichle et al., 2003). Likewise, in the competitor model SWIFT (Engbert, Longtin, & Kliegl, 2002; Engbert, Nuthmann, Richter, & Kliegl, 2005; Risse et al., 2014; Schad & Engbert, 2012) incomplete lexical processing affects saccades by modulating word activations.

The present experiment

Empirical, logical and computational considerations suggest that very early and incomplete levels of lexical processing might be sufficient to guide eye-movements during reading. However, it is unknown how long a word has to be presented at minimum for it's lexical properties to affect eye movements. In the present study, we investigated this question via a variation of the fast-priming paradigm. For 32 ms after fixation onset on a specific word position in a sentence, we presented a high-frequency (HF) or a low-frequency (LF) word (i.e., "prime" or "word1") at that position. The prime was then replaced with a second word (i.e., "target" or "word2") of medium frequency that was unrelated to either the HF or the LF prime; the target word remained visible for the rest of the trial. To exclude preview-effects and to control that prime processing was restricted only to the experimental time window of

32 ms; as in other fast priming experiments, the prime was forward-masked with a random letter string before it was fixated.

Our timing procedure was identical to that used in previous fast-priming studies (e.g., Sereno & Rayner, 1992). By analogy, word1 in our paradigm therefore relates to the prime word in fast-priming studies, and word2 relates to the target word. In contrast to fast-priming studies, however, the word information collected in the initial 32 ms of fixation was irrelevant for recognition of word2 in both frequency conditions, as both words1 were similarly unrelated to the later word2. Instead, word2 functioned merely to mask the HF or LF word1 from further processing.

If early and incomplete lexical processing can prematurely influence saccade programming as predicted, then fixation durations associated with the target location should be longer if a LF prime was presented at fixation onset and should be shorter when the prime was of HF. At a more detailed level, we aimed at investigating the temporal distribution of word frequency effects across fixation durations. Based on strictly direct fixation-by-fixation adjustment of fixation times (Rayner & Pollatsek, 1981) immediate effects should be expected in the first or single fixation on the target word as the processing acquired during a fixation would immediately affect the termination of this fixation. However, effects in the second or later fixation on the target word (i.e., in case of refixations) or on the posttarget word would argue against a fixation-by-fixation adjustment and support the notion of different degrees of a temporal delay in lexical control.

Method

Subjects

Thirty-six students from the University of California, San Diego received course credit for participation. All were native speakers of English, had normal or corrected-to-normal vision, and were naive concerning the purpose of the experiment.

Materials and Design

Subjects read 64 English sentences for comprehension. Sentence order was randomized for each subject individually. We used the gaze-contingent display change technique (McConkie & Rayner, 1975; Rayner, 1975) to implement the fast priming paradigm (Sereno & Rayner, 1992). Each sentence contained one word position with two matched primes and one unrelated target (see Appendix, Table A1 for a list of the stimuli). At the beginning of each trial, a non-word preview was displayed instead of the words. When the eyes crossed an invisible boundary that was located before the space preceding the target position, an initial display change replaced the non-word preview with a prime word of either high or low frequency. Allocation of prime frequency condition to sentences was counterbalanced over subjects. Primes were replaced by words 32 ms after fixation onset and remained on the screen for the remainder of the trial.

Word frequency for high frequency primes was *M* = 28,966 (*SD* = 42,318), for low frequency primes it was *M* = 2,595 (*SD* = 4,336), and for target words it was *M* = 22,639 (*SD* = 39,635; Corpus of Contemporary American English, http://corpus.byu.edu/coca/). Primes were selected to be of the same length as the corresponding target, which varied between 4 and 7 letters (4 letters: 26 words; 5 letters: 18 words; 6 letters: 18 words; 7 letters: 6 words). Primes did not semantically fit into the sentences because we expected that (a) prime processing should be subliminal due to a presentation time of 32 ms and visual masking in parafoveal vision and (b) that very early and shallow prime processing would influence saccade programming. This effectively eliminates the possibility of primes being predictable from the preceding context. For each sentence both high and low frequency primes were selected to be similarly unrelated to the target word: two prime words were chosen from the same semantic category, which differed from the semantic category of the target word (e.g., high frequency prime: *apple*; low frequency prime: *berry*, target: *laser*). Also, to exclude differences between primes in their orthographic relation to the target, both primes were chosen to share no letters with the target in the same letter position (though in two cases, both primes shared one – i.e., the same – letter with the target, e.g., high frequency prime: *hair*; low frequency prime: *nail*; target: *case*).

Procedure

An SR Research Eyelink 1000 eyetracker was used to record subjects' movements of the right eye with a sampling rate of 1000 Hz. Subjects read sentences on a 19-inch CRT monitor with 150 Hz refresh rate and 1024 by 768 pixels resolution. Viewing was binocular and viewing distance was approximately 50 cm. A three-point horizontal Eyelink calibration routine was used, and repeated for validation errors greater than .4° visual angle. At the start of each trial, a black square (0.8 degrees of visual angle) appeared on the left side of the computer screen, which coincided with the left side of the first letter in the sentence. Upon detection of a stable fixation within this area, the sentence replaced it on the screen. Subjects were instructed to read silently for comprehension and to press a button on a keypad when they finished reading the sentence. Comprehension questions in two-alternative choice format appeared on the screen after a third of all the items, and subjects responded via button presses.

Nominal display time for primes was 32 ms, measured from fixation onset to target onset. Fixation onset was determined using the online parsing algorithm of the Eyelink 1000 eye tracker. There was variability in the actual duration of the prime word during fixation due to variability in the start of a fixation following the initial display change and variability in the CRT monitor's raster position (see Figure 1). On average, the prime word was visible during fixation for 26.58 ms and trials were included in the analyses only if the prime duration was greater than 10 ms and smaller than 40 ms; this selection criteria resulted in a total of 2,088 valid trials.

Data Selection

We removed data according to standard exclusion criteria: trials including blinks when or immediately before fixating the target word, problems with the timing of prime presentation, and erroneous triggers of the boundary during fixations on the pre-target word were discarded. This selection removed n = 343 invalid trials, equivalent to 16.4% of the data. Exclusion rate was similar for high-frequency words (n = 174, 16.5%) and for low-frequency words (n = 169, 16.3%), and resulted in a total of 1,745 valid trials. In 10.1 % of these trials, the target word was skipped, leaving a total of 1,569 trials for analysis of first-pass reading fixations (each containing a valid first fixation duration on the target word). 1,031 of these trials contained a valid single fixation duration on the target.

Figure 1 displays distributions of actual prime durations. Average prime duration in valid trials was 27.00 ms for high frequency primes and 26.94 ms for low frequency primes, $t < 0.33$. In single fixation cases average prime durations were 27.16 ms for high frequency primes and 27.02 ms for low frequency primes, $t < 0.58$.

- insert Figure 1 about here -

Statistical Analyses

We fitted linear mixed-effects models (LMMs) using the lmer program from the lme4 package (Bates, Maechler, & Bolker, 2013), which is implemented in the R System for Statistical Computing (R_Development_Core_Team, 2013), and fitted generalized linear mixed-effects models (GLMMs) using the R-package glmmadmb, which provides an interface to the ADMB software (Fournier et al., 2011). Statistical analyses focused on the effect of prime frequency. In a post-hoc analysis, we also included prime duration and the interaction with prime frequency. For the fixed effects, factors were effect-coded (-0.5, +0.5). In the (G)LMMs, we tested the random structure of effects including random intercepts for subjects and items, random slopes for the main effects over subjects, and random correlations. Non-significant random effects were then removed from the models[1]. Fixation durations were log-transformed to conform to assumptions of normal distribution in LMMs. In the LMMs, for directed hypotheses (i.e., one-tailed testing) we took values of $|t| > 1.645$ to indicate significance ($p < .05$), whereas for undirected hypotheses (i.e., two-tailed testing) values of $|t| > 1.96$ indicated significance (Kliegl, Ping, Dambacher, Yan, & Zhou, 2011) and values of $|t| > 2.576$ indicated high significance ($p < .01$).

Results

Immediate Effects of Prime Frequency

Table 1 summarizes the results in condition means for fixation durations and probability measures. Based on previous research (for reviews see Rayner, 1998, 2009), we expected that single fixation durations – SFD, cases in which the target received only one fixation – and first fixation durations – FFD, the duration of the initial fixation on a word – should be immediately longer for low frequency primes than for high frequency primes. The same effect might be weaker or absent in the first of multiple fixation durations – FMD, cases of multiple successive fixations on a word, which often reflect a suboptimal reading pattern. It is visible in Figure 2 that SFD on target words were 7 ms longer if a low-frequent prime was provided at the beginning of fixation rather than a high-frequent prime ($b = 0.03$, $SE = 0.02$, $t = 1.69$, $p < .05$, one-tailed; Markov Chain Monte Carlo [MCMC] simulations of a simple intercept-variance LMM: $p < .05$ one-tailed). In contrast, prime frequency had no significant effect on FFD ($b = 0.01$, $SE = 0.01$, $t = 1.0$), and no effect on FMD ($b = -0.004$, $SE = 0.02$, $t = -0.19$). Although the frequency-effect size was expectedly small, when the target was fixated only once the associated fixation duration (i.e., SFD) showed an immediate influence of the frequency of the briefly presented irrelevant prime word before presentation of the target word, but this effect was numerically absent for less optimal reading patterns.

- insert Table 1 about here -

- insert Figure 2 about here -

- insert Figure 3 about here -

Distributional analyses are informative to better understand the timing of cognitive influences on eye fixations during reading (Reingold et al., 2012; Staub, 2011; Staub et al., 2010; White & Staub, 2011). As a first step, Figure 3 displays histograms of SFD. It is clear that for high frequency primes the distribution of SFD is slightly but consistently shifted to the left compared to low frequency words in a range between 180 ms and 380 ms. Moreover, there is some hint for a reduced saccade count below 180 ms. This reduction might reflect saccadic inhibition resulting from the display change (Reingold & Stampe, 2002, 2004), which – based on previous findings – can be expected to be maximal at 130 ms in the present data (i.e., 100 ms after the display change). To determine the earliest moment in time when prime frequency affected SFDs, we performed a survival analysis based on inverse cumulative probability distributions (Reingold et al., 2012). Statistical testing was performed using subject-based bootstrapping. As the statistical criterion for the onset of prime frequency effects, we determined the lowest fixation duration where differences between high and low frequency primes were significant in at least 5 consecutive time bins (cf. Reingold et al., 2012). We performed one-tailed statistical tests based on the expectation that survival should be lower for high-frequency primes (which corresponds to shorter fixation durations in standard mean-based analyses) than for low-frequency primes. As a result (see Figure 4), the first effect of prime frequency was found at a fixation duration of 207 ms. At this duration, survival was reduced for high-frequency primes, indicating that more saccades had been triggered for high than for low-frequency primes up to this point in time. This result is consistent with the overall finding of shorter SFDs for high frequency primes, and suggests that prime frequency affected fixations only 207 ms after the prime word was visible to the reader.

- insert Figure 4 about here -

Delayed Effects of Prime Frequency

We also performed (G)LMM analyses testing the effect of prime frequency on more delayed eye-movement measures (see Table 1) including (a) target refixations, (b) gaze durations (GD) as the sum of all fixation durations on the target word before moving on to another word (GD is often viewed as an immediate measure in other studies), (c) go-past times (GPT) as the time from the first encounter of a word until its right word-boundary is crossed, (d) regressions originating from the target (given the prime/target was fixated after crossing the boundary), and (e) total reading times (TRT) as the total time spend on the target word including any revisits after the target has been left. The main effect of prime frequency was not significant for any of these variables ($|ts| < 1.60$, $|zs| < 1.23$), except for GPT, which was marginally increased for high-frequent primes compared to low-frequency primes (b = -0.03, SE = 0.02, t = -1.94). The prime frequency effect in GPTs was substantial (19 ms), but as seen from Figure 5 (left panel) the effect was in the opposite direction as compared to SFDs: High frequency primes seem to increase the time readers spend re-reading parts of text prior to the target. There were no significant effects in fixation durations on the posttarget word (t-values ≤ 1.51).

- insert Figure 5 about here -

Overall, our a priori analyses revealed reliable immediate effects of prime frequency in early SFDs, and a trend for a delayed prime frequency effect in GPTs, which was reversed compared to the early effect. As we expected rather small effects from such a subtle manipulation as presenting an irrelevant word for only 32 ms in foveal vision, finding the frequency effect significant not in all eye-movement measures is perhaps not surprising. In the discussion we will argue in detail why we view these two significant results as evidence that such early frequency-effects are reliable and persistent in influencing the saccadic decisions over a longer period of time.

Post-hoc Analyses of Prime Duration

Previous studies showed that fast priming effects can be highly specific to certain time windows (H. W. Lee et al., 1999). Although we used a fixed presentation interval for all trials (32 ms), actual presentation times (in terms of prime visibility after fixation onset) varies in fast priming studies from trial to trial (see the Procedure section). Based on this variation, we computed the prime duration for each trial post-hoc as the actual time of prime visibility starting with the earliest moment that the prime was available after fixation onset at the target location until the prime was removed and replaced by the target. For statistical analysis, we performed a median split (*Median* = 28 ms for both high and low frequency primes) such that short prime durations ranged from 11 to 27 ms (*M* = 23 ms, *SD* = 4.6), whereas long prime durations ranged from 28 to 36 ms (*M* = 29 ms, *SD* = 1.4) .

- insert Figure 6 about here -

First, we tested whether immediate effects of prime frequency differed between short and long effective prime durations. For SFDs, the prime frequency main effect was again significant, and showed an even higher level of statistical significance compared to the a priori analysis ($b = 0.04$, $SE = 0.02$, $t = 2.30$, $p < .05$). This increase highlights the benefit of statistically controlling for an influence of prime durations: Long prime durations were associated with longer SFDs ($b = 0.04$, $SE = 0.02$, $t = 1.93$) and prime duration interacted with prime frequency (b = -0.08, SE = 0.04, t = -2.07, $p < .05$; interaction for FFDs and FMD was not significant: t–values = -1.58 and -0.32). As Figure 6 illustrates, for short prime durations the prime frequency effect was strong (15 ms) and highly significant (t = 2.73, $p < .01$), while for long prime durations the prime frequency effect was small (3 ms) and not significant (t = 0.18).

- insert Figure 7 about here -

Next, we tested whether prime duration influenced delayed effects of prime frequency. We found significant interactions of prime frequency and prime duration in GD (b = -0.068, SE = 0.031, t = -2.17, $p < .05$), TRT (b = -0.078, SE = 0.038, t = -2.04, $p < .05$) (see Figure 7), and regression probability (b = 0.724, SE = 0.344, z = 2.11, $p < .05$; see Figure 5). For these variables, the main effect of prime frequency was significant in TRTs (b = 0.039, SE = 0.019, t = 2.08, $p < .05$) and marginal in regression probability (b = -0.294, SE = 0.170, z = -1.73, $p < .10$). To test whether the prime frequency effect on TRTs is truly delayed and independent of the 1^{st} firstpass fixation on a word (i.e., independent of the SFD-effect), we computed the cumulative duration of the 2^{nd} and later fixations (by subtracting FFDs from TRTs). We found a significant interaction between prime frequency and prime duration (b = -0.191, SE = 0.073, t = -2.64, $p < .01$, see Figure 7), supporting an influence of prime frequency on delayed fixations. The interaction of prime frequency and prime duration ($|t| < 0.93$ and $|z| < 0.10$) as well as the main effect of prime duration ($|ts| < 0.71$; $|zs| < 1.10$; for GDs: t = 1.78) were not significant for the other variables.

In the post-hoc analyses, the prime frequency effect was evident particularly for short prime durations, but not for long prime durations ($|ts| < 0.84$, $|z| < 0.35$). Moreover, the direction of the prime frequency effect was reversed between measures. It was in the standard direction (mirroring the effect observed for SFDs) in GDs, TRTs, and 2^{nd} and later fixation durations: For short prime durations, GDs were 13 ms shorter for high-frequency than for low-frequency prime words (b = 0.051, SE = 0.025, t = 2.11, p < .05) and TRTs were substantial 34 ms shorter in the high-frequency than the low-frequency prime condition (b = 0.079, SE = 0.030, t = 2.60, p < .01). The opposite prime frequency effect was found for short prime durations in regression probabilities: For prime durations below 28 ms, regression probability was 7.4% larger for high-frequency than for low-frequency primes (b = -0.656, SE = 0.275, z = -2.38, p < .05), and this increase implied nearly a doubling of the regression rate.

Discussion

In an experiment utilizing a variation of the fast-priming technique (Sereno & Rayner, 1992), we presented either a high- or low-frequent prime word1 for a nominal 32 ms in foveal vision and then replaced it with an unrelated target word2. We aimed at studying whether lexical word processing influences fixation durations when the word is visible for only very short presentation times. Moreover, we were interested in the detailed time course of such an influence across fixations and within distributions of fixation durations. Post-hoc analyses examined whether target word frequency effects are specific to certain time windows of word presentation times, as has been found before (H. W. Lee et al., 1999).

Immediate and delayed effects of early frequency information

The present results show that a very brief presentation of a word is sufficient to obtain an effect of its lexical word-frequency on several eye-movement measures. Easy words seemed to have immediately advanced the decision to move the eyes away from the later target word, indicated by the shorter single fixation durations (SFD) in the case of briefly presented high-frequency prime words compared to low-frequency prime words before presentation of the target word. A distributional analysis of SFD even suggests that the frequency effect is significant as early as 207 ms after fixation onset. First fixation durations (FFD) and gaze durations (GD) showed a similar but not significant trend, and the effect was numerically absent in the first of multiple fixation durations (FMD). These results suggest that 32 ms of prime word presentation supports lexical processing in optimal situations when a single fixation suffices to read a word. In contrast, 32 ms did not seem to be efficient during suboptimal eye-movement patterns involving multiple fixations on a word. Accordingly, in FFD and GD the mixture of single and multiple fixation cases seems to have weakened the small effect of the early frequency information.

Moreover, there was additional variance in the data with respect to the effective presentation time of the prime word. Although experimentally fixed to 32 ms, it varies slightly between trials due to different display-change delays based on the monitor's refresh-cycle position at the moment when the saccade triggered the display of the prime, and to differences in the following fixation onset. When the variance in effective prime durations was statistically controlled in the post-hoc analyses, prime-frequency effects were highly persistent with significant effects particularly for prime durations below 28 ms. Apart from immediate effects in SFD, the post-hoc analyses confirmed delayed effects on GD and on the second or later fixations on the target word.

Finding effects for very short prime durations is consistent with previous studies of fast priming during reading (Frisson et al., 2014; H. W. Lee et al., 1999, 2002; Y. A. Lee et al., 1999; Rayner et al., 1995; Sereno, 1995; Sereno & Rayner, 1992). However, previous studies have manipulated the prime-target relation and provided evidence that briefly presented primes influence eye movements by modulating later processing of a visible target word (mostly in terms of facilitation effects). In the present study, to the contrary, we used a variation of the paradigm where briefly presented prime words (words1) were followed by an unrelated target word (word2). Contrary to previous results from the fast-priming paradigm, this early cognitive influence on eye-movements is independent of any specific word2-priming by word1 processing, and instead results from lexical prime word1 processing.

One might argue that replacing a word during its fixation causes an unnatural disruption during reading. In fact, it has been shown that display changes in foveal vision lead to saccadic inhibition resulting in a decrease of the frequency of making a saccade within 100 ms after the visual event, and that this effect can be modulated by cognitive factors (Reingold & Stampe, 2004; Slattery, Angele, & Rayner, 2011). In the present experiment we observed some evidence that the likelihood of making a saccade was reduced in the time window up to 200 ms (see Figure 3). Thus, it seems possible that saccadic inhibition might be slightly enhanced for instances of briefly presented low-frequency words and may contribute to our finding that the distribution of single fixation durations appeared to be shifted to the right for low- compared to high-frequency primes. By this mechanism, enhanced saccadic inhibition for low frequency prime words may have caused a somewhat earlier onset of the prime frequency effect (at 207 ms) compared to earlier studies reporting an onset at 254 ms (Reingold et al., 2012; in the no-preview condition). However, the size of any possible such interaction between word frequency and saccadic inhibition was not large enough to provide statistical support in our study. Instead, the earliest influence of prime frequency on fixation durations occurred 207 ms after prime onset, suggesting that it did not originate (solely) from early saccadic inhibition effects, but rather from the use of the frequency information for initiating saccade programs.

The present results corroborate previous evidence for immediate fixation-by-fixation adjustments of eye movements with respect to current word-processing difficulties (Inhoff, 1984; Reingold et al., 2012; Staub et al., 2010) within neurophysiological constraints (Reichle & Reingold, 2013), and demonstrate that such adjustments occur even for extremely short presentation times. They support the hypothesis that early, shallow and incomplete lexical processing can prematurely facilitate saccade programs in the case of high-frequency primes, and can delay saccade generation in the case of low-frequency primes. This result is consistent with previous findings on early cognitive word processing during reading based on the fast-priming paradigm (Rayner & Sereno, 2003), the disappearing text paradigm (Liversedge et al., 2004; Rayner et al., 2003), distributional analyses of fixation durations (Reingold et al., 2012; Staub et al., 2010), and electrophysiological recordings (Dimigen et al., 2011). It suggests that cognitive eye-movement control is based on early and incomplete lexical processing, and thus supports central assumptions embedded in computational models of eye-movement control during reading (Reichle et al., 1998, 2003, 2012; Engbert et al., 2005; Risse et al., 2014; Schad & Engbert, 2012).

Word frequency, however, also affected later eye-movement decisions, suggesting that early lexical processing also has delayed influences on eye movements. In particular, the effect on the second and later fixation durations (which do not contain any immediate fixation durations such as SFD or FFD) support the notion that early frequency effects are persistent and influence several subsequent saccadic decisions downstream. This finding suggests that early frequency information obtained after nominal 32 ms of prime word presentation remained in the eye-movement control system even after the prime information turned irrelevant due to presentation of the target.

In addition to immediate and delayed effects of early frequency information, we obtained irregular eye-movement patterns visible in inverse prime frequency effects for GPTs and the number of regressions out of the target word. Increased GPTs in cases of easy high-frequency primes and shorter GPTs in cases of difficult low-frequency primes suggest that easy primes were sometimes processed substantially (Howes & Solomon, 1951; Johnson, Thomson, & Frincke, 1960) – maybe even up to the level of the reader's awareness. Thus, while our findings clearly support an impact of early and incomplete lexical processing stages in eye-movement control, higher levels of cognitive processing also seem to guide the eyes during reading. Conscious processing of some high-frequency primes may have triggered regressive saccades because our primes did not semantically fit into the sentences and readers may have sought to clarify the observed semantic mismatch. As a related explanation, the late reversed effect of prime frequency might emerge because readers have to inhibit the representation of high-frequency words stronger than those of low-frequency words (Nakayama, Sears, & Lupker, 2010).

Direct and indirect lexical control of eye movements during reading

In addition to providing insight into the time course of the interaction between cognitive processing and oculomotor control, the present findings may also be instructive with respect to the more general question about the type of such control (e.g., Reingold et al., 2012). The present finding of immediate effects in single fixations on the target word clearly supports the notion of direct fixation-by-fixation control of eye movements during reading. The difference in local processing difficulty restricted to an early time-window after fixation onset immediately affected the first saccadic decision on the target word. At the same time, the findings also demonstrate the limits of immediate cognitive control. Given that no parafoveal preview was available in our study word frequency did not affect single fixations with durations of less than 200 ms, which likely reflects the expression of tight neurophysiological constraints on processing times (Reichle & Reingold, 2013; Reingold et al., 2012). Moreover, the temporal delay of the frequency effect into the second or later fixations is difficult to clearly attribute to the direct control type. As Reingold et al. (2012, Footnote 1) noted, the concept of immediacy in the adjustment of fixation durations as one important characteristic of direct lexical control is not well defined. A strict view would require that the information obtained during a fixation immediately modulates the saccade that terminates the ongoing fixation and not the next one, similar to the definition of direct control in current-fixation control models (Rayner & Pollatsek, 1981). However, the timing of cognitive influences may be more variable than is captured in a restrictive definition of direct control. For illustration, simulations with a computational model in which the foveal processing difficulty immediately changed the rate with which a processing threshold was reached that triggered a new saccade program (Trukenbrod & Engbert, 2014) have shown that such immediate adjustments can prolong the current fixation, the next fixation, or both (for a similar mechanism in reading see Risse et al., 2014; Schad & Engbert, 2012).

Aware of the intricacies associated with the concept of immediacy, Reingold et al. (2012) proposed a definition of direct control that emphasized immediacy at the level of words rather than at the level of each individual fixation. According to this view, any influence on fixation durations would be considered immediate and thus attributed to direct control as long as it represents the processing of the fixated word. In other words, any fixation on word n that is modulated by the local processing difficulty of word n is evidence for direct control of fixation durations during reading irrespective of whether it is the first, second, or later fixation on that word. Such a concept may explain some of the delayed effects in the present experiments (e.g., the results in GD). However, effects in GPT or regression probability would need to be accounted for by additional processes. In contrast, Reingold et al. (2012) defined indirect control during reading in terms of delayed fixation-duration adjustments based on the global processing difficulty of the previous words – similar to global control models as distinguished in Rayner and Pollatsek (1981). According to this view, effects of lexical difficulty should be delayed on words following the location of processing difficulty. In the present study, we did not find evidence for such spillover effects.

In summary, tight physiological time constraints during reading provide a challenge for the cognitive system to quickly adjust eye movements to local processing difficulties. Using a novel variant of the fast-priming paradigm, we found that the lexical frequency of a word that was presented for 32 ms in foveal vision and subsequently masked moderated eye movements, with an onset of the frequency effect only 207 ms after word onset. This finding provides support for the hypothesis that cognitive eye movement control during reading is in part based on a very early and incomplete level of lexical analysis and provides temporal constraints for the modeling of this process. The finding moreover supports (and demonstrates the limits of) a strict version of fixation-by-fixation theories of direct cognitive control and suggests that the eye-movement control system operates under physiological time constraints in a highly immediate and optimized manner.

Acknowledgements

We thank Ralf Engbert, Reinhold Kliegl, and the Deutsche Forschungsgemeinschaft (grant no. FOR 868, Research Unit „Computational Modeling of Behavioral, Cognitive, and Neural Dynamics“) for financial support to DJS and SR which enabled them to undertake a research visit to UCSD. The research was also partially supported by grant HD26765. This work had its origins in the time when KR was an Alexander von Humboldt Visiting Professor at the University of Potsdam and was implemented when DJS and SR were visiting researchers at UCSD. We thank Daniel Lee for assistance with the creation of the text material. We thank Eyal Reingold for his helpful comments on the manuscript.

Footnotes

1. To improve generalizability of our findings, we refit all statistical models without removing non-significant random effects [including random slopes for main effects, interactions (where present), and random correlations; cf., Barr et al., 2013]. Based on these random effects structures, from a total of 12 significant GLMM-tests of prime frequency effects reported in the present study, nine effects remained significant (including all effects for SFD, TRT, and 2nd and later fixations), two were marginal (for gaze durations and regressions), and only one post-hoc test (for gaze durations) turned non-significant, clearly supporting the reliability of the present findings.

2 We performed several control analyses to further check the validity of these post-hoc analyses involving the prime duration factor. We ran several control models for five dependent variables of interest (SFD, GD, TRT, 2nd and later fixations, regression probability). First, to check whether effects of prime duration are confounded with potentially correlated oculomotor factors, we statistically controlled for the oculomotor variables target word landing position (linear and quadratic), incoming saccade amplitude and pre-boundary fixation duration by adding these covariates to the (G)LMMs reported above. Next, the median prime duration of 28 ms occurred very frequently in the data (see Figure 1). To avoid a decision on a cut-off below or above the median, we created a 3-level factor coding prime durations < 28 ms, = 28 ms, and > 28 ms, and tested the interaction of prime frequency with this 3-level factor via likelihood ratio tests. We tested additional models combining the 3-level factor with the oculomotor covariates and, last, added higher-level interactions between the oculomotor covariates and prime frequency. In total, we thus performed 4 control analyses for each of the 5 dependent variables. The results from these analyses

supported our overall findings, as the interaction between prime frequency and prime duration was significant or marginal in 17 out of these 20 tested control models.

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Figure Captions

Figure 1: Histograms of prime durations computed as the difference between target word fixation onset and prime offset. Separate histograms are displayed for all valid trials (left panel) and for single fixation cases (right panel), as well as for the high frequency (dots and solid lines) and low frequency (triangles and dashed lines) prime condition.

Figure 2: Prime-word frequency effect on single fixation durations on the target word. Error bars are cell-based S.E.M..

Figure 3: Histogram of single fixation durations for primes of low and of high frequency.

Figure 4: Distributional analysis of prime word frequency effects on single fixation durations. Main panel: Shows the survival distribution (i.e., inverse cumulative probability) for the low (dashed line) and high (solid line) frequency prime conditions. Inset: Displays the difference in survival between high and low frequency primes (black line) as a function of fixation duration; the grey area shows 95% confidence from a between-subject bootstrap analysis using one-tailed testing; dashed vertical lines indicate the first and last fixation duration showing significant prime frequency effects (criterion: at least 5 consecutive significant durations). Lower panel: Densities of single fixation durations for low (dashed line) and high (solid line) frequency primes.

Figure 5: Effect of prime-word frequency on go-past times (left panel), and the interaction of the prime-word frequency effect with prime duration (split at the median of 28 ms) for target-based regression probability (right panel). Error bars are cell-based S.E.M..

Figure 6: Interaction of prime-word frequency and prime duration (median split) for target word single fixations. Error bars are cell-based S.E.M..

Figure 7: Interaction of the prime-word frequency effect with prime duration (split at the median of 28 ms) for gaze durations (left panel), total reading times (middle panel), and the second and later fixation durations (right panel). Error bars are cell-based S.E.M..

Figures

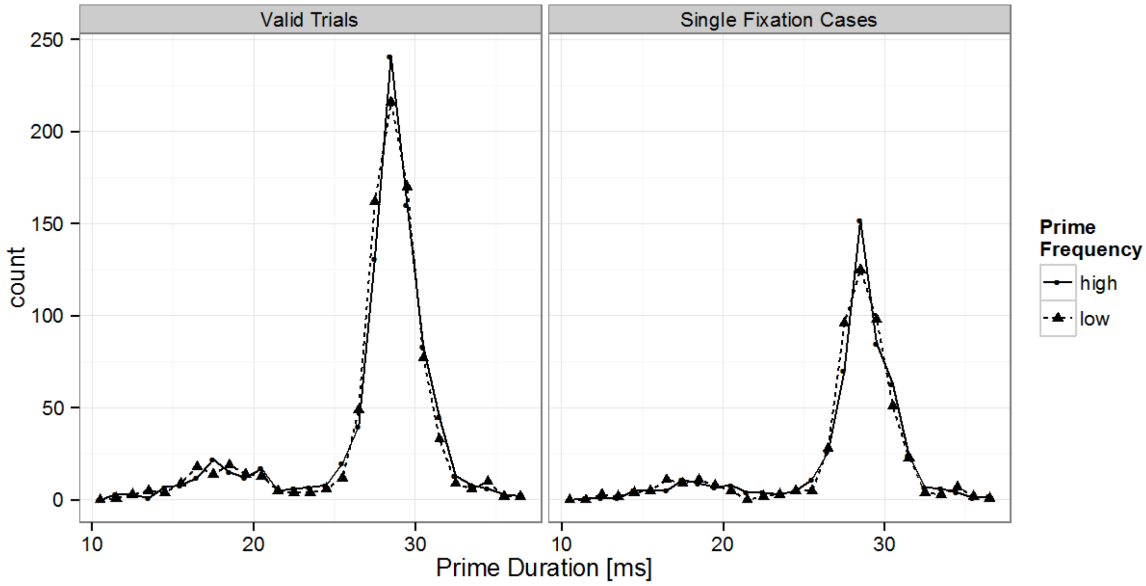


Figure 1

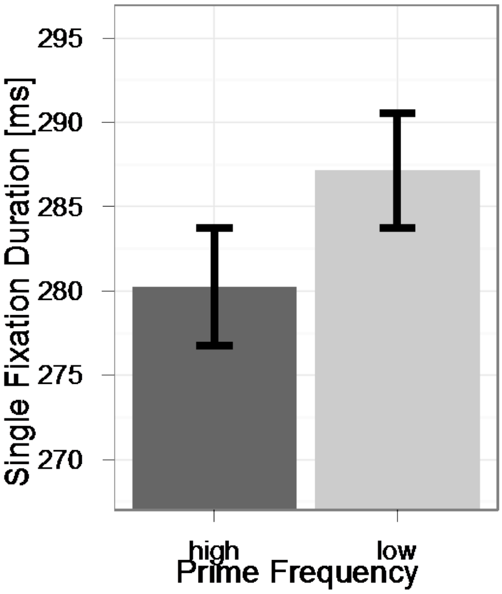

295
290
285
280
275
270
Single Fixation Duration [ms]
high
low
Prime Frequency

Figure 2

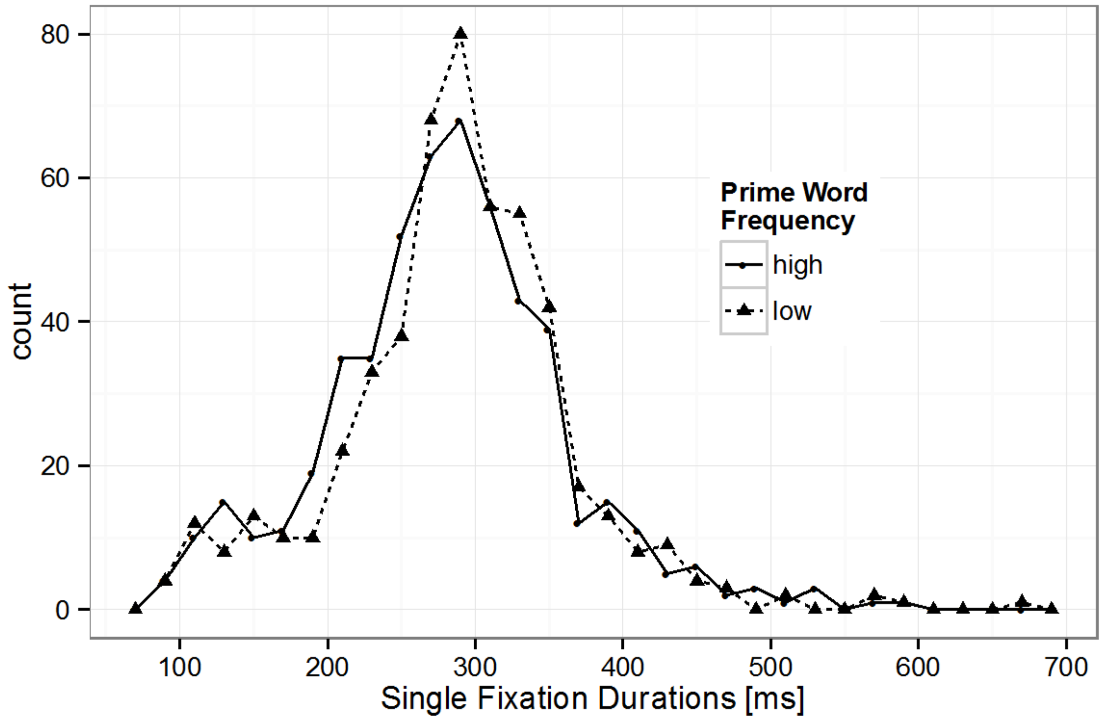

count
Single Fixation Durations [ms]
Prime Word Frequency
high
low
0
20
40
60
80
100
200
300
400
500
600
700

Figure 3

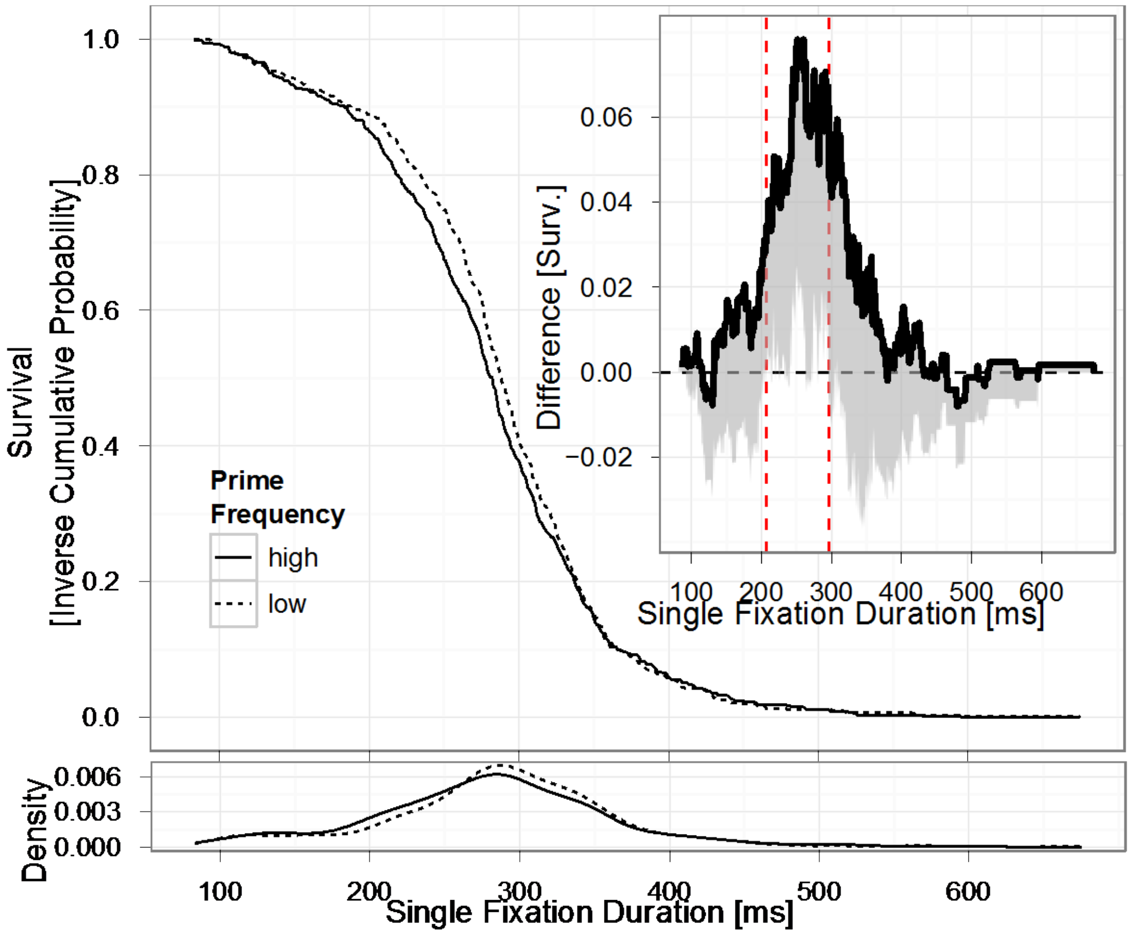
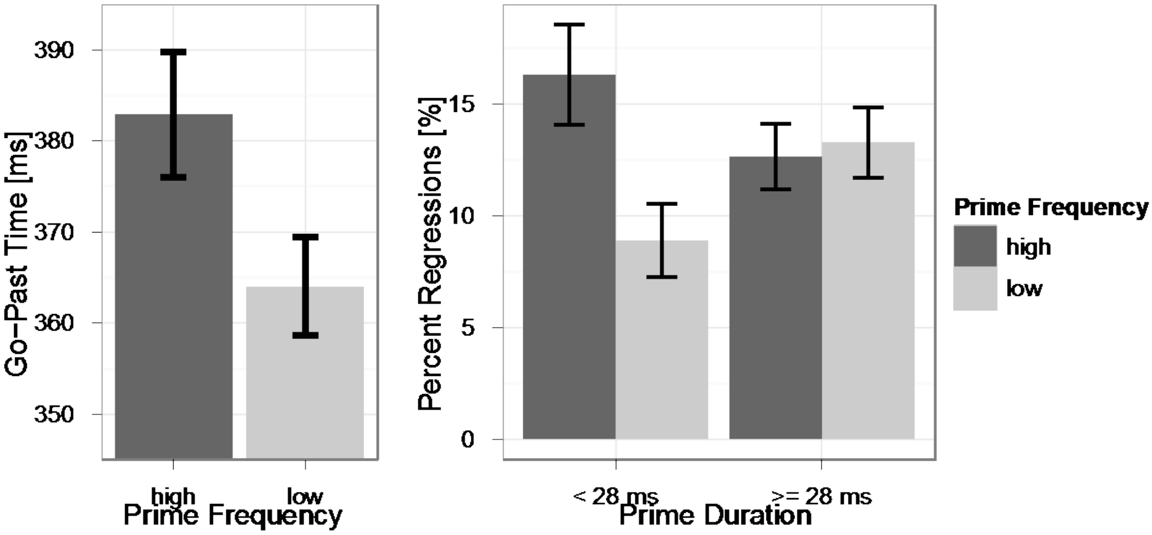

Survival
[Inverse Cumulative Probability]
1.0
0.8
0.6
0.4
0.2
0.0
Prime
Frequency
high
low
Difference [Surv.]
0.06
0.04
0.02
0.00
−0.02
100 200 300 400 500 600
Single Fixation Duration [ms]
Density
0.006
0.003
0.000
100
200
300
400
500
600
Single Fixation Duration [ms]

Figure 4



Go−Past Time [ms]
390
380
370
360
350
high
low
Prime Frequency
Percent Regressions [%]
15
10
5
0
< 28 ms
>= 28 ms
Prime Duration
Prime Frequency
high
low

Figure 5

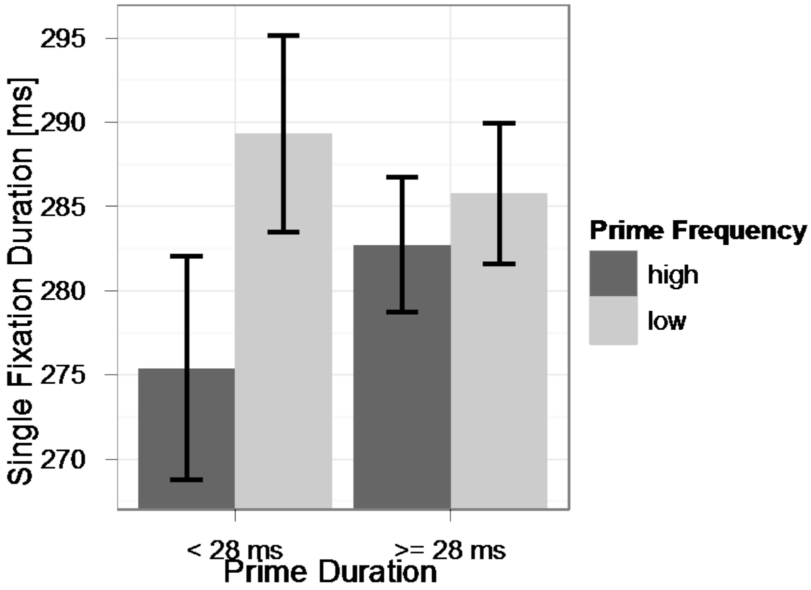

295
290
285
280
275
270
Single Fixation Duration [ms]
< 28 ms
>= 28 ms
Prime Duration
Prime Frequency
high
low

Figure 6

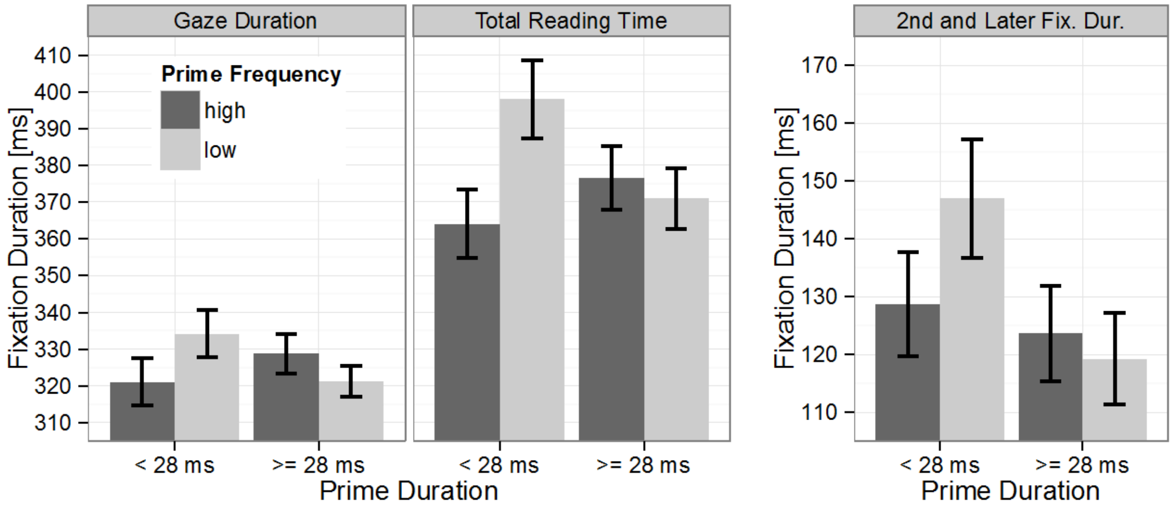

Gaze Duration
Total Reading Time
2nd and Later Fix. Dur.
Prime Frequency
high
low
Fixation Duration [ms]
410
400
390
380
370
360
350
340
330
320
310
170
160
150
140
130
120
110
< 28 ms
>= 28 ms
Prime Duration

Figure 7

Tables

Table 1

Mean fixation durations and saccade probabilities as a function of prime duration and prime frequency.

Prime Duration	Prime Freq-uency	**Fixation Duration [ms]**					**Saccade Probability [%]**	
		SFD *M(SD)*	FFD *M(SD)*	Gaze *M(SD)*	TRT *M(SD)*	Go-Past *M(SD)*	Ref-ixation	Reg-ression
< 28 ms	High	275 (61)	259 (48)	309 (59)	351 (80)	376 (131)	30 (25)	13 (16)
< 28 ms	Low	288 (53)	270 (45)	327 (68)	396 (103)	359 (82)	30 (24)	9 (11)
>= 28 ms	High	289 (37)	270 (30)	329 (58)	378 (96)	374 (79)	32 (22)	15 (19)
>= 28 ms	Low	293 (40)	268 (27)	321 (50)	382 (92)	361 (69)	34 (22)	12 (12)

Note. Means and standard deviations are computed over subject means.

Appendix

Table A1.

Prime and target words used in the present experiment.

Nr	High Freq. Prime	Low Freq. Prime	Target Word		Nr	High Freq. Prime	Low Freq. Prime	Target Word
1	blue	teal	foot		35	beef	veal	mask
2	toilet	urinal	marble		36	chicken	bologna	plastic
3	food	grub	lint		37	squid	prawn	model
4	alcohol	whiskey	pyramid		38	bean	beet	sand
5	liver	renal	sauna		39	corn	leek	pill
6	oxygen	cobalt	bridge		40	cabbage	soybean	blender
7	pianist	harpist	sweater		41	ginger	radish	school
8	sister	nephew	monkey		42	potato	turnip	anchor
9	vanilla	saffron	college		43	lettuce	parsnip	stapler
10	rain	hail	jeep		44	test	quiz	bomb
11	salmon	angler	poodle		45	paper	sheet	anvil
12	bass	tuna	sign		46	house	villa	wheel
13	garlic	chives	bottle		47	army	navy	star
14	water	juice	scarf		48	door	knob	lake
15	bull	boar	wine		49	cash	coin	fire
16	walnut	cashew	string		50	paint	chalk	group
17	rose	lily	jail		51	alarm	siren	lunch
18	crow	wren	flag		52	crown	tiara	knife
19	dove	gull	lens		53	fire	lava	tent
20	robin	quail	magma		54	button	zipper	pencil
21	piano	banjo	ocean		55	folder	binder	camera
22	guitar	violin	barrel		56	match	flint	stair
23	wolf	mule	yarn		57	hall	dorm	leaf
24	gold	jade	dust		58	hair	nail	case
25	snake	gecko	arrow		59	brain	lungs	jelly
26	oyster	mussel	garage		60	root	weed	sink

27	chair	stool	dough		61	head	calf	bowl
28	ship	raft	bulb		62	port	pier	bell
29	hammer	pliers	branch		63	marker	eraser	window
30	tissue	napkin	soccer		64	figure	statue	powder
31	skull	femur	crate		65	hand	foot	dish
32	waste	scrap	blood		66	sword	saber	frame
33	orange	banana	shield		67	dollar	nickel	prison
34	apple	berry	laser		68	glass	flask	photo

Highlights

- In a new version of the fast priming paradigm we study effects of prime frequency with constant prime-target relation
- We find prime frequency effects on eye movements during reading for prime durations of 32 ms
- Using distributional analyses, we find highly immediate and also delayed prime frequency effects
- These results provide constraints for mechanisms of eye movement control