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Reversed preview benefit effects: Forced fixations emphasize the importance of parafoveal vision for efficient reading

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Abstract

Current theories of eye movement control in reading posit that processing of an upcoming parafoveal preview word is used to facilitate processing of that word once it is fixated (i.e., a foveal target word). This *preview benefit* is demonstrated by shorter fixation durations in the case of valid (i.e., identical or linguistically similar) compared to invalid (i.e., dissimilar) preview conditions. However, we suggest that processing of the preview can directly influence fixation behavior on the target, independent of similarity between them. In Experiment 1, unrelated high and low frequency words were used as orthogonally crossed previews and targets and we observed a *reversed preview benefit* for low frequency targets—shorter fixation durations with an invalid, higher frequency preview compared to a valid, low frequency preview. In Experiment 2, the target words were replaced with orthographically legal and illegal nonwords and we found a similar effect of preview frequency on fixation durations on the targets, as well as a bimodal distribution in the illegal nonword target conditions with a denser early peak for high than low frequency previews. In Experiment 3, nonwords were used as previews for high and low frequency targets, replicating standard findings that "denied" preview increases fixation durations and the influence of target properties. These effects can be explained by *forced fixations*, cases in which fixations on the target were shortened as a consequence of the timing of word recognition of the preview relative to the time course of saccade programming to that word from the prior one. That is, the preview word was (at least partially) recognized so that it should have been skipped, but the word could not be skipped because the saccade to that word was in a non-labile stage. In these cases, the system pre-initiates the subsequent saccade off the upcoming word to the following word and the intervening fixation is short.

Introduction

Since Javal (1878) first reported that readers make ballistic eye movements as they read, it has been a central tenet of reading research that the reason for this is to place the *fovea* (the center of vision) on the word that is to be processed with the highest efficiency (see Huey, 1908; Rayner, 1998, 2009a). Indeed, the fovea is the region of the visual field with the highest acuity and acuity drops rather precipitously with increasing eccentricity (i.e., in the *parafovea* and *periphery*). While it is generally accepted that a fair amount of lexical processing occurred for a parafoveal word prior to it being skipped (Rayner, 2009a), the

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situation is less clear when the word is fixated, and therefore processed both parafoveally and foveally. Because of the acuity differences across the visual field noted above, there is an implication that, if not skipped, the majority of word processing occurs during direct fixation on the word and relatively little high-level lexical recognition had occurred prior to this, while the word was being viewed parafoveally. The following experiments were designed to test whether this is truly the case or, if not, what type and degree of word processing occurs for a word in parafoveal vision and how that processing influences subsequent foveal processing and eye movement programming once the reader moves their eyes to directly fixate the word.

The Role of Foveal and Parafoveal Information in Reading Efficiency

Early evidence for how much more effective the fovea is than the parafovea for word recognition comes from a study by Bouma (1973) in which subjects reported the identity of a word that was briefly presented (i.e., for 100 ms) at various eccentricities. Not surprisingly, word recognition accuracy was 100% when the word was presented foveally (i.e., at 0 degrees) and decreased with increasing eccentricity. However, it is difficult to make firm claims about natural reading based on single word recognition studies due to the lack of many aspects of natural reading that affect word recognition processes in single word paradigms (e.g., parafoveal preview and the sentence or discourse context; Rayner, 1998; 2009a; Schotter, Angele, & Rayner, 2012). During natural reading (i.e., via eye movements), readers have access to the currently fixated word in foveal vision, and simultaneously have access to surrounding words, parafoveally. Results from the *disappearing text paradigm* (Ishida & Ikeda, 1989; Liversedge et al., 2004; Rayner, Liversedge, White, & Vergilino-Perez, 2003; Rayner, Liversedge, & White, 2006), in which a word disappears or is masked 60 ms after the start of a fixation (although the delay varies across conditions) indicate that reading is not disrupted if the foveal word is available for at least the first 60 ms of the fixation (Liversedge et al., 2004; Rayner et al., 2003). However, reading is disrupted if the parafoveal word disappears within the first 60 ms of fixation on the preceding word (Rayner et al., 2006) suggesting a potential paradox: while word processing is more efficient inside the fovea than outside of it (e.g., Bouma, 1973), to some extent parafoveal processing plays an equally (or arguably more) important role for reading efficiency (e.g., Rayner et al., 2006).

One way to solve this apparent paradox is to assume that attention is dissociated from fixation location part of the time (Pollatsek, Reichle, & Rayner, 2006), as is assumed by the E-Z Reader model of oculomotor control in reading (Reichle, Pollatsek, Fisher, & Rayner, 1998). That is, the greater disruption to reading caused by removing or masking the parafoveal word compared to the foveal word after 60ms can be explained by two assumptions of the model. The first assumption is that attention is allocated serially to words, which when (partially) identified causes the initiation of saccade programs. The second assumption is that approximately 50 ms of attention allocation is sufficient for visual apprehension of the text, which then is converted to an abstract memory code used for word identification that persists even once the physical text disappears. Under these assumptions, attention is allocated to a word at the beginning of a fixation on it and then shifted to the upcoming word after a certain amount of time (which varies depending on how difficult the current word is to identify). When the foveal word had disappeared after 60ms there was sufficient time for the visual information to be apprehended so that word identification and consequent saccade programming was not disrupted. In contrast, when the parafoveal word had disappeared after 60ms, by the time attention had shifted to the upcoming word it was no longer available for word identification. In this latter case, the word then needs to be directly fixated before the word identification process can start, thus delaying saccade programs and lengthening fixation durations, causing the apparent disruption in reading efficiency.

Boundary paradigms—The paradigms mentioned above provide general estimates of the use of visual information from text in different areas of the visual field but provide less detailed information about what type of information is accessed from the fovea vs. parafovea and how such sources of information are used. For this purpose, researchers turn to the *boundary paradigm* (Rayner, 1975). With this paradigm, researchers are able to quantify *preview benefit*—faster processing of the fixated *target* word with an valid *preview* of the word (i.e., how it appears before it is directly fixated) compared to an invalid or masked preview (see Rayner, 1998; Schotter et al., 2012 for reviews)—but the exact nature and source of this processing benefit is still not entirely clear.

Initially, the explanation for preview benefit was that readers integrate information obtained from the preview with information obtained from the target and this integration is easier as the preview and target are more similar. For example, Rayner (1975) introduced the boundary paradigm with valid or invalid (i.e., visually similar and dissimilar word and nonword) previews, and concluded,

> while at one level of perceptual processing masking may occur as the input from one fixation overrides the image from the prior fixation, at a higher level the information from the two fixations is integrated. In the present study, when visual or semantic discrepancies were introduced between two successive fixations, this integration failed. (p. 80)

Additionally, Pollatsek, Lesch, Morris, and Rayner (1992) used valid and invalid (i.e., visually or phonologically similar or dissimilar word) previews, and concluded, “phonological coding is used to preserve the ‘memory’ of a word from one fixation to aid in its identification on the next fixation.” (p. 159). Thus, these interpretations imply that parafoveal information is used in service of the foveal processing that occurs on the word once it is fixated. However, it may be possible (and the comparison between the foveal and parafoveal disappearing text studies suggests) that in some cases parafoveal information *itself* is used for reading, potentially without the involvement of or need for foveal information. Indeed, recent research using the boundary paradigm has found evidence for preview benefit from a preview word that was completely unrelated to the target word, so long as the preview itself was a sensible word in the preceding sentence context (Schotter & Jia, 2016; Veldre & Andrews, 2016; Yang, Li, Wang, Slattery, & Rayner, 2014; Yang, Wang, Tong, & Rayner, 2012).

Parafoveal Processing and Word Skipping

There is one clear instance where parafoveal information influences reading without respect to the subsequent foveal information after the saccade: when a word is skipped. The skipping decision is based on exclusively parafoveal information (i.e., from word *n+1*) because, at that point, the foveal information (i.e., if the word were to be fixated and become word *n*) is not yet accessible to the reader. Word properties that affect fixation times are also known to affect word skipping (Rayner, 1998), for example high frequency and/or predictable words are more likely to be skipped and, when fixated, receive shorter fixations than low frequency and/or unpredictable words. Thus, it is clear that some degree of word processing had occurred for the words parafoveally and been used to make the skipping decisions. But what about fixations when the word is not skipped?

There are at least two possible ways in which properties of the preview could affect fixation durations on the subsequently fixated target without respect to foveal target information. The first account regards *mislocated fixations* (Drieghe, Rayner, & Pollatsek, 2008; Nuthmann, Engbert, & Kliegl, 2005), the idea that since there is motor error in targeting saccades (McConkie, Kerr, Reddix, & Zola, 1988) an intended skip can actually land short, leading to a fixation on the word that was intended to be skipped while attention is allocated to the upcoming word, the intended saccade target. The second account regards *parallel saccade programs* (Morrison, 1984), the idea that if the currently programmed saccade to the upcoming word is in a non-labile (not cancelable) stage the system can pre-initiate the subsequent saccade off of that word if it is recognized (at least to the point where it would have otherwise been skipped). The pre-initiation of the subsequent saccade causes the intervening fixation to be short; we term these fixations *forced fixations* (see below). These accounts are similar in many respects (for example, they both regard cases in which the preview word was intended to be skipped but was not), but the key difference between them regards their predictions about the distribution of landing positions on the target word.

Mislocated Fixations

On a mislocated fixation account, because there is systematic error in targeting saccades (McConkie et al., 1988) long intended saccades (e.g., skipping saccades) tend to undershoot their targets and instead land on the end of the previous word. Because the error of the landing location can be detected very quickly, these saccades will be followed by a short fixation and then a corrective saccade to the intended location (i.e., the following word). These short fixations should be more likely when the preview word is high frequency because they yield higher (intended) skipping rates, but most importantly, they should be more likely when the landing position is at the end of the target word (Nuthmann et al., 2005). As will become clear below, while we do not deny that mislocated fixations do occur during reading (and in our experiments), we propose here and will demonstrate below that the effect of a parafoveal preview on fixation durations on the target is unlikely to be due to them. Instead, we favor an account based on forced fixations.

Forced Fixations

In order to understand the idea of forced fixations, it is first necessary to describe some of the constraints imposed on the reading system by saccade programming mechanisms. Within the architectures of the E-Z Reader model (Reichle et al., 1998) and a parallel-attention alternative model, SWIFT (Engbert, Nuthmann, Richter, & Kliegl, 2005), there are two stages of saccade programming: the first is labile, meaning that it can be cancelled and the second is non-labile, meaning that it cannot be cancelled. This two-step process was inspired by an earlier model of reading developed by Morrison (1984), who implemented these two saccade programming stages based on the empirical work of Becker and Jürgens (1979). In Becker and Jürgens' experiment, subjects were required to make a saccade to a stimulus that was presented at various eccentricities in the periphery. On some trials, the location of that target stimulus moved before the saccade program executed. If the target moved late enough during the prior fixation, two independent eye movements were observed with a brief intervening fixation. If the target moved early during the prior fixation, a partial or complete redirection of the first saccade was observed. Becker and Jürgens noted that the critical temporal variable determining whether there was one or two saccades was the time between the target movement and the (first) saccade execution.

While Becker and Jürgens' experiment involved saccades to simple stimuli that moved location, the fact that they found evidence for parallel programming of saccades that result in either the cancelation of the first saccade, or a sequence of saccades with a short intervening fixation duration is an important premise for the models of reading mentioned above. In the models, (partial) word recognition is the process that initiates or delays saccade programming away from the word. If the system is in the non-labile stage and the upcoming word (*n*+1, to which the saccade is currently being programmed) is recognized, at least to the point where it would otherwise be skipped (i.e., were saccade programming still in the labile stage), the system may begin programming the subsequent saccade off of word *n*+1 to word *n*+2. This pre-programming of the saccade then shortens the subsequent fixation on word *n*+1, as noted by Morrison (1984, p. 678), "If saccades during reading can be programmed in parallel, then some saccades will not appear to be programmed in response to the immediately preceding fixation, because they were programmed or initiated before the information had been processed or even during the prior fixation".

Estimates of saccade planning time vary, but range from 125–175 ms (we use 150 ms for simplicity; Becker & Jürgens, 1979; Rayner, Slowiaczek, Clifton, & Bertera, 1983; see Rayner, 1998). Thus, if the subsequent fixation on word *n*+1 lasts 200 ms, then the planning of the eye movement that ends the fixation began in the first 50 ms. Given that this is approximately the same amount of time that it takes for information from the retina to reach the brain (i.e., the eye-brain lag: see Rayner et al., 2003; Reichle & Reingold, 2013), it is therefore possible that the duration of the fixation on the word is determined by the properties of the preview alone, without knowledge of the foveal target information. Moreover, the decision could even be made shortly before the eyes even land on the target word, which would lead to fixations even shorter than 200 ms. Morrison (1984) describes a scenario in which,

> parafoveal encoding of the first word does not succeed before [the non-labile stage] is completed… that will cause a saccade to land on the preferred viewing location of the first word… During this lag, suppose parafoveal encoding succeeds. Attention then shifts to the second word to the right and elicits another saccade.

> The second saccade will have its amplitude computed sometime during the very beginning of the fixation on the first word and will be issued even before the new information gets analyzed at a cortical level [i.e., the eye-brain lag]. In this case the fixation pause on the first word will be extremely brief, perhaps no more than 50 ms to 100 ms. Throughout such a brief fixation, attention is directed to the next word and a saccade there is imminent. (pp. 680–681)

We refer to fixations of this kind as forced fixations because, had the prior saccade not been in the non-labile stage, the word would have been skipped. Thus, these fixations occupy an interesting middle ground between a skip and a true fixation in that the reader is actually fixating the word, but only because the saccade to that word was committed. However, like the probability of observing a skip (for which the decision must be made before the target information is encountered), the duration of the forced fixation should not be influenced by properties of the fixated target because there is not enough time for information about the foveal target to reach the brain before the outgoing saccade is executed. Importantly, in contrast to an explanation via mislocated fixations, the distribution of landing positions of these fixations should not be systematically shifted toward the end of the target word, but instead should be distributed around the preferred viewing location (between the beginning and center of the word; Rayner, 1979), as noted by Morrison in the quote above. The studies described here were designed to investigate these types of fixations by using the boundary paradigm to dissociate the preview information from the target information.

The Importance of the Choice of Preview Conditions

It is difficult to dissociate scenarios in which parafoveal information facilitates reading on its own, versus scenarios in which it facilitates reading through integration with foveal information, as suggested by Rayner (1975; Pollatsek et al, 1992). The reason for this is because previous studies have chosen preview conditions that make such a comparison difficult. For example, in the Pollatsek et al. (1992) study mentioned above, which tested for phonological preview benefit, the homophone previews did not necessarily make sense in the sentence context (e.g., "The generous man gave every sent/cent to charity."). In fact, researchers have recently begun discussing preview benefit effects both in terms of the *benefit* obtained from having a valid (e.g., identical) versus an invalid preview, as well as the *cost* associated with an inappropriate (e.g., nonword or anomalous word) versus an appropriate preview (e.g., Kliegl, Hohenstein, Yan, & McDonald, 2013; Marx, Hawelka, Schuster, & Hutzler, 2015). Therefore, to avoid the cost of an inappropriate preview we must use preview conditions that contain words that, on their own, are sensible in the context and are either valid or invalid (i.e., identical or unrelated in orthography, phonology, and semantics) with respect to the target. Additionally, to determine whether the preview facilitated reading on its own or by means of integration with the foveal target we must compare valid preview conditions with invalid conditions in which the preview is an easier versus more difficult to process stimulus than the target.

The three studies presented below serve to pursue the possibility that there might be forced fixations—fixations for which the duration is determined by the ease of processing the preview and may not show any sensitivity to the identity of the target (e.g., the fact that it is different from the preview in invalid preview conditions). In Experiment 1 we employ the boundary paradigm with high and low frequency previews (e.g., *phone* and *scarf*, respectively) crossed with the same high and low frequency words as targets, creating two valid preview conditions and two invalid preview conditions (one where the preview is higher frequency than the target and the other where it is lower frequency than the target). In the method and results of Experiment 1 we refer to the valid conditions as "identical" and the invalid conditions as "display change" because the term invalid is derived from a theory based on integration and is only relevant if the preview and target information are compared or integrated; however, on a forced fixation account the relationship between the two is irrelevant and "display change" is a more theory-neutral term. As long as skipping rates are relatively low, these conditions allow us to test for the presence of forced fixations. Since we hypothesized that these forced fixations are caused by an easy to process preview, such an account predicts that mean fixation durations would be shorter in the low frequency target, display change preview condition (i.e., where the preview is a higher frequency word) than in the low frequency target, identical preview condition (i.e., where the preview is also low frequency) because there should be more forced fixations in the former case. This pattern of data would be surprising because all extant conceptualizations of preview benefit predict that no invalid (i.e., display change) preview condition should be faster than the valid (i.e., identical) preview condition. Importantly, the account also predicts that we would observe the standard preview benefit (i.e., shorter fixations in the identical preview condition than the display change condition) for the high frequency target because the preview in the display change condition is a more difficult to process stimulus than the target itself (i.e., the identical preview) and would therefore lead to fewer forced fixations. To further explore forced fixations we conducted Experiment 2, in which the target words were replaced with nonwords that were either orthographically legal/pronounceable (e.g., *gamip*) or orthographically illegal/unpronounceable (e.g., *gkmbp*). And to facilitate comparisons to prior research and the predictions of extant models of oculomotor control in reading we conducted Experiment 3, in which the legal and illegal nonwords served as the previews for the high and low frequency words that were the targets.

Experiment 1

Method

Participants—Twenty-four undergraduates from the University of California, San Diego, participated in this experiment for course credit. All were native English speakers, had normal vision, and were naïve to the purpose of the experiment.

Apparatus—Eye movements were recorded with an SR Research Ltd. Eyelink 1000 eye tracker (sampling rate of 1000 Hz) in a tower setup that restrained head movements with forehead and chin rests. Viewing was binocular, but only the eye movements of the right eye were recorded. Subjects were seated approximately 60 cm away from an HP p1230 CRT monitor with a screen resolution of 1024 × 768 pixels and a refresh rate of 150 Hz. Text was displayed in black, 14-point, fixed-width Courier New font on a white background. Sentences were always displayed in the vertical center of the screen in one line of text, and 3.8 characters subtended 1° of visual angle. Display changes were completed, on average, within 4 ms of the tracker detecting a saccade crossing the invisible boundary, which was located at the beginning of the space preceding the target word.

Materials—144 high and low frequency target pairs that were matched in length and word class (noun, verb) were embedded in neutral sentence frames (see Table 1). Critically, these high and low frequency target pairs were designed to have limited orthographic, phonological, and semantic overlap. Across all target pairs, only 18.5% of letters were shared between the high and low frequency targets (or roughly 1 letter per word on average). Of this 18.5% of shared letters, 54.4% were cases of overlap at one or both of the last two letter positions, and 67.8% of these cases could be explained by morphological constraints on the language (i.e., by plural nouns ending in *s*, or the verb inflections *ed* and *ing*, the latter of which only occurred once). Critically, only 13.1% of letter overlap that occurred did so at the first letter position, which is important because word-initial letters are particularly important for word identification (e.g., Rayner & Kaiser, 1975; White, Johnson, Liversedge, & Rayner, 2008). The majority of letter overlap was therefore restricted to later positions in the words. Since these words overlapped minimally in orthography and were not homophones, the degree of phonological overlap was also minimized. Semantic relatedness was low (2.38 on a 1–7 scale) and was assessed via the norms described below. Lexical frequencies (per 400 million) for all stimuli were computed via log-transformed HAL frequency norms (Lund & Burgess, 1996) using the English Lexicon Project (Balota et al., 2007). High frequency target words had an average log frequency of 10.48 (range 8.21–13.25; raw count per million = 159). Low frequency target words had an average log frequency of 6.81 (range 2.83–8.9; raw count per million = 4)[1]. Target words were on average 5.88 letters long (range 4–9). Two sentence frames were created for each high and low frequency pair, for a total of 288 experimental sentences. An example stimulus is shown in (1), with the high/low frequency target words italicized (the full set of stimuli is listed in the Appendix).

1. The boy found a red *phone/scarf* on his way to school.

Normative data—10 Native English speakers from the United States, who did not participate in the reading experiment, participated in an online norming task through Amazon's Mechanical Turk service for monetary compensation. They completed a cloze norming task to evaluate the predictability of the target words. This norming task revealed that the sentences were very neutral, with (on average) the high frequency target being produced less than 4% of the time, and the low frequency target being produced less than 1% of the time. An additional set of 10 participants from Mechanical Turk participated in a sentence acceptability-rating task. This task was administered to ensure that the high and low frequency target words fit equally well into each sentence frame. The average acceptability scores (on a 1–7 scale) for sentences with the high frequency targets and low frequency targets were 5.34 and 5.35 respectively. A third set of 10 participants from Mechanical Turk rated the high and low frequency target pairs for degree of semantic

[1]Frequency data for one low frequency item "emulating" was unavailable. Additionally, although the high frequency member of each target pair was always higher frequency than its low-frequency counterpart, eight of our high frequency words (< 6%) fell into the low frequency range (i.e., their raw count per million was below 18).

relatedness. This task was administered to ensure that the high and low frequency members of each target pair were not semantically related. The average rating of semantic relatedness across all target pairs was 2.38 (on a 1–7 scale), demonstrating that there was very little semantic overlap between our high and low frequency targets.[2]

Procedure—Subjects were instructed to read the sentences for comprehension and to respond to occasional comprehension questions using a gamepad to indicate "yes" or "no" responses. At the start of the experiment, the eye-tracker was calibrated with a 3-point calibration scheme. At the beginning of the experiment, subjects received five practice trials, each with a comprehension question to allow them to become comfortable with the experimental procedure.

Each trial began with a fixation point in the center of the screen (that served as a drift correct), which the subject was required to fixate until the experimenter initiated the trial. Then a fixation box appeared on the left side of the screen, which was located where the beginning of the sentence would appear. Once a stable fixation was detected within the box, the box disappeared and was replaced by the sentence, which remained on the screen until the subject pressed a button signaling that they understood the sentence and were ready to move on. The experiment consisted of 288 experimental sentences in which an invisible boundary was located at the end of the pre-target word. While a subject's eyes were to the left of the boundary, the preview word was either the high frequency word (e.g., *phone*) or the low frequency word (e.g., *scarf*). When the eyes crossed the boundary, either an identical target or the higher- or lower-frequency member of the pair replaced the preview word. Thus, there were four conditions: (1) high frequency target, identical preview, (2) high frequency target, display change, (3) low frequency target, identical preview, and (4) low frequency target, display change. The four conditions were counterbalanced across participants and items in a Latin-square design. Because we constructed two experimental sentences for each pair of high and low frequency words, each participant contributed data to 2 conditions for each pair of target words. Comprehension questions followed 62 (21%) of the experimental sentences and accuracy was high (94%). Order of sentence presentation was randomized for each participant, and the experimental session lasted approximately forty-five minutes.

Results

Fixations shorter than 81 ms were combined (i.e., summed) with an adjacent fixation if they were within one character space of each other because these fixations probably preceded corrective saccades. However, fixations shorter than 81 that were further from an adjacent fixation remained in the dataset[3] based on two *a priori* decisions. The theoretical justification for this is that forced fixations are expected to be shorter than normal (i.e.,

[2]The current stimuli were normed in the semantic relatedness judgment task along with a set of semantic associates from Rayner and Schotter (2014) and a set of synonyms from Schotter (2013). In the present norming, the semantic associates and synonyms received average ratings of 4.29 and 5.92 respectively. The high and low frequency items from the current study were rated significantly lower than either the synonyms or semantic associates (both ps < .001), further demonstrating that semantic overlap was indeed low.

[3]Single fixations shorter than 81 ms that were not merged with an adjacent fixation were extremely rare across all of the experiments (there were 12 in Experiment 1, 7 in Experiment 2, and 7 in Experiment 3, less than a fraction of one percent of the fixations in each experiment). Were these to be excluded, they would have been counted as a skip in the data, but due to their rarity, the inclusion of these fixations is unlikely to make the results differ if they were excluded.

"perhaps no more than 50 ms to 100 ms"; Morrison, 1984, p. 681) and the methodological justification is that there is a precedent to retain short fixations (i.e., to not have a short fixation cutoff) when short fixations are of theoretical interest, for example in research investigating distributions of fixation durations (e.g., survival curve analyses; Reingold, Reichle, Glaholt, & Sheridan, 2012). All fixations longer than 800 ms were eliminated. Trials in which there was a blink or track loss on the target word during first pass reading were excluded, as were trials in which the display change was triggered by a saccade that landed to the left of the boundary (i.e., j hooks) or trials in which the display change completed late. Additionally, gaze durations longer than 2,000 ms and total times longer than 4,000 ms were excluded. These exclusions left 5809 trials available for analysis (84% of the original data).

We report standard reading time measures (Rayner, 1998) used to investigate the time-course of word processing in reading, including *first fixation duration* (the duration of the first fixation on the word, regardless of how many fixations are made), *single fixation duration* (the duration of a fixation on a word when it is the only fixation on that word in first pass reading), *gaze duration* (the sum of all fixations on a word prior to leaving it, in any direction), *go-past time* (the sum of all fixations on a word and any words to the left of it before going past it to the right), and *total time* (the sum of all fixations on a word, including time spent re-reading the word after a regression back to it). In addition, we also analyzed three measures of fixation probability, including *fixation probability* (the probability that the target was fixated at least once during first-pass reading), *probability of regressing out of the target* (i.e., to reread prior words in the sentence), and *probability of regressing into the target* (i.e., from subsequent words in the sentence).

Data were analyzed using inferential statistics based on generalized linear mixed-effects models (LMMs) with custom contrasts conducted two ways. These custom contrasts allow us to directly test for the preview effects (i.e., display type) of interest, rather than collapsing across conditions and then conducting follow up tests. We achieve this by specifying the contrasts to estimate the preview benefit in one target frequency condition and the interaction (to assess the degree to which that effect is different in the other target frequency condition). That is, because we expect the preview effect to be different between the target frequency conditions, it is less informative what the effect of preview is collapsed across the two target frequency conditions. While the interaction term provides an estimate of the difference between the two preview effects, in order to assess the significance of the preview effect in each of the target frequency conditions independently, we ran two models on the data—one in order to estimate the preview effect in the high frequency target condition, and the other to estimate the preview effect in the low frequency target condition. Between the two models all other estimates should be nearly identical.

In the first model, the intercept represents the high frequency target condition (collapsed across display type), the contrast of frequency estimates the target frequency effect (collapsed across display type), the contrast of display type (identical vs. change) estimates the effect of display type in the high frequency target condition only, and the interaction estimates the difference between the display type effect in the low frequency target condition from that in the high frequency target condition. We conducted the same analysis again, but with the low frequency target condition as the baseline of the frequency contrast; the display type contrast, and all other contrasts were the same as the first model. This coding scheme allowed us to estimate the effect of display type in the two target conditions independently, which will be important given that the interactions between target frequency and display type were significant and crossed over. In addition, we entered subjects and items as crossed random effects (see Baayen, Davidson, & Bates, 2008), using the maximal random effects structure (Barr, Levy, Scheepers & Tily, 2013)[4].

In order to fit the LMMs, we used the lmer function from the lme4 package (version 1.1–8; Bates et al., 2015) within the R Environment for Statistical Computing (R Development Core Team, 2015). For fixation duration measures, we report linear mixed-effects regressions on the raw data: regression coefficients (b), which estimate the effect size (in milliseconds) of the reported comparison, and the (absolute) t-value of the effect coefficient. However, because our fixation time response measures are skewed (i.e., are better characterized as an ex-Gaussian than a Gaussian distribution; Staub, White, Drieghe, Holloway, & Rayner, 2010), we also ran LMMs in which we applied a log-transformation (which makes ex-Gaussian distributions more Gaussian) to the data before fitting the model (which assumes a Gaussian distribution). Log-transformation had almost no effect on the patterns of significance, so for transparency (i.e., so the effect coefficients can be interpreted as effect size in milliseconds) we report the results from the untransformed models. However, there is one notable exception where the significance of the statistical test differed between the log and raw models (the pattern of data was exactly the same) and that is discussed in the text below.

For binary dependent variables (fixation probability data), generalized mixed-effects regression models (GLMMs) were used with a logit link function, and regression coefficients (b), which represent effect size in log-odds space, and the (absolute) z value and p value of the effect coefficient are reported. Absolute values of the *t* and *z* statistics greater than or equal to 1.96 indicate an effect that is significant at approximately the .05 alpha level. Reading measures on the target word are shown in Table 2, results of the LMMs on fixation duration measures are reported in Table 3 and results of the GLMMs on fixation probability measures are reported in Table 4.

Fixation duration measures—For all reading time measures there was a main effect of target word frequency (all ts > 2.51) with longer reading times in the low frequency target condition than the high frequency target condition. For all measures there was also a significant effect of display type (identical vs. change) for the high frequency target condition (all ts > 3.00) with longer reading times when the display changed (i.e., the preview was low frequency) than when it was identical (i.e., the preview was high frequency). Most importantly, for all measures there was a significant interaction between

[4]Some models showed convergence failures, in which case individual items with few observations and/or random slopes were removed and the results of the first model to converge are reported. In Experiment 1, one of the items was removed from the following models because of extreme data loss due to blinks and issues with display: log FFD with LF baseline, raw and log SFD with LF baseline, raw and log GZD with HF baseline, log GZD with LF baseline, log GPT with HF baseline, raw GPT with LF baseline, raw and log TVT with HF baseline. In addition, we removed the following random effects: all random slopes for items in the log SFD with HF baseline, log GPT with HF baseline, log TVT with HF baseline, and the random slope of the interaction for items in raw TVT with HF baseline.

target frequency and display type (all ts > 2.46) indicating that the effect of display type was different for low frequency targets than for high frequency targets. Across the different measures, this interaction manifested differently.

For first pass reading measures (i.e., all measures that end when eyes move past the word to the right: first fixation, single fixation, gaze duration, and go-past time) there was a crossover interaction such that reading times were shorter for the low frequency target when the display changed (i.e., the preview was high frequency) than when it was identical (i.e., the preview was low frequency; see Figure 1). In a model that tested directly for the reversed preview benefit for low frequency target words, none of the reverse preview benefit effects were significant in the analyses on the raw data (all ts < 1.81). However, the reverse preview benefit effect was significant in all models for log-transformed data (FFD: $t = -2.51$; SFD: $t = -2.26$; GZD: $t = -2.48$; GPT: $t = -1.98$), suggesting that the effect was either only present, or more pronounced in the short duration tail of the distribution. That is, the log transformation shrinks the long duration end of the distribution and therefore magnifies the differences observed on the short end of the distribution relative to the variance in the model (thus providing more power for the significance test in cases where the difference is driven by the short duration end of the distribution). Critically, the pattern of data is exactly the same for the model on the raw data and the log-transformed data, indicating that the effect is reliable, the difference is that the log transformed model has more power to detect a difference, leading to the difference in statistical significance across models. When we compared the Akaike Information Criterion (AIC; a measure of the quality of a statistical model's fit to the data) for the raw and log-transformed models, all the AICs for the log-transformed models were lower than for the models on the raw data (less than 5727 for all log-transformed models and greater than 67727 for the raw models), suggesting the log-transformed models provided better fits to the data. The difference between the raw duration models and the log-transformed duration models and the interpretation that the difference is due to effects in the short fixation durations is exactly in line with the idea of forced fixations, which should all be short in duration (see Figure 2, right hand panel where the difference between the two distribution curves for the low frequency target words is apparent before 350 ms but the two curves overlap at later time points).

The total time measure (which includes re-reading of the target from subsequent words in the sentence and for which the distribution is less influenced by forced fixations) showed a different pattern for the interaction: the display change effect was in the same direction for both target frequencies, but was significantly smaller for the low frequency target than for the high frequency target. However, the standard preview benefit (shorter fixations in the identical condition than in the display change condition) in total time for the low frequency target word was significant both in the model of the raw data ($t = 2.42$), and in the model on the log-transformed data ($t = 1.98$).

Fixation probability measures—Because the identity of the target is not known at the point that a skipping decision is made, we analyzed fixation probability with only preview frequency included in the model. The effect of preview frequency was not significant ($p = .11$). For the models for regression probabilities the fixed effects structure echoed that of the fixation duration models with the high frequency target as the baseline. For regressions out of the target, none of the effects were significant (all ps > 0.35). For regressions into the target, the effect of target frequency was not significant ($p = 0.45$), the effect of display type was significant (i.e., regressions were more likely when the display changed than when it did not) for the high frequency target condition ($p < .001$) and the lack of a significant interaction ($p = .19$) suggests that the effect was of equivalent magnitude for the low frequency target.

Together, these data suggest that, in the absence of a preview frequency effect on skipping, initial reading time measures (i.e., those that end with the completion of first-pass reading) show a standard preview benefit for high frequency target words and an apparent reversed preview benefit for low frequency target words (when the display changed and the preview was higher frequency than the target/identical preview). In contrast, total time on the target word shows a different pattern, where both types of target words show the same pattern (a standard preview benefit), but the effect of display type is smaller for low frequency targets. These data show longer re-reading when the display had changed compared to when it did not change (which is echoed by the significant effect of display type on regressions into the target) such that the crossover interaction in first-pass measures turns into an under-additive interaction in total time. These data suggest that readers not only made more regressions into the target, but also spent longer re-reading the target when the display had changed than when it had not (possibly indicating explicit awareness of the display change: see Angele, Slattery, & Rayner, 2016; Slattery, Angele, & Rayner, 2011), and this effect was not qualified by the frequency of the target word.

To investigate this finding further, we analyzed go-past time on the post-target word to determine if these effects are being generated by regressions back from the word immediately following the target. This model was specified in the same way as the duration measures on the target word and showed that the effect of target word frequency was not significant ($t = 1.41$)[5]. However, the effect of display type in the high frequency target condition was significant ($M_{identical} = 243$ ms, $M_{change} = 272$ ms; $b = 24.96$, $SE = 10.35$, $t = 2.41$) and the lack of an interaction ($t = 0.25$) suggests that the effect of display type was similar in the low frequency target condition ($M_{identical} = 257$ ms, $M_{change} = 287$ ms). Thus the increased re-reading in the display change conditions seems to be due to regressions that were triggered once the eyes moved to the post-target word.

Discussion

The results of Experiment 1 revealed a significant cross-over interaction between target frequency and display type that was caused by a standard preview benefit (faster processing with a valid (i.e., identical) preview compared to an invalid (i.e., unrelated) preview) for high frequency target words and an apparent reversed preview benefit (slower processing with a valid preview compared to an invalid preview) for low frequency target words. While the reversed preview benefit for low frequency targets was not significant in analyses on the raw fixation time data, the effects were significant in a model with log-transformed fixation time measures, suggesting that the effect was either caused by or most pronounced in the short

[5]The effect of target word frequency was significant in the model for log-transformed data ($t = 2.11$). None of the other effects changed significance with the transformation.

duration portion of the fixation distribution (Figure 2). This point is important because that is exactly the part of the distribution where forced fixations are hypothesized to occur.

To further investigate the hypothesis that effects of preview and target should show different time courses across the fixation duration distribution, we plotted Vincentiles of single fixation duration across conditions in Experiment 1 (Figure 3). We chose single fixation duration because it constituted the majority of first-pass fixations (80–83% in Experiment 1) and is more likely to contain forced fixations because refixation cases either reflect difficulty in processing on the first fixation (i.e., not the scenario predicted in forced fixations) or corrections of suboptimal landing positions (see below). Comparison across conditions in Figure 3 supports the hypothesis of forced fixations caused by properties of the preview: preview frequency has more of an effect on shorter fixations (note the vertical distance between open squares and closed circles at Vincentiles .1 through .5 on the left-hand portion of the figure) and target frequency had more of an effect on longer fixations (note the vertical distance between black symbols and grey symbols at Vincentiles .7 through 1.0 on the right hand side of the figure). The differential effects of these two variables is most notable when considering the display change conditions (those connected with the dotted lines) where there is a cross-over between the high frequency preview- low frequency target (grey open square) and low frequency preview- high frequency target (black closed circle) conditions at the 0.6 quantile. In contrast, the identical preview conditions (solid lines) never show a cross-over (the grey closed circles are always above the black open squares).

To test for this statistically, we followed the quantile regression analysis used by Risse and Kliegl (2014; using the 'quantreg' package: Koenker, 2015), which tested for an effect of preview frequency, target frequency, and the interaction at each of the Vincentiles, individually (Table 5). The analysis showed that preview frequency was the only effect that was significant in the earlier Vincentiles (all $ps < .001$ except for the .79 Vincentile, $p < .01$) and continues being significant until the last two Vincentiles (both $ps > .06$). The effect of target frequency is not significant in the earliest Vincentiles (all $ps > .19$), but is significant at later Vincentiles (from the .59 Vincentile onward; all $ps < .05$). The interaction between preview and target frequency was only significant in the .69 Vincentile ($p < .05$) and the .79 Vincentile ($p < .01$), whereas it was not significant in the other Vincentiles (all $ps > .08$).

As discussed in the Introduction, these data suggest that properties of the preview word may have a direct effect on reading time on the target once it is fixated without necessarily requiring integration. Critically, due to the constraints imposed by the retina-brain lag and saccade program timing, this is either only true or more true for short fixations, which we term forced fixations, for which there is little opportunity for properties of the target to be recognized and processed before the eye movement program is initiated. Importantly, these data cannot be explained by a mislocated fixation account (which would predict more mislocated fixations at the end of the target word following high frequency previews). To visualize these effects, we plotted the landing site distributions for 5 and 6 letter words (the majority of the words in our study, 80%) as a function of launch site (grouped to create a more manageable figure, but was entered as a continuous factor in the analysis reported below) and preview type (Figure 4). As can be seen in the figure, there is almost no effect of word frequency on landing position.

To test for a difference in landing site statistically, we conducted an LMM on landing position with preview frequency, word length, and launch site as fixed effects, the maximal random effects structure for subjects, and the intercept and slopes for preview and launch site for items (because word length is a between-items factor). This analysis revealed the standard significant effect of word length, in which landing positions were shifted rightward for longer words ($b = .37$, $SE = .05$, $t = 7.48$) and launch site, in which landing positions were shifted leftward for further launch sites ($b = -.34$, $SE = .03$, $t = 13.65$). However, the effect of preview was not significant ($t < .01$, which replicates the null effect also reported by Rayner, Binder, Ashby, & Pollatsek (2001, Experiment 2), suggesting that mislocated fixations could not account for the effects of preview frequency on forced fixations, reported above.

In addition, we analyzed the landing site distributions as a function of fixation type (first of multiple fixations, which are fixations that are followed by refixations on the word, presumed forced fixations (single fixations with durations ≤ 200 ms), and long fixations (single fixations with durations longer than 200 ms). This analysis was similar to the one reported above, except instead of preview frequency as a factor, we included fixation type with successive differences contrasts (the first compared first of multiple fixations to forced fixations and the second compared forced fixations to long fixations) and its interaction with launch site. This analysis revealed the standard significant effects of word length ($b = .39$, $SE = .04$, $t = 8.99$) and launch site ($b = -.33$, $SE = .03$, $t = 12.92$). The comparisons between the fixation types and their interactions with launch site show a complex, but strikingly clear pattern (see Figure 5).

As can be seen in Figure 5, the landing site distributions were mostly similar between the forced and long fixations (the contrast between the two types was not significant: $b = .04$, $SE = .11$, $t < .38$), except that there were noticeably more forced fixations that landed at beginning word positions (e.g., the space before the word) when the launch site was further away (the interaction with launch site was significant: $b = .06$, $SE = .03$, $t = 2.32$). Crucially, this is the opposite of the pattern that would be predicted by the mislocated fixations account, which predicts that the forced fixations are the consequence of failed skipping of the target, which would predict more forced fixations that land at positions at the end of the word. What is also clear from Figure 5 is that the landing site distribution for first of multiple fixations is shifted leftward compared to the distribution for forced fixations (the contrast between these fixation types was significant: $b = .63$, $SE = .23$, $t= 2.69$). However, there were always more first of multiple fixations than forced fixations at the beginning of words, regardless of launch site (the interaction was not significant: $b = .02$, $SE = .04$, $t < .56$), suggesting that these distributions were truly different and not only driven by launch site. Thus, some of the single fixations that we termed forced fixations may in fact be *intended* first of multiple fixations, but due to oculomotor error resulted in an overshoot that landed on the post-target word. Crucially, these erroneously counted forced fixations only occurred when the fixation was located at beginning landing sites (sub-optimal landing positions as a consequence of a far launch site where it is least likely that the preview would have been inside the perceptual span). Thus, the sub-optimal landing position effect is a subset of mislocated fixations, but importantly is not related to preview frequency (which had no effect on landing position: Figure 4) and cannot be driving the effects of preview on forced fixations reported above.

We will elaborate our explanation in the General Discussion, but first we motivate the second experiment. One notable aspect of our data is that the preview conditions for a given target that lead to faster reading are the conditions in which the preview is high frequency, regardless of whether the preview is valid (i.e., identical) or not. For example, a high frequency preview may allow the reading system to initiate saccade programs off of the to-be-fixated word sooner than a low frequency preview, leading to a savings in time once the (target) word is ultimately fixated. However, a problem interpreting these data is that display condition is confounded with target type. Therefore, we conducted Experiment 2 in which the target words were replaced with the same nonwords for both high and low frequency preview conditions.

Experiment 2

If forced fixations are responsible for the apparent reversed preview benefit for low frequency targets in Experiment 1, we expect to find shorter reading times following a high frequency preview than following a low frequency preview for any difficult to process target stimulus. Thus, in Experiment 2 we used nonword targets in order to more clearly separate the effects of preview processing compared to target processing (or the relationship between the two). To do this, we selected two nonword targets to pair with the same previews and sentences that were used in Experiment 1: one that is more difficult to process (i.e., an illegal nonword) and another that is still a nonword, but more wordlike and therefore could *seem* easier to process (i.e., a legal nonword). We manipulated how word-like the targets were by selecting stimuli that *could be* words in English (e.g., pronounceable/orthographically legal nonwords like *gamip*) and contrasting those with stimuli that clearly are not words in English, which we created by replacing the vowels with consonants (e.g., unpronounceable/ orthographically illegal nonwords like *gkmbp*). If the preview is used to plan saccades away from the ultimately fixated target stimulus, we would expect an approximately similar number of forced fixations[6] in Experiment 2 as we observed in Experiment 1. Furthermore, when the fixation is not a forced fixation, the use of nonword targets should slow foveal processing of the target (since nonwords do not have a representation in the reader's mind), potentially delaying the influence of target word type on reading times, and allowing us to better distinguish the separate influences of the preview and target on reading time measures. On this account, we would expect to see evidence of bimodality in the distribution of reading times, with the earlier mode representing forced fixations and the later mode representing either target processing, or some combination of preview and target processing.

Method

Participants—An additional set of twenty-four undergraduates from the University of California, San Diego, who did not participate in Experiment 1, participated in this

[6]While it is not possible to definitively identify forced fixations (because that would require identifying when the saccade was planned) we assume that short fixations (i.e., shorter than 200 ms) are likely to be forced fixations, given the timing constraints detailed in the Introduction.

experiment for course credit. All were native English speakers, had normal vision, and were naïve to the purpose of the experiment.

Apparatus—The apparatus was identical to Experiment 1.

Materials—Materials were identical to Experiment 1 except that there was no identical preview condition. Instead, the high and low frequency targets were replaced with nonword targets that were either orthographically legal and pronounceable (e.g., *gamip*) or orthographically illegal and unpronounceable (e.g., *gkmbp*). Orthographically legal targets were created such that there was very little orthographic overlap with either the high or low frequency preview words (e.g., *phone* and *scarf*). On average the legal nonwords shared 0.4 and 0.33 letters with the high and low frequency previews respectively, and the illegal nonwords shared 0.23 and 0.22 letters with the high and low frequency previews respectively. Across all items, there were only 10 nonwords (5 legal and 5 illegal) that shared the same first letter with either the high or low frequency preview. Finally, since the targets are nonwords they do not have a semantic representation that could be shared with either preview. The orthographically illegal targets were created by replacing the vowels in the orthographically legal targets with consonants (*a* was replaced with *k*, *e* was replaced with *g*, *i* was replaced with *b*, *o* was replaced with *h*, and *u* was replaced with *p*).

Procedure—The procedure was identical to Experiment 1 except that the four conditions were: (1) high frequency preview-legal nonword target, (2) high frequency preview-illegal nonword target, (3) low frequency preview-legal nonword target, and (4) low frequency preview-illegal nonword target. Comprehension accuracy was high (85%) because the comprehension questions did not directly ask about the target word (in any experiment), but not as high as when the target was a real word (in Experiment 1). Additionally, subjects were not alerted to the presence of nonwords prior to the start of the experiment, however if they asked about the presence of nonwords during the experiment, the experimenter instructed them to try and understand the sentences as best they could.

Results

Data processing procedures were the same as for Experiment 1, leaving 5830 trials for analysis (84% of the original data). Data analysis procedures were similar to Experiment 1, except that because of the use of two invalid target conditions, the factor display type (identical vs. change) cannot be defined in this experiment so we could not specify contrasts in the same way as in Experiment 1. Instead, we specified the fixed effects in the LMMs akin to an analysis of variance (ANOVA): the intercept represents the grand mean across conditions, preview frequency was entered as a centered predictor, target type (legal vs. illegal) was entered as a centered predictor, and the interaction tested for additivity of the effects. For the random effects structure, we used the maximal random effects structure for subjects and random intercepts and slopes, where possible[7]. Reading measures on the target word are shown in Table 6, results of the LMMs on fixation duration measures are reported

[7]In Experiment 2, we removed the slope of the interaction for subjects in the model on raw go-past time and the slope of the interaction for items in the model on raw total time;

in Table 7 and results of the GLMMs on fixation probability measures are reported in Table 8.

Fixation duration measures—The effect of preview frequency was significant in all first-pass reading time measures (all ts > 3.04) but was not significant in total time (t = 1.80)[8]. The effect of target type was not significant in the first-pass measures (all ts < 1.42), but was significant in total time (t = 5.66). None of the interactions were significant (all ts < 1.40), suggesting that the two effects were additive (see Figure 6).

Fixation probability measures—For fixation probability, there was a significant effect of preview word frequency (p < .05) such that readers were more likely to fixate the target when the preview was low frequency than when it was high frequency. For regressions out of the target, there was a significant effect of preview frequency (p < .01), but neither the effect of target type nor the interaction were significant (both ps > .58). For regressions into the target, the effect of preview frequency was not significant (p > .05), the effect of target type was significant (p < .001), and the interaction was not significant (p = .73). As with the previous experiments, we analyzed go-past time on the post-target word. The pattern of data echoed that of the probability of making a regression into the target: only the effect of target type was significant (t > 5.12) such that readers spent more time rereading legal than illegal nonword targets.

Additional analyses—As mentioned above, we would expect a similar amount of forced fixations in Experiment 2 as we observed in Experiment 1 since both experiments used the same preview conditions and forced fixations should not be influenced by properties of the target. While we cannot definitively determine whether an individual fixation was a forced fixation or not, we estimated the number and proportion of single fixations that could be considered forced fixations (i.e., fixations with a duration ≤ 200 ms; see description of timing constraints described in the Introduction and Morrison, 1984). In Experiment 1, there were more forced fixations in the high frequency preview conditions (460 (43%) and 420 (41%) for the high and low frequency target conditions, respectively) than in the low frequency preview conditions (326 (31%) and 348 (33%) for the high and low frequency target conditions, respectively). These numbers parallel what was observed in Experiment 2: there were more forced fixations in the high frequency preview conditions (389 (39%) and 386 (38%) for the legal and illegal nonword target conditions, respectively) than in the low frequency preview conditions (316 (32%) and 276 (27%) for the legal and illegal nonword target conditions, respectively).[9] To test for the significance of the effects of preview and experiment on the rate of presumed forced fixations, we conducted a logistic mixed effects regression (presumed forced fixations—single fixations with durations ≤ 200 ms—were coded as 1 and other single fixations were coded as 0) with preview frequency (high vs. low), Experiment (1 vs. 2), and the interaction between them as fixed effects, the maximal random effects structure for items, and the intercept and effect of preview for subjects

[8]The effect of preview word frequency was significant in the model on log-transformed total viewing time. None of the other effects changed significance after the transformation.

[9]As with Experiment 1, these results could not be explained by a mislocated fixation account because landing site distributions were almost identical between high and low frequency preview conditions.

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(because experiment was a between-subjects factor). This analysis revealed a significant effect of preview frequency ($b = -.53$, $z = 6.79$, $p < .001$), but no effect of experiment or an interaction (both $ps > .61$).

Discussion

The results of Experiment 2 demonstrate quite clearly that properties of the preview word can have a direct effect on the time spent reading the target once it is fixated without necessarily requiring integration. There was little to no orthographic, phonological, or semantic information shared between the preview and target, yet readers spent less time on the nonword targets following a high frequency preview than a low frequency preview. That is to say that we observed an effect of the preview frequency, not only on the decision of whether or not to skip the target, but also on all first pass reading times on the unrelated, nonword target further supporting the idea that the reversed preview benefit for low frequency target words in Experiment 1 was caused by the high frequency preview leading to more forced fixations. We further explore the idea of forced fixations below, and in detail in the General Discussion.

We also observed an effect of target legality that didn't emerge until later measures (e.g., total time, regression in probability). Interestingly this effect was in the opposite direction of what might have been predicted, such that readers spent more time overall reading the legal than illegal nonword targets. This may reflect a strategy on the part of the subjects. Unlike when nonwords are presented as parafoveal previews, the manipulation used in this experiment was not subtle, and subjects became aware of the presence of nonwords in the sentences. However, the orthographically legal nonwords were still word-like (i.e., pronounceable, legal letter sequences), and as such may have been harder to detect as nonwords initially, leading subjects to process them like very low frequency words. The orthographically illegal nonwords on the other hand were visibly distinct (i.e., unpronounceable, illegal letter sequences), such that subjects may have been able to detect them more rapidly, and chose to allocate their time to processing the other words of the sentence rather than spending additional time trying to decode such nonword stimuli. Importantly, since this was only observed in the late measure of total time, an explanation via strategic processing should only apply to reading that reflects post-identification processes. In contrast, the data observed for first-pass reading time differed from that of total time.

To further explore forced fixations in Experiment 2, we examined the distribution of single fixation durations across conditions (Figure 7). There is clear evidence of bimodality in the illegal nonword target condition (right hand panel), as would be predicted by forced fixations. Additionally, the earlier mode of the distribution is more pronounced (i.e., denser) in the high frequency preview condition (solid line) than in the low frequency preview condition (dashed line). Furthermore, the peak of the earlier mode is around 180 ms, which is well in line with the timeline suggested in the introduction: based on the time required for saccade programming (about 150 ms) and the eye-brain lag (about 50 ms), forced fixations should terminate within 200 ms. Note that there is little evidence of bimodality in the legal nonword target condition, due to the fact that legal nonwords are very similar to low frequency words. Therefore, they may be processed in a way that is more similar to words than illegal nonwords are, and this may diminish the bimodality in the distribution. Thus, the illegal nonword target condition is a critical addition to our understanding of forced fixations. That is, because illegal nonwords are obviously not recognizable words, once the language processing system registers them, there may be a distinct inhibitory signal that the system should abort processing them or switch to some other strategy (we return to this in the General Discussion). Therefore, the inclusion of this condition allows us to dissociate situations in which the reading process progresses normally (in the case of normal reading and forced fixations) and situations in which it cannot progress normally (once unrecognizable target nonword information is encountered). The inhibitory effect of the illegal nonword target, which lengthens single fixation durations, may be qualitatively different than the strategic effect mentioned above (which reduces re-reading and therefore shortens total time).

In Experiment 2 we found additional evidence that processing of the preview can have a direct influence on processing of the target in the absence of a relationship between the two stimuli. Note that there were distinct influences of the preview word frequency on reading time on the target, both in the analyses of the mean fixation durations, as well as on the distribution of single fixation durations. In contrast, there was no effect of the target stimulus (legal vs. illegal nonword) on fixation durations on the target itself until total time, which includes rereading of the target once the eyes have left it, fitting nicely with the conclusion from the Vincentile plots of Experiment 1 that the influence of the preview has an earlier time course than the influence of the target.

Before exploring the mechanisms underlying forced fixations in the General Discussion, we briefly discuss a third experiment. So far, the experimental conditions we have employed in these experiments are fairly unique compared to most boundary paradigm studies, which use nonwords as the unrelated, denied preview baseline condition. Furthermore, all extant attempts to model the boundary paradigm have simulated data with nonword mask previews. Therefore, we conducted a third experiment along these lines (using the nonwords in Experiment 2 as previews and the high and low frequency words as targets).

Experiment 3

On a view involving forced fixations, preview words that are difficult to identify (e.g., nonwords) should delay saccade decisions, eliminating or reducing forced fixations and leading to longer overall reading times on the target and a greater influence of the target word properties than was observed in Experiments 1 and 2. That is, there should be relatively few forced fixations when the previews are nonwords because they should not provide a signal to move the eyes forward. Therefore, we conducted a third experiment in which we used the nonword stimuli as previews and the word stimuli as targets in order to collect data that is (1) more similar to previous work, (2) more related to modeling attempts that have simulated the boundary paradigm (see General Discussion), and (3) in which we do not expect to observe as many forced fixations.

Method

Participants—An additional set of twenty-four undergraduates from the University of California, San Diego, who did not participate in Experiments 1 or 2, participated in this experiment for course credit. All were native English speakers, had normal vision, and were naïve to the purpose of the experiment.

Apparatus—The apparatus was identical to Experiments 1 and 2.

Materials—Materials were identical to Experiment 2 except that the high and low frequency words served as targets and the orthographically legal and illegal nonwords served as previews.

Procedure—The procedure was identical to Experiment 2 except that the four conditions were: (1) legal nonword preview-high frequency target, (2) illegal nonword preview-high frequency target, (3) legal nonword preview-low frequency target, and (4) illegal nonword preview-low frequency target. Comprehension accuracy was high, comparable to Experiment 1 (96%) because all fixated target words were real words.

Results

Data processing procedures were the same as for Experiments 1 and 2, leaving 5781 trials for analysis (84% of the original data). Data analysis procedures were the same as in Experiment 2 in that we specified the fixed effect in the LMMs akin to an analysis of variance (ANOVA) except that the factor of legal vs. illegal nonword was for the preview stimulus and the factor of high vs. low frequency word was for the target stimulus. The intercept represents the grand mean across conditions, target frequency was entered as a centered predictor, preview type (legal vs. illegal) was entered as a centered predictor, and the interaction tested for additivity of the effects. For the random effects structure, we used the maximal random effects structure for subjects and random intercepts and slopes for the effect of preview for items, where possible[10]. Reading measures on the target word are shown in Table 9, results of the LMMs on fixation duration measures are reported in Table 10 and results of the GLMMs on fixation probability measures are reported in Table 11.

Fixation duration measures—The effect of target word frequency was significant in all reading time measures (all ts > 1.98)[11]. The effect of preview type was not significant in any measure (all ts < 1.31). None of the interactions were significant (all ts < 0.65), suggesting that the two effects were additive (see Figure 8).

Fixation probability measures—There were no significant effects of any variables (target word frequency, preview type, or the interaction) on any of the fixation probability measures (all ps > 0.20). As with Experiments 1 & 2, we analyzed go-past time on the post-

[10]For the model of raw SFD we removed the slope of the interaction for subjects, for the model of raw GPT we removed the slope of the interaction for items, for the model of raw TVT we removed the slope of the interaction for subjects and items, and for the model of log TVT we removed the slope of the interaction for subject.

[11]The effect of target type was not significant in the model for log-transformed first fixation duration. None of the other effects changed significance after the transformation.

target word. The pattern of data echoed that of the probability of regression into the target: none of the effects were significant (all ts < 1.40)[12].

Together, these data show that when the preview stimulus is an unrecognizable nonword, the identity of the preview (i.e., orthographically legal vs. illegal) does not have an effect on fixation durations on the target. In contrast, the effect of properties of the target (i.e., frequency) was significant for all reading time measures, suggesting that when the preview did not provide sufficient information to program the subsequent eye movement (i.e., in this experiment all the previews were nonwords) that the system waited for the necessary foveal (target) information to make a saccade decision.

Discussion

Unlike in Experiments 1 and 2, where we observed effects of preview frequency on target fixation durations following difficult to process nonword previews, we did not observe any differential processing of the fixated target as a function of preview type. Instead, saccade decisions were delayed (relative to Experiments 1 and 2) and determined by the frequency of the target. Thus, the data obtained in Experiment 3 lend further evidence to the idea that the patterns of data obtained in Experiments 1 and 2, which used high and low frequency real word previews, were due to forced fixations. To further explore whether forced fixations were involved in Experiment 3, as in Experiments 1 and 2, we examined the distribution of single fixation durations (Figure 9). Here, there is a clear shift in the distribution whereby the mode does not peak until around 225 ms, compared to the mode in Experiment 1 and the earlier mode in Experiment 2, which both peaked around 180 ms (a 45 ms difference). Moreover, there are few, if any fixations with durations shorter than 100 ms, whereas there were some when the previews were real words, in Experiments 1 & 2. This is well in line with estimates from prior work that nonword previews delay mean fixation durations by about 30–50 ms (Hyönä, Bertram & Pollatsek 2004; Rayner, 2009a).

General Discussion

In the studies reported here we observed several important effects. First, in Experiment 1 we found an apparent reverse preview benefit for low frequency target words: shorter fixation durations following a preview of a different, higher frequency word than following an identical preview. This finding suggests that properties of the preview stimulus (if it is easy to process) can have a direct influence on fixation durations on the target, even if the target stimulus is different from the preview. Below we elaborate on an explanation of this effect via forced fixations—pre-programming of saccades based on the imminent recognition of the preview when the saccade toward that word is committed (i.e., is in the non-labile stage). Second, in Experiment 2 we found further evidence for these forced fixations even when the target stimulus was an unrecognizable nonword, allowing us to observe a dissociation between forced fixations, short fixations determined by preview information, and longer fixations that indicate a recognition of the target nonword. In Experiment 3, we replicated standard boundary paradigm studies using nonwords as previews for real word targets and

[12]The effect of target frequency reached full significance (t = 2.16) in the model for the log-transformed post-target go-past time data. None of the other effects changed significance after the transformation.

replicated prior findings that such unrecognizable stimuli delay mean fixation durations by about 45 ms, requiring target information in order for the saccade to be triggered. Lastly, comparison of the mean fixation durations across experiments suggests that denying access to useful word information (i.e., through the use of nonword stimuli) parafoveally versus foveally has an approximately similar detriment to early reading time measures, but the effect is more exaggerated in later reading time measures (e.g., total time) for foveally viewed nonwords compared to parafoveally previewed nonwords (see Figure 10).

Forced fixations and direct control of eye movements

The idea of forced fixations that we introduced in the Introduction is compatible with the concept of *direct lexical control of eye movements* described by Reingold et al. (2012), which states that the influence of linguistic properties of words (e.g., lexical frequency) has a rapid enough effect on the processes involved in reading that the durations of most fixations are sensitive to such properties. We demonstrated this with a word frequency manipulation when cloze probability was controlled (i.e., extremely low), but word predictability may also play a role, since it has a clear effect on skipping probability, as well as fixation durations when the word is not skipped (Rayner, 1998). Reingold et al. (2012) note,

> although it is possible to conceive of numerous specific direct lexical control mechanisms, logically, there are only two non-mutually exclusive general types of possible mechanisms, which assume either that: (1) the fluency in lexical processing triggers saccadic programming (henceforth referred to as the triggering mechanism), or that (2) regardless of the nature of the mechanism that triggers reading saccades, difficulty in lexical processing produces delays in the initiation or the execution of the saccade terminating the fixation (henceforth referred to as the interference mechanism). (p. 180)

Their study, which employed nonword previews for high or low frequency targets (similar to current Experiment 3), found evidence that saccade decisions were delayed when preview was denied by nonword masks: mean single fixation durations were 37–51 ms longer with nonword previews than identical previews (similar to the estimate of 45 ms we observed in Experiment 3). Moreover, using survival analyses of fixation durations they found that nonword previews delayed the effect of target word frequency by approximately 100 ms. On their account, the triggering mechanism is associated with the ease of processing the fixated word *n* and parafoveal preview reduces the time necessary for foveal information to trigger saccades. However, the idea of forced fixations we describe here extends this to predict that easy enough processing of the parafoveal word *n+1* can affect saccade decisions once that word becomes the foveal word *n* even without information from the new foveal target being recognized (Morrison, 1984). On this view, forced fixations are part of the triggering mechanism, and either the detection of a difference between preview and target stimulus and/or the difficulty associated with attempting to process an illegal nonword target are part of the interference mechanism. In fact, the data from Experiment 2, in which there was a clearly visible bimodal distribution for illegal nonword targets supports Reingold et al.'s (2012) suggestion of a hybrid model, which combines both a triggering mechanism (responsible for the earlier mode in our distributions) and an inhibition mechanism (responsible for the later mode).

Contrasts to other explanations

Preview cost—Other recent explanations of preview effects invoke the idea of preview cost (in the case of invalid previews) as opposed to benefits (Kliegl et al., 2013; Marx et al., 2015). On such accounts, an invalid preview imposes a processing cost to saccade decisions, rather than a valid preview allowing a processing benefit. As noted above, preview effects are likely best conceived as a combination of cost and benefit. That is, difficult to identify or unrecognizable previews do not allow saccade initiation and delay saccade decisions until recognizable target information is obtained (i.e., cause a processing cost), whereas easy to recognize previews allow for pre-initiation of saccades (i.e., cause a processing benefit; see Figure 10).

Delayed parafoveal-on-foveal effect—Alternatively, some have suggested an even more complex relationship between parafoveal preview processing and foveal target fixation durations. Risse and Kliegl (2014) conducted an experiment similar to current Experiment 1 in that they used high and low frequency previews for high and low frequency targets. However, they did not analyze their data in a way that would address the issue of reversed preview benefit effects, and the higher skipping rates that they observed (15–25% compared to the 8–11% that we observed) decreased the probability of observing forced fixations in their data. That is, forced fixations would otherwise be skips if the signal of imminent recognition of word *n+1* had occurred in the labile stage of saccade planning from word *n* to word *n+1*. Their account of the preview frequency effect regards the idea of a *parafoveal-on-foveal (PoF) effect*, which implies that difficulty associated with processing the parafoveal word *n+1* should interfere with processing of the foveal word *n*, manifested by increased fixation durations on word *n* before word *n+1* is even fixated. These effects are not reliably observed in experimental studies (see Drieghe, 2011), with one exception: fixations prior to skipping are longer than fixations prior to fixating the upcoming word, and the likelihood of skipping is influenced by word length, frequency, and predictability. Therefore these properties may exhibit a PoF effect, but note that this requires comparison between different types of trials (i.e., skips vs. fixations). Moreover, PoF effects are not predicted within the architecture of oculomotor models of reading. For example, such effects are not predicted by E-Z Reader because attention required for lexical processing is allocated serially, nor are they predicted by SWIFT because the only mechanism to delay saccade decisions is *foveal* inhibition. Still, researchers have sought support for the PoF hypothesis because they believe it would be more in line with the spirit of SWIFT and that evidence for such effects would adjudicate between the models.

Risse & Kliegl (2014) did not find PoF effects, but rather described the effect of preview frequency as a *delayed parafoveal-on-foveal effect* whereby the cost of processing a low frequency parafoveal preview affected processing efficiency once the target word was fixated instead of influencing fixation durations on the pre-target word (where a traditional PoF effect is hypothesized to be observed). Perhaps what was implied by their account is that the *source* of the effect is parafoveal-on-foveal (i.e., generated during processing that occurred for word *n+1* when word *n* was fixated) but it is "delayed" in the sense that it cannot be *measured* until word *n+1* is fixated. However, we find the explanation by means of preview benefit that arises from pre-initiation of upcoming saccade programs a more straightforward conceptualization of the effect.

Mislocated fixations—Researchers have invoked the idea of mislocated fixations to account for PoF effects (Drieghe et al., 2008), and could similarly argue that they may account for the preview effects reported here because of a difference in intended skipping between high and low frequency words. We think this is unlikely for three reasons. First, the skipping rates in our study were quite low and therefore the likelihood of intended skips that land on the target due to mislocated fixations should similarly be low. Second, and more importantly, such an account would predict that the landing site distributions for high and low frequency preview words should be different (i.e., shifted rightward for high frequency previews relative to low frequency previews). However, this was not the case (see Figure 4). Finally, while we admit that we likely did observe some mislocated fixations in our study (e.g., fixations located at sub-optimal landing positions, as seen in the larger proportion of short fixations located at beginning landing sites; Figure 5) they cannot exclusively account for the effects of preview on short fixations and, as noted above, preview frequency did not affect landing position.

Implications for Oculomotor Models of Reading and Simulations of the Boundary Paradigm

The results of these experiments, and the proposed account of how parafoveal and foveal information influence reading behavior have implications for oculomotor models of reading, particularly with respect to how they simulate the boundary paradigm (in which preview and target information are dissociated). Previous attempts to model this paradigm have either assumed lexical processing does not start until direct fixation on the target (Pollatsek et al., 2006; Sheridan & Reichle, 2015) or re-set lexical processing of the word (i.e., set it back to 0) once the display change occurred (Risse, Hohenstein, Kliegl, & Engbert, 2014). However, both of these approaches are artificial solutions to modeling the boundary paradigm because they hinge on the assumption that something different is happening within the reading system in boundary studies compared to during normal reading. There are two issues with such assumptions: (1) the reading system does not know, a priori whether a word will change or not, so it is implausible to think that it would delay lexical processing until direct fixation (as described by Pollatsek et al., 2006), and (2) it would seem inefficient for the system to decide on every fixation whether the word had changed between parafoveal preview and foveal target and to reset lexical processing to zero when it had (as described by Risse et al., 2014), if, for the majority of reading experiences, words do not change during saccades (except for in an experiment employing the boundary paradigm).

The issues noted above are not issues with the approaches themselves, but rather with the extension of those approaches to more general reading situations. In particular, both approaches described above were designed to explain scenarios of "denied" preview in which the preview stimulus is an unrecognizable nonword, which lengthens mean fixation durations by about 30–50 ms relative to a valid, identical preview condition (Hyönä et al., 2004; Rayner, 2009a) and delays the effects of the properties of the word stimulus by approximately 100 ms (Reingold et al., 2012). Those approaches worked well for their purposes and are plausible explanations for why the single fixation durations in current Experiment 3, with nonword previews for high and low frequency word targets, were approximately 45 ms longer than in current Experiment 1, with high and low frequency previews (Figure 10). However, as noted previously, the accounts cannot explain why first-pass reading times on the low frequency target are faster with an invalid (i.e., different, higher frequency preview) than with a valid (i.e., identical) preview—under both the delayed processing and reset processing assumptions, valid preview conditions should always be fastest.

Given that any approach at modeling the boundary paradigm must make assumptions that are parsimonious with respect to normal reading (i.e., should hold equally well when explaining reading without display changes), we elaborate on an idea described by Schotter, Reichle, and Rayner (2014; see also Schotter & Jia, 2016; Schotter, Lee, Reiderman, & Rayner, 2015). Schotter et al. (2014) reported a simulation using the E-Z Reader model of the data from Schotter (2013), a boundary paradigm study demonstrating semantic preview benefit for synonyms. Importantly, in that study, all the previews (including the unrelated baseline condition) were real words, allowing them to estimate how far into processing of the preview the model had progressed. Note that this approach does not address the boundary paradigm per se (because it does not address what happens after the display change has occurred), but it does circumvent issue 1 (described above) in that processing of the preview should be estimable both when the word will and will not change during the saccade toward it.

To elaborate on this account, we will discuss how these effects are manifested within the context of the E-Z Reader model. We do not intend to suggest that the E-Z Reader model is the only one capable of modeling the data with these assumptions, we do this out of convenience because it builds directly on the work carried out by Schotter et al. (2014) and we merely use this as an example to explain, qualitatively, data from the current studies. Obviously, in order to make firm conclusions about how the models account for various patterns of data, formal simulations will need to be conducted (Rayner, 2009b). The architecture of the E-Z Reader model describes word processing as occurring in two stages —the first of which triggers the programming of a forward saccade when it completes. Because this first stage (L_1) only constitutes partial or cursory word identification (the completion of the second stage (L_2) constitutes full recognition) a saccade can be programmed away from the parafoveal word *n+1* (if the preview is or seems easy to identify and word recognition is considered imminent) while the eyes are still fixating the previous word *n* (see Figure 11). Below, we describe how the model explains various types of saccade behaviors: skipping the parafoveal preview, forced fixations on the foveal target, and long fixations on the foveal target.

Skipping—Skipping behavior is the clearest case of saccade decisions that should be based only on the ease of processing the preview since target information is not yet available. Within the model, skipping occurs if the parafoveal word is guessed, or L_1 for word *n+1* completes while the saccade from word *n* to *n+1* is in the labile stage, causing that saccade to be cancelled and a new saccade (from word *n* to *n+2*) to be programmed (see Reichle & Drieghe, 2013; first (leftmost) scenario in Figure 11). The effect of preview type is clearly seen in skipping probabilities in the current experiments—average skipping rates were 11%, 8%, 6%, and 5% for high frequency, low frequency, legal nonword, and illegal nonword preview conditions, respectively. Note that the sizes of these effects are relatively small compared to other skipping studies because we ensured a relatively long word length (4–9 characters) in order to decrease skipping and increase the opportunity to observe forced fixations.

Forced Fixations—If L_1 for word *n+1* completes while the saccade from word *n* to *n+1* is in the non-labile stage (M_2), as represented in the second (middle) scenario of Figure 11, planning of the subsequent saccade from word *n+1* begins (as described by Morrison, 1984 on pp. 680–681 and as simulated by Schotter et al., 2014). In this scenario, word *n+1* will be fixated, but only for a brief amount of time (because the saccade away from that word is already part-way through the programming stages). Since the saccade from word *n* to word *n+1* executes at the same time regardless of how difficult word *n+1* is to process, the earlier initiation of the saccade from word *n+1* based on easy-to-process preview information, results in a shorter fixation on word *n+1* (i.e., preview benefit).

Once the eyes fixate a new location it takes time for perceptual information to be transmitted from the retina to the brain (i.e., there is a retina-brain lag), which is estimated to take around 50 ms (see Reichle & Reingold, 2013). The latency for a saccade program to execute once it is initiated during reading is estimated to take about 150 ms (Reichle & Reingold, 2013; Reingold et al., 2012). Taken together, we can assume that short fixations (e.g., those shorter than 200 ms) should be those that are only influenced by properties of the preview, rather than the target, since the retina-brain lag implies that there had not been enough time for the target information to affect cognitive processing before the decision to move the eyes had been made. This is the reason for the reversed preview benefit in Experiment 1, as well as the earlier mode in the bimodal distribution of single fixation durations in Experiment 2.

The simulations conducted by Schotter et al. (2014) estimated that the model reached L_2 by or before the target information was available (i.e., forced fixations occur) 8% of the time (i.e., on 8% of trials) whereas the experiments reported here estimate that fixations shorter than 200 ms (i.e., forced fixations) occurred on 30% of the single fixation cases (19% of all trials; i.e., skips, single fixations, refixations, and trials excluded for blinks or inaccurate display changes)[13]. It is possible that this discrepancy is due to our criterion of 200 ms for a forced fixation being too long (150 ms for saccade programming is an average estimate and some estimates go as low as 125 ms) and we might therefore be slightly overestimating the number of forced fixations. However, we must point out that the estimates cannot be directly compared between the simulations conducted by Schotter et al. (2014) and the fixation durations measured here because the simulations merely estimate the likelihood of reaching L_2 (which coincides with the initiation of saccade programming) and do not estimate the duration of the fixation that is ended when the saccade is executed.

[13]We thank an anonymous reviewer for pointing this out.

Long Fixations—The scenarios involving forced fixations described above should only occur when the preview is easy to recognize (e.g., is a high frequency word). As mentioned above, when the preview is not easy to recognize (e.g., is a nonword or very low frequency word) saccades will not be initiated based on parafoveal preview, the word will be fixated, and the system will require detailed foveal target information in order to trigger the subsequent saccade (third (rightmost) scenario in Figure 11). This explains why nonword previews increase mean fixation durations by about 30–50 ms and delay the effect of target word frequency by about 100 ms (Sheridan & Reichle, 2015). The critical question, however, is what does the system do in display change cases (i.e., once it has two conflicting sources of information—the parafoveal preview and the foveal target)?

How might we model the long fixation cases?—There are two possibilities for how parafoveal and foveal information may influence long fixation duration. First, since long fixations occur when the parafoveal preview did not provide a signal of imminent recognition, that preview information would be discarded and only target information would be used. This might be more likely in the case of orthographically illegal nonword previews; in fact, in our study illegal nonword preview conditions lead to the longest fixation durations on real word targets (Figure 10). This possibility is covered by both of the extant methods of modeling the boundary paradigm in that delaying lexical processing (i.e., Pollatsek et al., 2006) and resetting lexical processing to 0 after a display change (i.e., Risse et al., 2014) both imply that only target information is used for lexical identification and saccade initiation. Additionally, Morrison (1984) suggested that reading may become more serial (i.e., only foveal) when "parafoveal encoding does not succeed. Certain conditions may encourage more serial control than do others. Decreased parafoveal perceptibility due to physical factors of legibility, lack of contextual constraints, or unfamiliarity and difficulty with the text all could force the eyes into a predominantly serial, word-by-word mode." (p 681.)

A second possibility is that the system would have made some progress toward word recognition based on the parafoveal preview. This might be more likely in the case of a very low frequency word, or orthographically legal nonword, since the system may confuse the stimulus with a real word (not necessarily the target word) and begin to recognize it as such. This scenario would lead to some progress toward completing L_1 from the parafovea, but not enough to trigger saccade programming as in forced fixation cases with high frequency previews. In the current studies, this may be why we see graded effects of preview conditions that do not lead to forced fixations (longest durations for illegal nonwords, shorter for legal nonwords, shorter still for low frequency words) for both types of real word targets even though they were orthographically dissimilar from the target words. Therefore, in our study the savings in processing time (i.e., shortening of fixation duration) for legal relative to illegal nonwords cannot be due to the system making progress toward identifying the correct (i.e., target) word, but may instead be considered savings in terms of "readying" the word recognition system much in the same way that activating one saccade program can "ready" the system and lead to savings in execution time even in the case of a cancelation and reprogramming of a different saccade target (see Reichle et al., 2003; Schotter et al., 2014).

Under the second scenario, in addition to the general readying for word recognition provided by (seemingly) recognizable stimuli, previous boundary studies have found that nonword previews that were orthographically similar to the target provided more preview benefit than those that were dissimilar from the target. It is possible that these previews may be more likely to be confused with the intended target word and would lead the word recognition system toward recognizing the target or a similar stimulus. In this case, there might be more savings in recovery time as the preview is more similar to the target, since the system would not have to move as far in representational space to reach identification of the correct word. This scenario is similar to the traditional explanation of preview benefit via integration that was initially proposed by Rayner (1975), "at a higher level the information from the two fixations is integrated… when visual or semantic discrepancies were introduced between two successive fixations, this integration failed." (p. 80). However, instead of completely failing (which would constitute resetting lexical processing), it may be more accurate to conceptualize the cost of an invalid preview (that does not cause a forced fixation or completely delayed lexical processing) as the consequence of needing to recover from moving toward a representation of the wrong lexical form.

Ultimately, in order to test these hypotheses, formal modeling will need to be conducted (Rayner, 2009b). These possibilities raise interesting challenges for current models of oculomotor control in reading, particularly for the latter hypothesis, which involves the system moving through representational space of words. In particular, the models currently do not specify how words are represented (although the models are moving in this direction; Reichle, 2015), and they will therefore need to have much more detailed accounts of how lexical processing occurs in order to fully explain the effects reported here. That is, currently the duration of lexical processing stages is influenced by word length, frequency, and predictability in that there is a mathematical relationship between these lexical properties and predicted fixation durations. However, the models currently do not explain the process through which the words are identified, how they are represented during that process, or the extent to which that process is error-prone, leading to potential misidentification of word forms and recovery from such errors. We believe this is an exciting new area of research that may lead to new insights into the reading process, not only with respect to preview benefit effects, but also with respect to the reading process, in general.

Conclusion

The studies reported here showed some interesting and counter-intuitive effects. Most notably, in Experiment 1 we reported a reversed preview benefit for low frequency target words—shorter fixation durations following a parafoveal preview of a different, higher frequency word than following an identical preview. We proposed that this effect can be explained by forced fixations, in which the system begins to pre-program the upcoming saccade when the signal that recognition of word *n+1* is imminent is obtained when the saccade toward word *n+1* is in the non-labile stage of programming (Morrison, 1984). We suggested that forced fixations may already be predicted by (at least) the E-Z Reader model of oculomotor control in reading and proposed a few possibilities for how the model might account for longer, non-forced fixations.

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Appendix

Complete set of stimuli including the two sentence versions (a,b) for each set of target words. Each sentence is shown with all possible targets (high frequency/low frequency/legal nonword/illegal nonword). In Experiment 1, high and low frequency words were used as both previews and targets, in Experiment 2, high and low frequency words were previews and nonwords were targets, in Experiment 3, nonwords were previews and high and low frequency words were targets.

Item	Sentence
1a	The boy found a red phone/scarf/gamip/gkmbp on his way to school.
1b	Danielle unfortunately forgot her new phone/scarf/gamip/gkmbp when she left home this morning.
2a	Ross was excited for the last month/rodeo/kapit/kkpbt of the summer season.
2b	Brad looked forward to the next month/rodeo/kapit/kkpbt when he would compete.
3a	Tim wanted to go to the massive party/swamp/gunip/gpnbp this weekend with his friends.
3b	Angelica intended to stop by the secret party/swamp/gunip/gpnbp on the way home.
4a	Rachel put the broken chair/broom/hunit/hpnbt in the guest room.
4b	Peter received a cheap chair/broom/hunit/hpnbt for his new office.
5a	The couple enjoyed the lovely beach/manor/wimup/wbmpp that they went to on their vacation.
5b	No one had been to the remote beach/manor/wimup/wbmpp for a number of years.
6a	Mike took the little horse/canoe/felum/fglpm to the other side of the river.
6b	The explorer used a sturdy horse/canoe/felum/fglpm to travel uncharted territory.
7a	Roy caught the sneaky child/thief/silop/sblhp trying to steal from the store.
7b	Marco managed to grab the nimble child/thief/silop/sblhp before he could get away.
8a	Stanley thought the graceful woman/eagle/kinop/kbnhp was an impressive sight.
8b	The painting showed a solitary woman/eagle/kinop/kbnhp sitting upon a rock.
9a	They found a large house/kiosk/ramit/rkmbt near the new mall.
9b	At the park there is a small house/kiosk/ramit/rkmbt which serves as an info center.
10a	The sound of his loud voice/cough/mitum/mbtpm drew attention to him.
10b	After weeks of having a raspy voice/cough/mitum/mbtpm Jim finally went to a doctor.
11a	Everyone was impressed when the talented bride/vicar/himit/hbmbt sang at the wedding.
11b	A close friend of the honored bride/vicar/himit/hbmbt gave a special performance.
12a	He dressed up like a scary judge/clown/kolim/khlbm for the costume party.
12b	It was tradition that the head judge/clown/kolim/khlbm lead the city’s parade.
13a	They went to the quiet hotel/patio/bumit/bpmbt to talk by themselves.
13b	Adam walked back to the remote hotel/patio/bumit/bpmbt for some rest and relaxation.

Item	Sentence
14a	Their day at the newly opened beach/lodge/humit/hpmbt turned out to be very relaxing.
14b	They stayed at the remote beach/lodge/humit/hpmbt for a few days.
15a	The gang member's tattoo was of a white heart/skull/jolum/jhlpm with a Latin phrase underneath.
15b	The biker's jacket had a large heart/skull/jolum/jhlpm on the back of it.
16a	Lisa enjoyed the fresh bread/aroma/situm/sbtpm as she walked into the kitchen.
16b	The bakery was known for its lovely bread/aroma/situm/sbtpm and tasty specialty coffees.
17a	Bobby saw a man with a deadly knife/steed/lagot/lkght at the circus yesterday.
17b	You must be careful while handling a lethal knife/steed/lagot/lkght or an accident could happen.
18a	Alice thought the awful color/stain/rakim/rkkbm ruined the living room.
18b	It turned out that the dark color/stain/rakim/rkkbm was not even noticeable.
19a	Kimmi loved the special story/pinup/domit/dhmbt in the latest magazine issue.
19b	Phil got his most recent story/pinup/domit/dhmbt published in the local newspaper.
20a	Nearby there is a neat store/motel/gilup/gblpp that opened just recently.
20b	They had to return to the small store/motel/gilup/gblpp after they realized what they forgot.
21a	Mindy said to her friend that the shiny metal/spoon/hunit/hpnbt looked nice against the white clothes.
21b	Tony crafted the silver metal/spoon/hunit/hpnbt into an art piece.
22a	Paul thought the strong taste/cider/kumit/kpmbt was very bold and delicious.
22b	Carlos liked the sweet taste/cider/kumit/kpmbt and got some more.
23a	Ben could not stop the loud radio/alarm/binit/bbnbt from making the annoying noise.
23b	Dennis set his noisy radio/alarm/binit/bbnbt to go off in the morning.
24a	Jeremy took his black truck/spear/kalot/kklht on the hunting trip.
24b	The attacker used a large truck/spear/kalot/kklht on his last victim.
25a	Laura placed a yellow stone/tulip/ritum/rbtpm in her new garden.
25b	I found a single stone/tulip/ritum/rbtpm in the middle of the clearing.
26a	The lawyer used the strange image/glove/furit/fprbt as evidence in the court case.
26b	Tom could not find the missing image/glove/furit/fprbt anywhere in the house.
27a	Andrew enjoyed the lovely dance/snack/hitum/hbtpm at last night's party.
27b	They had one final dance/snack/hitum/hbtpm before leaving the event.
28a	The girl stopped when her friend's cute smile/purse/corit/chrbt instantly caught her attention.
28b	Tony noticed Jill's huge smile/purse/corit/chrbt when she turned around.
29a	Alicia put the food on the clean table/stove/gimit/gbmbt and waited for her guests.
29b	They had their newly bought table/stove/gimit/gbmbt delivered to their home.
30a	Jen put on her black dress/apron/lopit/lhpbt and went into the kitchen.
30b	Her grandmother made her a custom dress/apron/lopit/lhpbt for her eighteenth birthday.
31a	Garrett walked into the large house/lobby/gumit/gpmbt and found that it was empty.
31b	The maids vacuumed the whole house/lobby/gumit/gpmbt at least once a week.
32a	Travis needed to get the broken chair/stein/jimit/jbmbt fixed before he could use it.
32b	Lisa made sure there was an extra chair/stein/jimit/jbmbt for her dinner guest.
33a	Dana found a fresh plant/peach/dolit/dhlbt on the kitchen counter.
33b	Carly liked the yellow plant/peach/dolit/dhlbt her mom bought at the store.
34a	They recognized the kind woman/donor/kilip/kblbp who gave a lot of money to their cause.
34b	The business made sure the rich woman/donor/kilip/kblbp was thanked for her service.

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Item	Sentence
35a	They put the broken glass/easel/himit/hbmbt in the dumpster last night.
35b	They needed to be careful with the fragile glass/easel/himit/hbmbt as it could break easily.
36a	Robert was shocked that the entire train/crypt/pimit/pbmbt was empty that night.
36b	The robbers had a secret train/crypt/pimit/pbmbt which held all the stolen money.
37a	Jared could not stand the annoying music/rhyme/sinat/sbnkt repeating over and over.
37b	Alex was able to memorize the simplest music/rhyme/sinat/sbnkt without too much effort.
38a	Cody opened a large account/satchel/trilits/trblbts and put money into it.
38b	Robert got an extra account/satchel/trilits/trblbts to put his additional money.
39a	Justin took his baby brother/terrier/slation/slktbhn to the park to play.
39b	Mary loved her new brother/terrier/slation/slktbhn so much that she spoiled him.
40a	Emily found the long chapter/tabloid/bratues/brktpgs too boring too read.
40b	Emma couldn’t wait to read the next chapter/tabloid/bratues/brktpgs of the intriguing story.
41a	The man was taken to the small council/dungeon/grature/grktprg after committing the crime.
41b	Peter was scared to see the royal council/dungeon/grature/grktprg and decided not to go.
42a	The aging professor teaches history/zoology/statote/stkthtg at the prestigious university.
42b	I took my favorite history/zoology/statote/stkthtg course my last year of college.
43a	He climbed to the top of the tallest machine/trellis/claunch/clkpnch and made the needed repairs.
43b	John was able to fix the broken machine/trellis/claunch/clkpnch very quickly despite complications.
44a	Josh feared that his broken marriage/ligament/ocrudios/hcrpdbhs could not be fixed.
44b	Luckily the man’s damaged marriage/ligament/ocrudios/hcrpdbhs gradually healed over time.
45a	Maddison found the only picture/mascara/clealth/clgklth she had in her bag.
45b	Tara picked up the lost picture/mascara/clealth/clgklth off the messy floor.
46a	Jacob found that the extended practice/tutorial/cheamren/chgkmrgn helped improve his skills.
46b	Daniel went to an optional practice/tutorial/cheamren/chgkmrgn after school last Friday.
47a	Hannah was annoyed that the difficult problem/anagram/steepod/stggphd took so long to solve.
47b	To find an answer to the confusing problem/anagram/steepod/stggphd you will need great skill.
48a	The police waited until the entire process/autopsy/steezen/stggzgn was finished before making a report.
48b	They couldn’t finish the lengthy process/autopsy/steezen/stggzgn due to unforeseen complications.
49a	Will always loved to learn about science/algebra/treeple/trggplg when he was in school.
49b	Kristen really liked to study science/algebra/treeple/trggplg because it taught her valuable skills.
50a	Everyone says they have great service/cuisine/thellar/thgllkr at the new restaurant.
50b	The restaurant had such awful service/cuisine/thellar/thgllkr that I don’t think we will go back.
51a	Samantha saw the young student/sparrow/drumble/drpmblg fall out of the tree.
51b	Jill thought the tiny student/sparrow/drumble/drpmblg was small for his age.
52a	Chris stayed in the hidden village/hammock/snepson/sngpshn for a long time.
52b	The traveler rested in the comfy village/hammock/snepson/sngpshn before starting his journey.
53a	David found a local company/brewery/sherile/shgrblg to sponsor the event.
53b	They took a tour of the large company/brewery/sherile/shgrblg on their business trip.
54a	Marissa complained that her rowdy husband/toddler/slernum/slgrnpm was hard to control.
54b	Polly had to rush her sick husband/toddler/slernum/slgrnpm to the hospital this morning.
55a	It was the best quality/emerald/theamer/thgkmgr ring she had ever seen.
55b	We could tell from the great quality/emerald/theamer/thgkmgr that the necklace was expensive.

Item	Sentence
56a	The businessman had great success/tequila/cheppes/chgppgs on his trip to Mexico.
56b	Much to his dismay, he didn't have very much success/tequila/cheppes/chgppgs at the bar last night.
57a	Stan received some much needed support/aspirin/chetson/chgtshn and began to feel better.
57b	Tom will need some strong support/aspirin/chetson/chgtshn if he plans to finish that project.
58a	Alex cleaned the dirty surface/platter/bleward/blgwkrd in the kitchen with a sponge.
58b	The server wiped down the large surface/platter/bleward/blgwkrd with a wet towel.
59a	The group was surprised that his unusual wisdom/whimsy/preels/prggls proved to be useful.
59b	William developed his unique wisdom/whimsy/preels/prggls when he lived abroad.
60a	Dan found some large leaves/acorns/theely/thggly under the tree outside.
60b	Sally got some unique leaves/acorns/theely/thggly on her trip to the park.
61a	Michael learned that his serious action/wounds/fleers/flggrs worried his friends and family.
61b	The soldier feared his recent action/wounds/fleers/flggrs would cause him to become ill.
62a	For some, a lovely turkey/wreath/smicks/smbcks is a symbol of the holiday season.
62b	Someone had left a large turkey/wreath/smicks/smbcks on their front porch.
63a	The handyman brought the wrong things/wrench/flicky/flbcky which made the repair job take longer.
63b	Luckily Kyle had the right things/wrench/flicky/flbcky needed for the job.
64a	Steve fixed the broken window/urinal/clifle/clbflg in the men's bathroom.
64b	The janitor cleaned the dirty window/urinal/clifle/clbflg and mopped the floor.
65a	Everyone knows that the region's dangerous winter/arctic/bligma/blbgmk climate makes it uninhabitable.
65b	Not many people brave the northern winter/arctic/bligma/blbgmk and its snow storms.
66a	They found the lost wolves/tokens/griles/grblgs in the dark forest.
66b	They kept the rare wolves/tokens/griles/grblgs in the new exhibit.
67a	The police said the criminal's unusual weapon/tattoo/plereo/plgrgh made him easy to identify.
67b	The gang members all had a trademark weapon/tattoo/plereo/plgrgh which distinguished them from other groups.
68a	The children took several stones/sweets/crooge/crhhgg with them to the lake.
68b	The museum had a display with various stones/sweets/crooge/crhhgg from around the world.
69a	The town had more stores/storms/chraws/chrkws than it could handle.
69b	A lot of odd stores/storms/chraws/chrkws recently came to the area.
70a	Thomas thought the pleasing voices/bongos/glumpy/glpmpy made the song special.
70b	The hit song featured beautiful voices/bongos/glumpy/glpmpy with a classical piano.
71a	The doctors explained that he had impaired vision/vitals/snuffy/snpffy after the car accident.
71b	The patient reported improved vision/vitals/snuffy/snpffy the day after treatment.
72a	Sam couldn't hear over the loud voices/walrus/studia/stpdbk at the zoo exhibit.
72b	I grew tired of the noisy voices/walrus/studia/stpdbk at the circus performance.
73a	Sarah couldn't hear her TV over the roaring volume/vacuum/clucco/clpcch from her neighbor's apartment.
73b	Mandy had to turn the blaring volume/vacuum/clucco/clpcch off so she could hear the phone.
74a	Someone stole the golden statue/medals/phubby/phpbby from the museum exhibit.
74b	They made sure to keep the prized statue/medals/phubby/phpbby under heavy security surveillance.
75a	The woman was surprised to see several trucks/tulips/scrung/scrpng all around the front yard.
75b	The town was known for its bright orange trucks/tulips/scrung/scrpng that could be seen all around.

Item	Sentence
76a	It felt like the great tunnel/tirade/chrove/chrhvg would go on forever.
76b	I could barely get through the long tunnel/tirade/chrove/chrhvg without feeling very nervous.
77a	They enjoyed the sweet apples/toffee/chrong/chrhng for dessert after dinner.
77b	Matt and Tracy bought fresh apples/toffee/chrong/chrhng at the farmer’s market.
78a	The feeling of the soft tissue/velvet/sproll/sprhll felt nice on her skin.
78b	Karen wrapped the present in black tissue/velvet/sproll/sprhll which looked very elegant.
79a	The animals will surely desire/devour/loumip/lhpmbp any food they see.
79b	The young children always desire/devour/loumip/lhpmbp any cookies or treats.
80a	After seeing the reports, the company expected/presumed/cantipum/ckntbppm that it would be a good year.
80b	The medical researcher really expected/presumed/cantipum/ckntbppm that his hypothesis would be true.
81a	The nurse made sure to gently cover/bathe/finut/fbnpt the baby every night.
81b	The babysitter remembered to quickly cover/bathe/finut/fbnpt the child before bed.
82a	The police man had to urgently direct/escort/sanide/sknbdg the woman to the hospital.
82b	A kind man offered to happily direct/escort/sanide/sknbdg her to the front office.
83a	They had to quickly take/haul/moni/mhnb the wood to the building site.
83b	The moving truck could easily take/haul/moni/mhnb the furniture to the new house.
84a	His boss would always accept/rebuff/tumlin/tpmlbn any offer from other businesses.
84b	Anna chose to boldly accept/rebuff/tumlin/tpmlbn the college acceptance letter.
85a	Mia had her attorney write/renew/gitum/gbtpm her new business contract.
85b	They agreed to annually write/renew/gitum/gbtpm their contract with each other.
86a	They threatened to brutally murder/harass/githum/gbthpm anyone who opposed them.
86b	The soldiers came to angrily murder/harass/githum/gbthpm the people in the enemy camp.
87a	Zack needed to securely stick/strap/ginut/gbnpt the pieces of equipment together.
87b	The new material was able to tightly stick/strap/ginut/gbnpt the two boxes together.
88a	The manly contractor hardly worked/winced/therns/thgrns when he broke his arm.
88b	The zealous college student worked/winced/therns/thgrns hard when he found out what was on the final.
89a	Evan was nervous because he had never served/smoked/strope/strhpg the gourmet meat before.
89b	The restaurant always served/smoked/strope/strhpg their meat dishes perfectly.
90a	Julie hoped she wouldn’t have to ever miss/bake/jast/jkst another delicious meal.
90b	After getting sick, Jill decided to never miss/bake/jast/jkst her favorite dessert again.
91a	The businessman had finally finished/endorsed/vanitium/vknbtbpm his new marketing campaign.
91b	The newly elected council finished/endorsed/vanitium/vknbtbpm their report from last week.
92a	Brian was able to carefully shape/carve/polim/phlbm the ice into a beautiful sculpture.
92b	My grandfather taught me how to precisely shape/carve/polim/phlbm wood into many different objects.
93a	The new fraternity brother posted/sorted/sprips/sprbps the updated event flyers.
93b	The school’s affairs director posted/sorted/sprips/sprbps a list of upcoming activities.
94a	Rachel was always diligently following/emulating/halfinate/hklfbnktg her brother’s good example.
94b	Young children are typically following/emulating/halfinate/hklfbnktg the example of their parents.
95a	The young couple steadily walked/trudge/bonume/bhnpmg along the dirt trail.
95b	Many of the hikers intently walked/trudge/bonume/bhnpmg up the top of the mountain.

Item	Sentence
96a	The student decided to cruelly force/bully/benat/bgnkt his classmate into doing his work.
96b	Dictators are known to angrily force/bully/benat/bgnkt their people into supporting them.
97a	The baby was tightly covered/bundled/feterni/fgtgrnb in some fresh blankets.
97b	The art dealer securely covered/bundled/feterni/fgtgrnb the paintings with thick cloth.
98a	James was able to easily decide/affirm/juitim/jpbtbm that she was correct.
98b	The police were asked to quickly decide/affirm/juitim/jpbtbm the cause of death.
99a	Unfortunately Jessica wasn't able to actually make/omit/lopa/lhpk her hard class last week.
99b	My grandma will normally make/omit/lopa/lhpk dinner on weekday nights.
100a	The young mother always makes/cooks/durms/dprms a very good meal.
100b	I heard the new diner makes/cooks/durms/dprms the best burger in town.
101a	The police were able to easily corner/detain/rathum/rkthpm the suspect in the parking lot.
101b	The patrol was forced to briefly corner/detain/rathum/rkthpm all the people until the fire ended.
102a	It surprised me that they actually believe/surmise/vanonit/vknhnbt that the news stories are true.
102b	After hearing the evidence, the jury will certainly believe/surmise/vanonit/vknhnbt that the man is guilty.
103a	The king decided to kindly advise/acquit/blatue/blktpg the criminal in court.
103b	The jury thought it was better to openly advise/acquit/blatue/blktpg the teenager than convict him.
104a	The young professor always writes/arises/thatus/thktps early in the morning.
104b	The old man usually writes/arises/thatus/thktps from his chair just before dinner.
105a	The general had to fully accept/weaken/steumy/stgpmy the power of his enemy.
105b	My friend tried to coolly accept/weaken/steumy/stgpmy my point of view, but he couldn't do it.
106a	The police had to quickly access/vacate/stelli/stgllb the restricted area of the building.
106b	The spy managed to smoothly access/vacate/stelli/stgllb the building without being spotted.
107a	The stubborn teen really wanted/abused/spench/spgnch his freedom from his parents.
107b	The power that the young ruler badly wanted/abused/spench/spgnch was taken away by his father.
108a	The responsible young woman values/washed/stoppe/sthppg her car almost everyday.
108b	The coin collector always values/washed/stoppe/sthppg his coins so they don't lose their shine.
109a	After a long time, Randy finally wasted/welded/snewed/sngwgd all his old scrap metal.
109b	The foreman was mad when his workers wasted/welded/snewed/sngwgd the pieces of good metal.
110a	The dedicated farmer usually turned/tilled/scrive/scrbvg the field in the spring.
110b	The diligent townspeople annually turned/tilled/scrive/scrbvg their land in hopes of a good harvest.
111a	They had to gently remove/unload/strang/strkng the items from the truck.
111b	The fishermen at the harbor remove/unload/strang/strkng their catch from their boat.
112a	Travis was able to safely change/detach/strofe/strhfg the damaged car battery.
112b	Luckily the boy could simply change/detach/strofe/strhfg the broken cable to fix the problem.
113a	The newly engaged couple bought/rented/scride/scrbdg a house that was out of their price range.
113b	The girl's wealthy parents bought/rented/scride/scrbdg a pony for her birthday.
114a	The manager was forced to reluctantly recall/negate/phrewn/phrgwn his company's latest offer.
114b	The senators knew they could completely recall/negate/phrewn/phrgwn the decision if needed.
115a	The inexperienced player almost caught/tossed/shrict/shrbct the ball too late.
115b	The bass fisherman nearly caught/tossed/shrict/shrbct all the fish in the lake.
116a	The construction workers noisily placed/nailed/tonacs/thnkcs the wooden boards together.

Item	Sentence
116b	Tyler and Jenny finally placed/nailed/tonacs/thnkcs all the pieces together.
117a	The tired businessman just missed/booked/fensil/fgnsbl the last flight home.
117b	The two suspects were missed/booked/fensil/fgnsbl by the police officer.
118a	The old woman often called/envied/nootsy/nhhtsy her sister on her birthday.
118b	The student who did poorly on the test called/envied/nootsy/nhhtsy everyone who had a good grade.
119a	The leader tried his best to confidently manage/govern/rulack/rplkck the people in a difficult time.
119b	Tim was never able to completely manage/govern/rulack/rplkck his notoriously bad temper.
120a	The fancy dessert suddenly burned/melted/topeta/thpgtk and was completely ruined.
120b	The novice cook by mistake burned/melted/topeta/thpgtk the butter in the pan.
121a	The suspicious teenager carefully opened/scaled/bulice/bplbcg the tall gate to get into the park.
121b	The skillful chef expertly opened/scaled/bulice/bplbcg the fish with a knife and took out the bones.
122a	The students were afraid and wouldn't verbally answer/assail/rilicy/rblbcy the notoriously strict teacher.
122b	The soldier was brave enough to blatantly answer/assail/rilicy/rblbcy the troop's harsh general.
123a	The rich man always mailed/gilded/roling/rhlbng the letters with a gold trim.
123b	The famous artist finally mailed/gilded/roling/rhlbng the sculpture the art dealer purchased.
124a	The elderly couple often stayed/lodged/pelash/pglksh at the inn during the winter.
124b	I wish I could have stayed/lodged/pelash/pglksh in the cabin all winter.
125a	The young boy eagerly turned/traded/folled/fhllgd in his tickets for a prize.
125b	The report told of a police officer that always turned/traded/folled/fhllgd in very dangerous criminals.
126a	The old man easily quoted/retold/tollen/thllgn some fantastic stories of the past.
126b	The only witness clearly quoted/retold/tollen/thllgn what they heard at the crime scene.
127a	The impatient man angrily looked/toiled/pampek/pkmpgk over the puzzle for hours.
127b	Even after sunset, the mother looked/toiled/pampek/pkmpgk in her vast garden.
128a	The plant was able to easily mature/wither/goncho/ghnchh in the bright sun.
128b	Removing support caused the business to slowly mature/wither/goncho/ghnchh in its own time.
129a	The pesky child always wanted/nabbed/tonder/thndgr cookies from the kitchen.
129b	The busy police force barely wanted/nabbed/tonder/thndgr the low profile criminal.
130a	The spoiled girl often needed/nagged/poniel/phnbgl her mom to buy her things.
130b	When my dogs were puppies they needed/nagged/poniel/phnbgl me for attention all the time.
131a	The new politician fairly united/upheld/foorer/fhhrgr each group's ideas and interests.
131b	He thought legal rights must be fully united/upheld/foorer/fhhrgr with basic human rights.
132a	The busy secretary hastily looked/rifled/georly/gghrly through the papers to find the document.
132b	Last night the sneaky thieves looked/rifled/georly/gghrly through the house and stole something.
133a	The leading soldier bravely lifted/rigged/nopgun/nhpgpn the flag up the pole.
133b	Ricky and Angela expertly lifted/rigged/nopgun/nhpgpn the sailboat's sail high into the air.
134a	They could not even afford/affirm/toplin/thplbn the cost of the contract.
134b	The company determined they could afford/affirm/toplin/thplbn the profit lost due to complaints.
135a	The teenage girl playfully smiled/winked/fopped/fhppgd at the cute boy.
135b	Philip looked at the audience and jokingly smiled/winked/fopped/fhppgd after his theater performance.
136a	Their business was sure to greatly expand/vanish/gorker/ghrkgr by the end of the year.
136b	Fred guessed that the liquid would quickly expand/vanish/gorker/ghrkgr in his science project.

Item	Sentence
137a	The art student carefully spread/daubed/poroos/phrhhs the oil paints on the canvas.
137b	The tired craftsman hastily spread/daubed/poroos/phrhhs the final coat of paint on the furniture.
138a	Lucas knew how to fairly market/barter/porlly/phrlly his services to customers.
138b	The successful farmer would market/barter/porlly/phrlly his produce in town every week.
139a	The startled player quickly jumped/lunged/losted/lhstgd forward to catch the ball.
139b	Richard’s new puppy eagerly jumped/lunged/losted/lhstgd at the squeaky toy.
140a	The engineer was able to quickly design/invent/posang/phskng a new type of airplane.
140b	The prisoner was able to cleverly design/invent/posang/phskng a way to escape undetected.
141a	The lawyer asked the witness if she could verify/attest/nosses/nhssgs the validity of the report.
141b	The simple experiment would verify/attest/nosses/nhssgs the truth of the claim.
142a	The army marched to hastily obtain/invade/ristal/rbstkl the strong enemy fortress.
142b	The land they wanted to fiercely obtain/invade/ristal/rbstkl could not sustain their troops.
143a	Lisa discovered she could never assume/deduce/coster/chstgr the truth of what he said.
143b	College students can often assume/deduce/coster/chstgr what a course will cover by the syllabus.
144a	She wanted to wholly change/invert/polanf/phlknf the pattern of the quilt.
144b	The pilot was able to easily change/invert/polanf/phlknf the direction of the plane.

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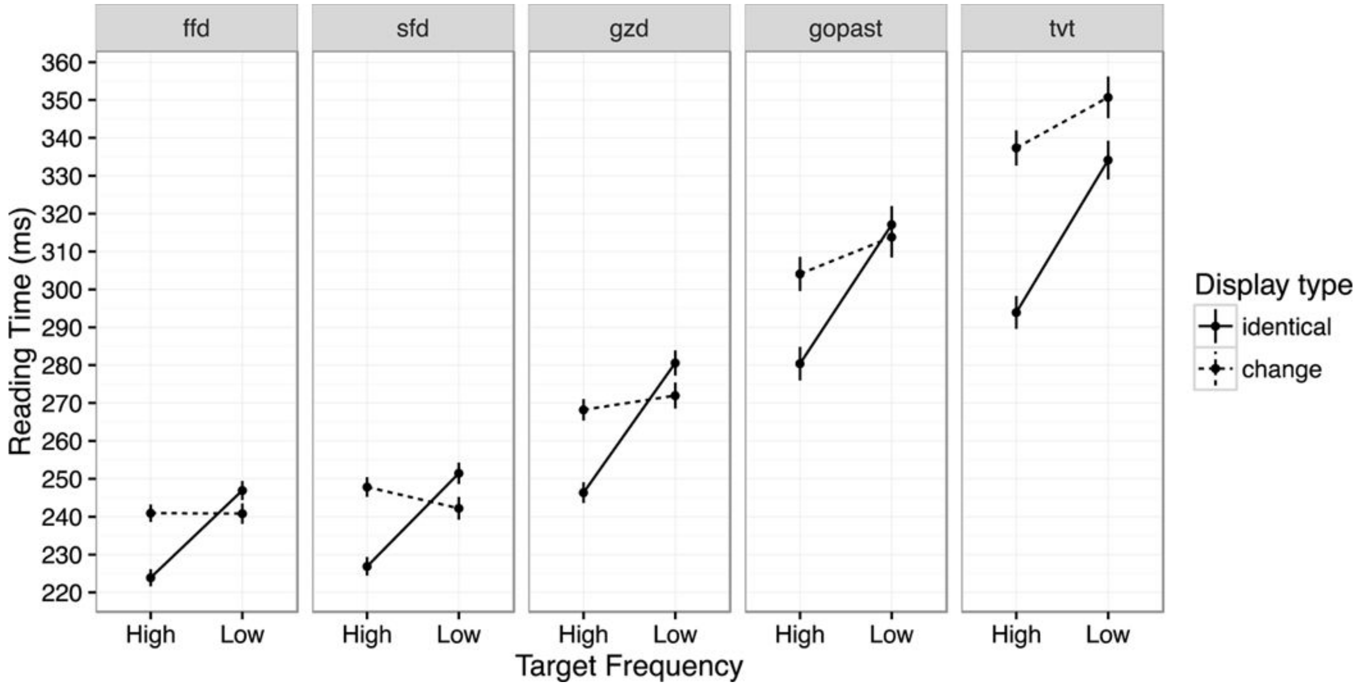

Figure 1.

Reading time on the target word in Experiment 1 as a function of target frequency and display type (identical vs. change), across 5 reading time measures (ffd = first fixation duration, sfd = single fixation duration, gzd = gaze duration, gopast = go-past time, tvt = total time). Error bars represent +/− 1 standard error of the mean.

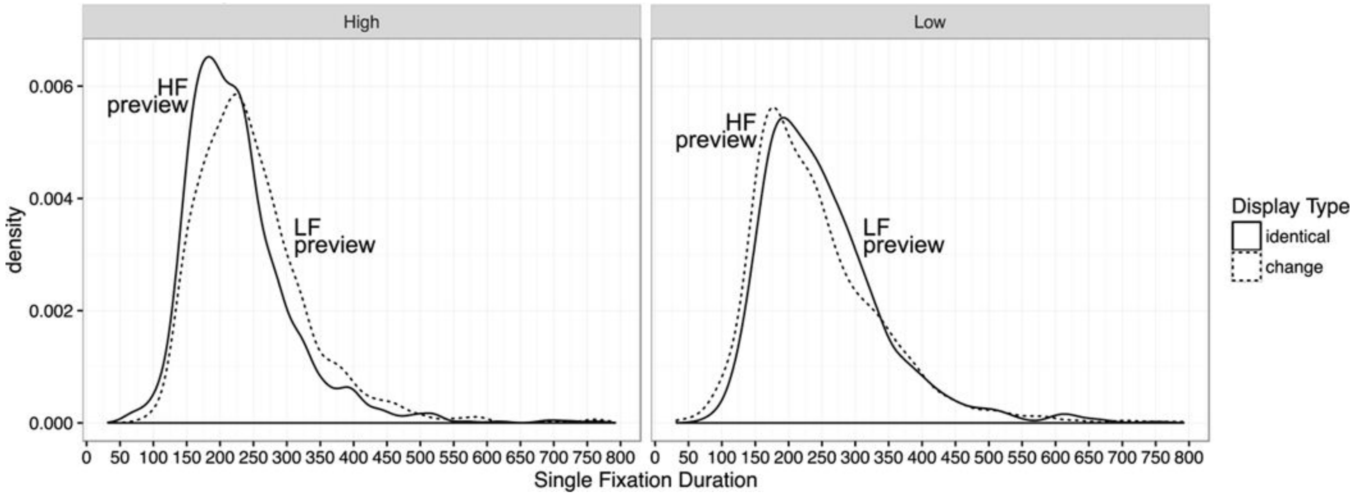

Figure 2.

Density distributions of raw single fixation durations in Experiment 1 for high frequency target words (left hand panel) and low frequency words (right hand panel) in the identical display conditions (solid lines) and display change conditions (dashed lines). Note that the reverse preview benefit for low frequency target words is visible in the right hand panel in that the dashed line is shifted further to the left than the solid line in the short duration portion of the distribution (i.e., until around 350 ms).

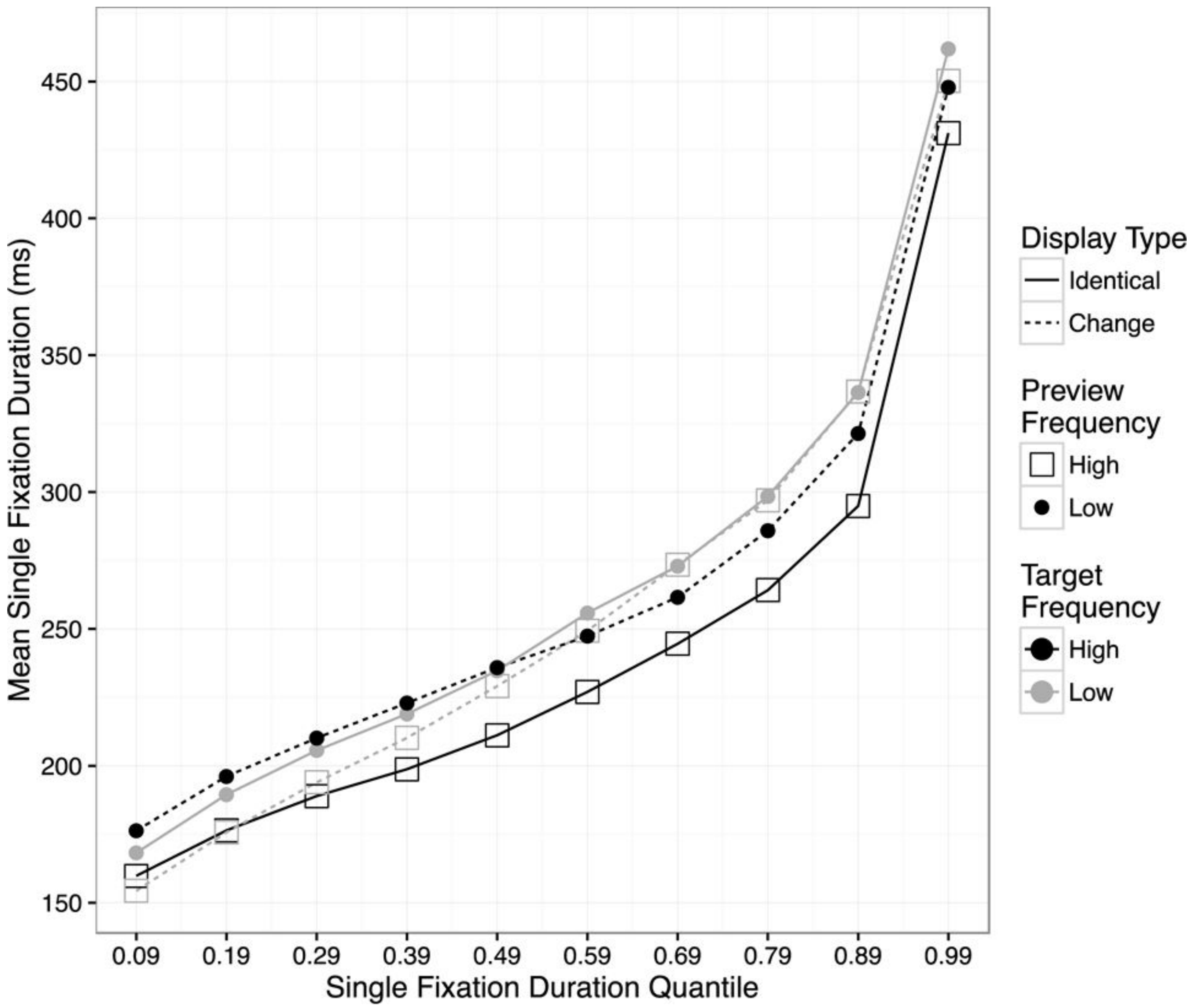

Figure 3.

Mean single fixation duration across quantiles and experimental conditions in Experiment 1. Shape represents preview frequency (open square = high, closed circle = low), color represents target frequency (black = high, grey = low), and line type represents display type (solid = identical, dotted = display change).

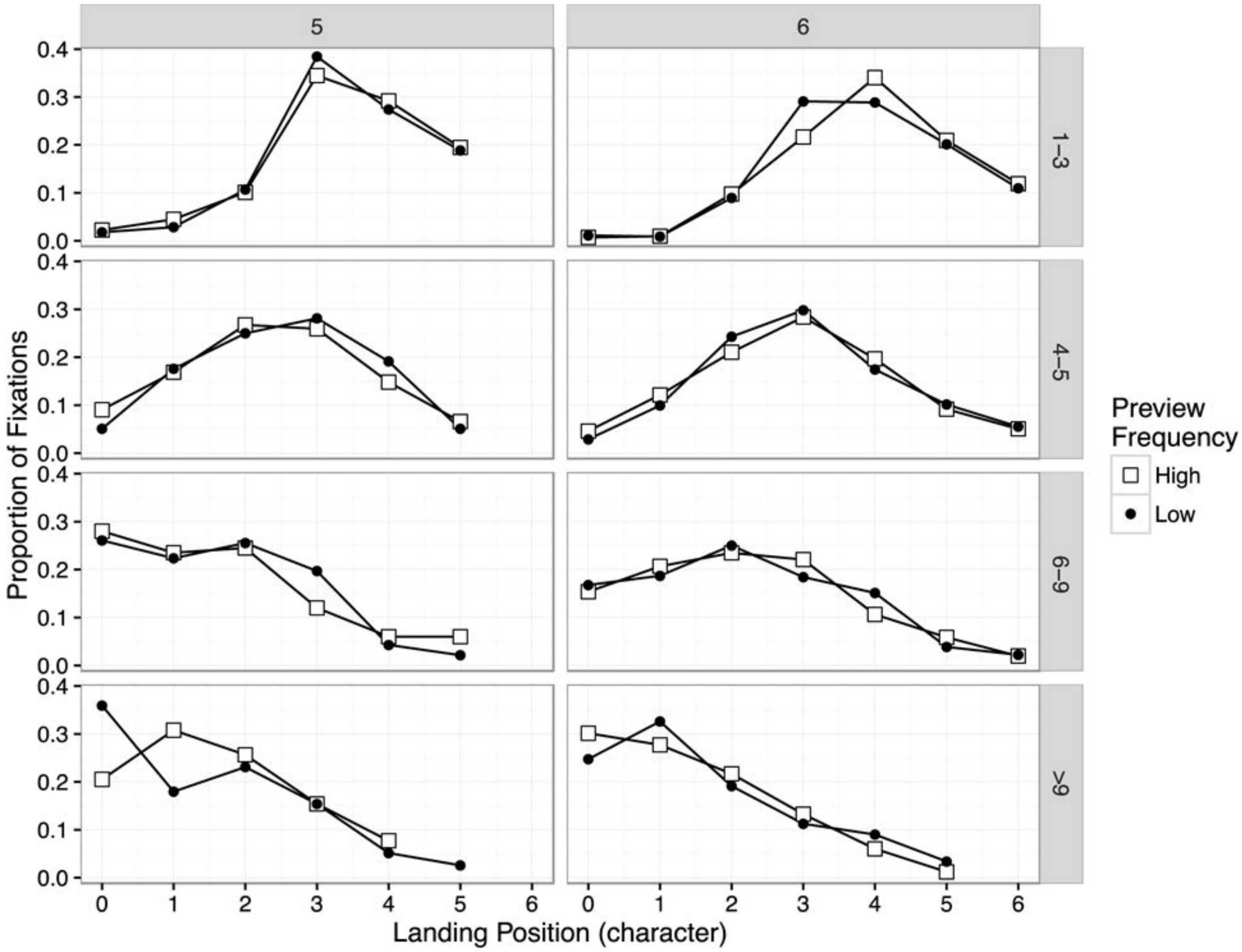

Figure 4.
Landing site distributions for 5- and 6-character target words as a function of launch site and word length for high and low frequency previews in Experiment 1. Shape represents preview frequency (open square = high, closed circle = low), columns represent word length (5 character words in the left column, 6 character words in the right column), and rows represent launch site in characters. Character 0 corresponds to the space to the left of the target word.

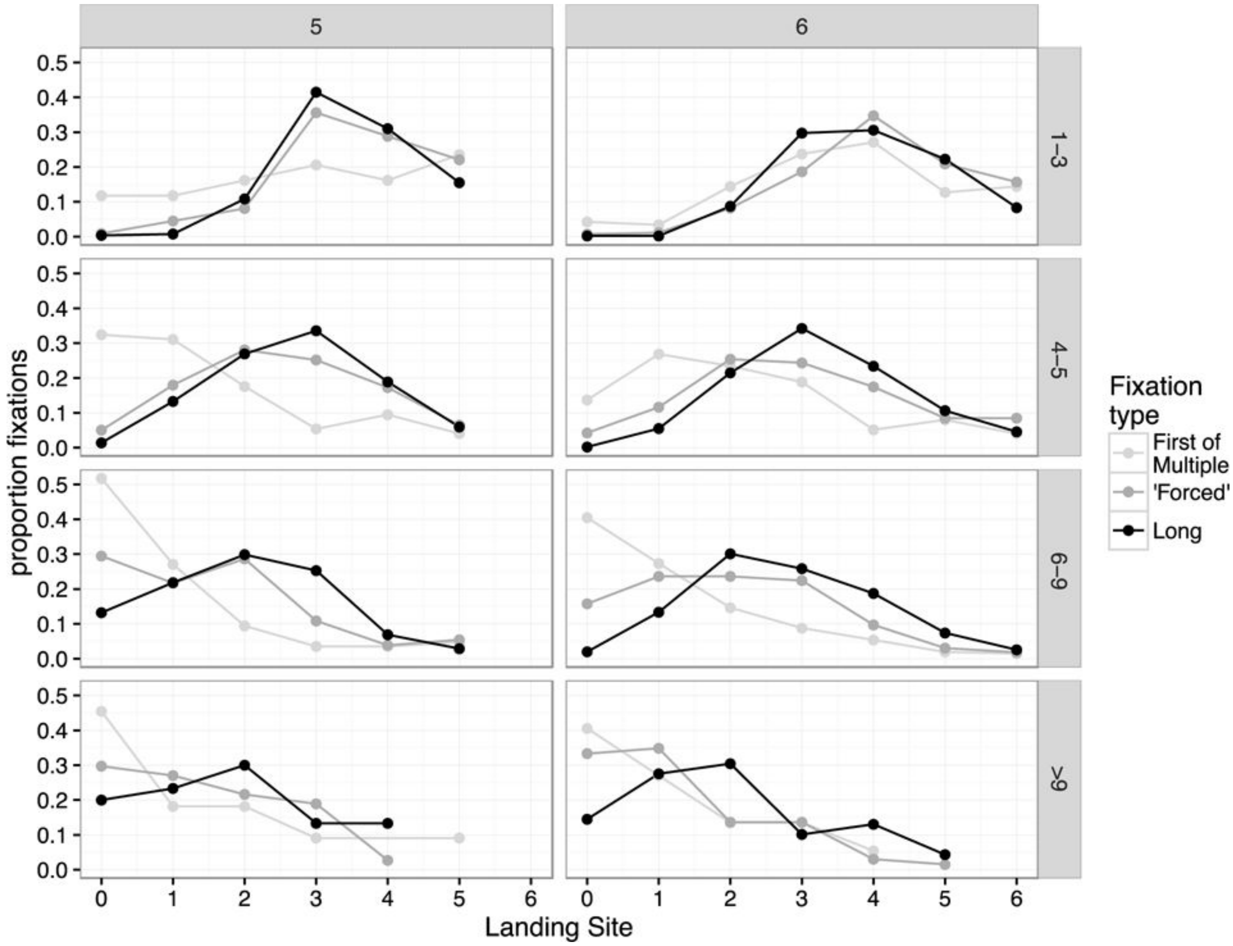

Figure 5.

Landing site distributions for 5- and 6-character target words as a function of launch site and word length for three types of fixations in Experiment 1 (first of multiple fixations, ‘forced’ single fixations (i.e., those shorter than 201 ms), and long single fixation durations (i.e., those longer than 200 ms)). Color represents fixation type (light grey = first of multiple fixations, medium grey = ‘forced’ single fixations, and black = long single fixations), columns represent word length (5 character words in the left column, 6 character words in the right column), and rows represent launch site in characters. Character 0 corresponds to the space to the left of the target word.

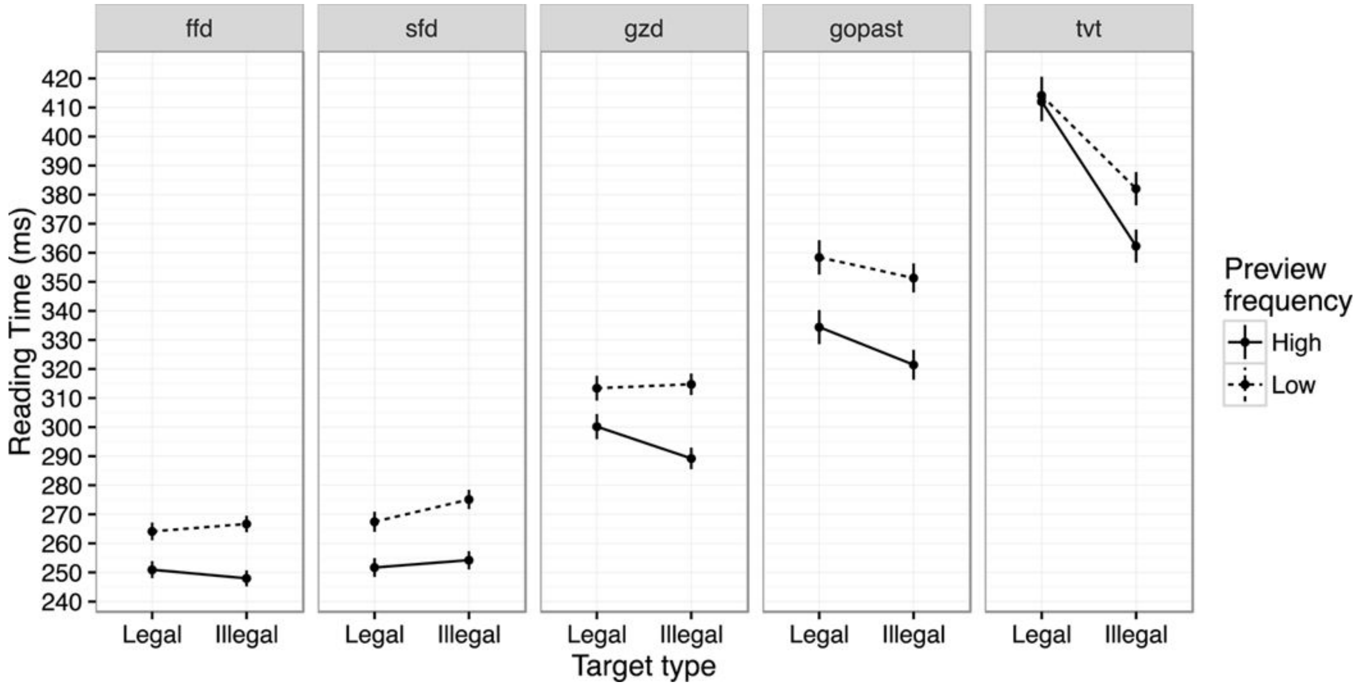

Figure 6.

Reading time on the target word in Experiment 2 as a function of preview frequency and target type (legal vs. illegal nonword), across 5 reading time measures (ffd = first fixation duration, sfd = single fixation duration, gzd = gaze duration, gopast = go-past time, tvt = total time). Error bars represent +/− 1 standard error of the mean.

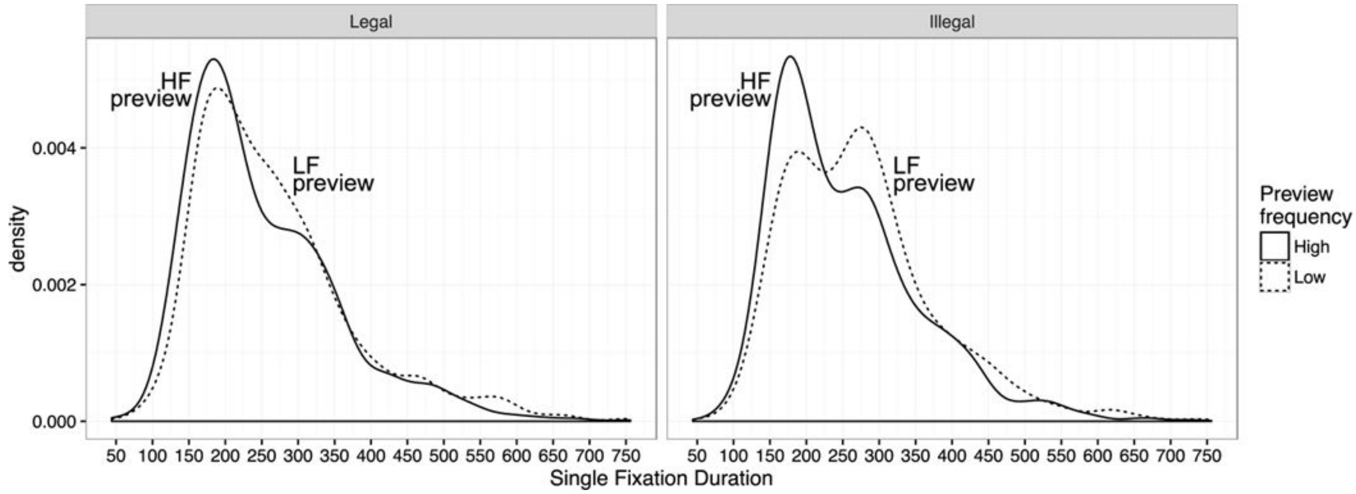

Figure 7.

Density distributions of raw single fixation durations in Experiment 2 for illegal nonword targets (left hand panel) and legal nonword targets (right hand panel) in the high frequency preview condition (solid lines) and low frequency preview condition (dashed lines). Note the bimodality in the distributions for the illegal nonword condition follows what would be predicted by the idea of forced fixations: the earlier mode is denser in the high frequency preview condition and peaks around 180 ms.

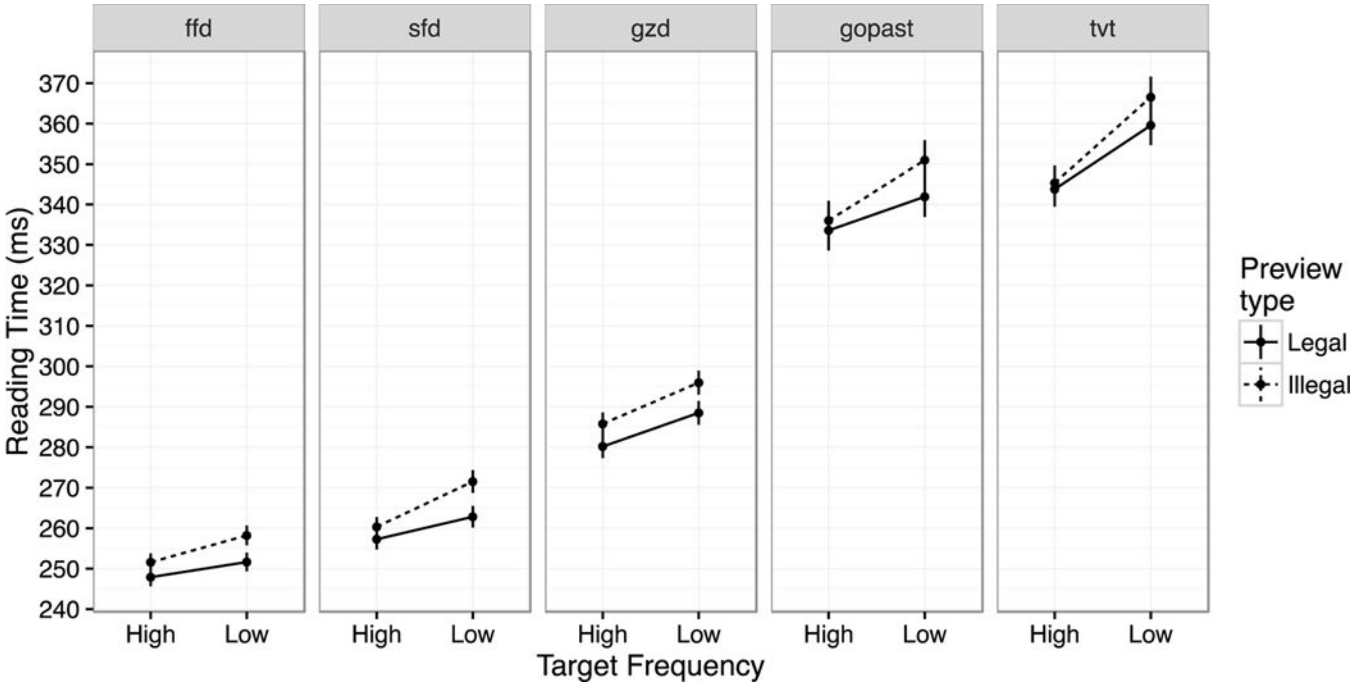

Figure 8.

Reading time on the target word in Experiment 3 as a function of target frequency and preview type (legal vs. illegal nonword), across 5 reading time measures (ffd = first fixation duration, sfd = single fixation duration, gzd = gaze duration, gopast = go-past time, tvt = total time). Error bars represent +/− 1 standard error of the mean.

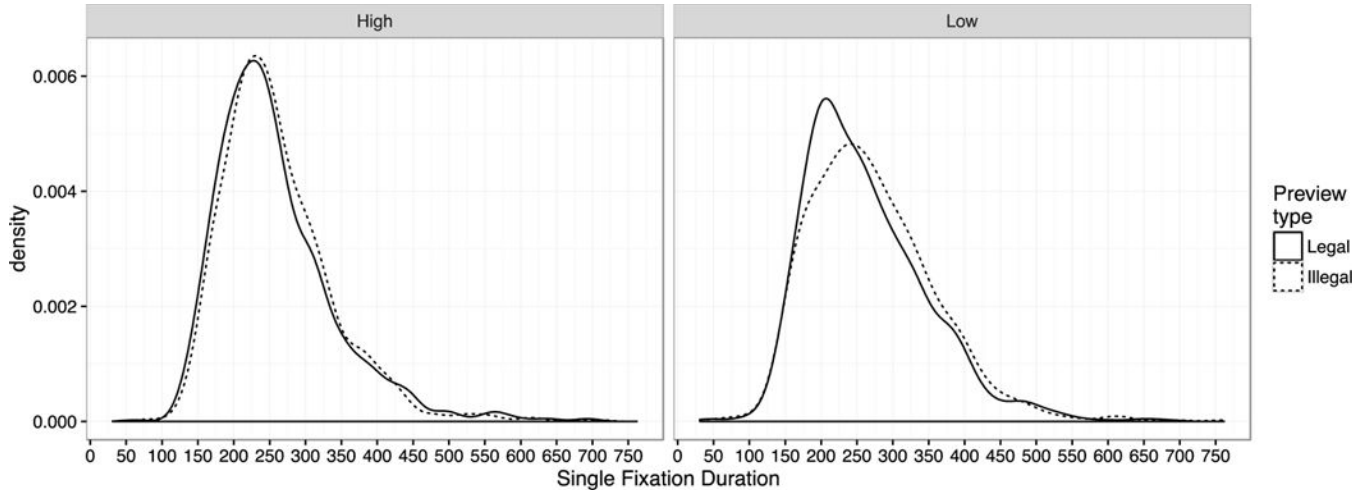

Figure 9.

Density distributions of raw single fixation durations in Experiment 3 for high frequency word targets (left hand panel) and low frequency word targets (right hand panel) in the legal nonword preview condition (solid lines) and illegal nonword preview condition (dashed lines). Note that there are few fixation durations shorter than about 100 ms, and the modes of the distributions are shifted later compared to the modes in Experiments 1 and 2, peaking around 225 ms.

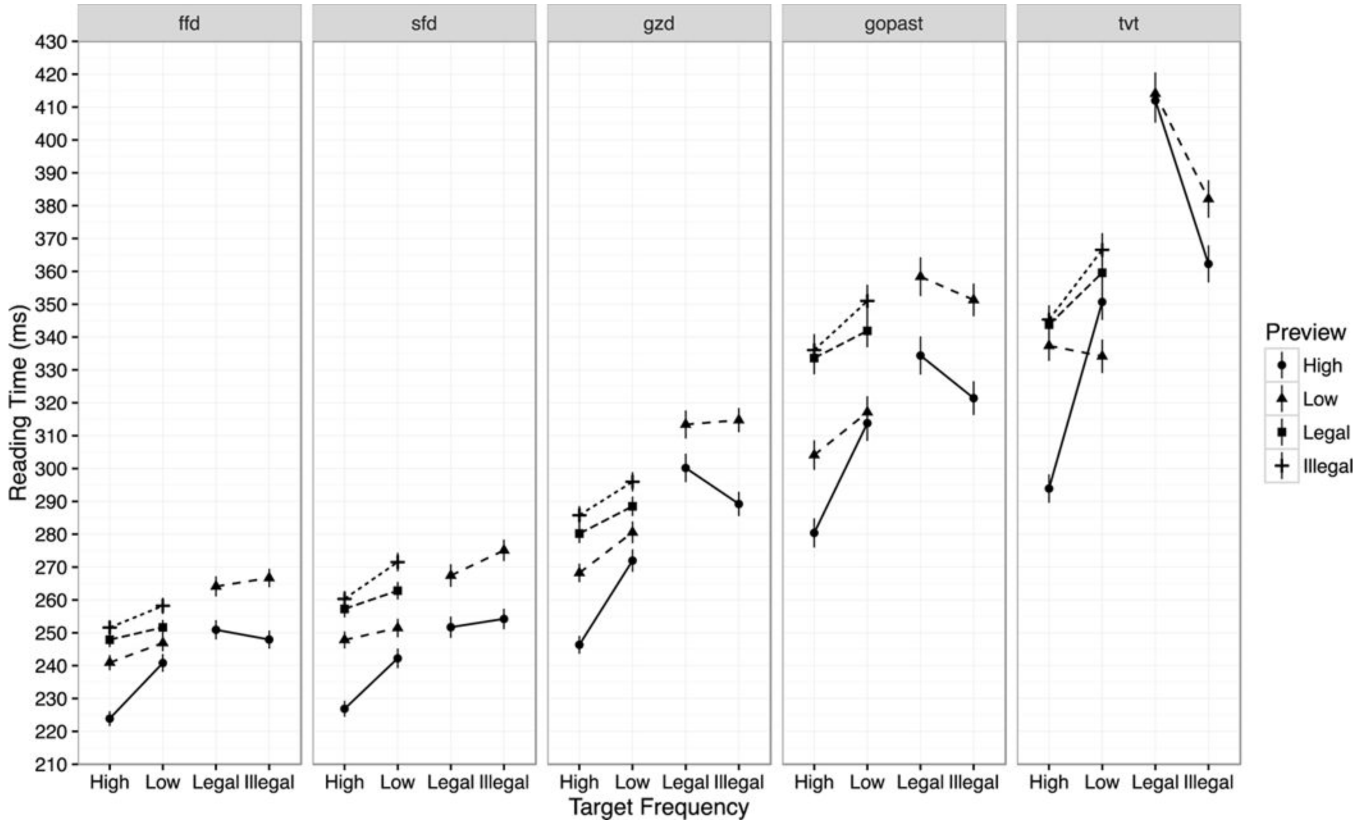

Figure 10.
Reading time on the target word in all three experiments as a function of target type and preview type, across 5 reading time measures (ffd = first fixation duration, sfd = single fixation duration, gzd = gaze duration, gopast = go-past time, tvt = total time). Error bars represent +/− 1 standard error of the mean.

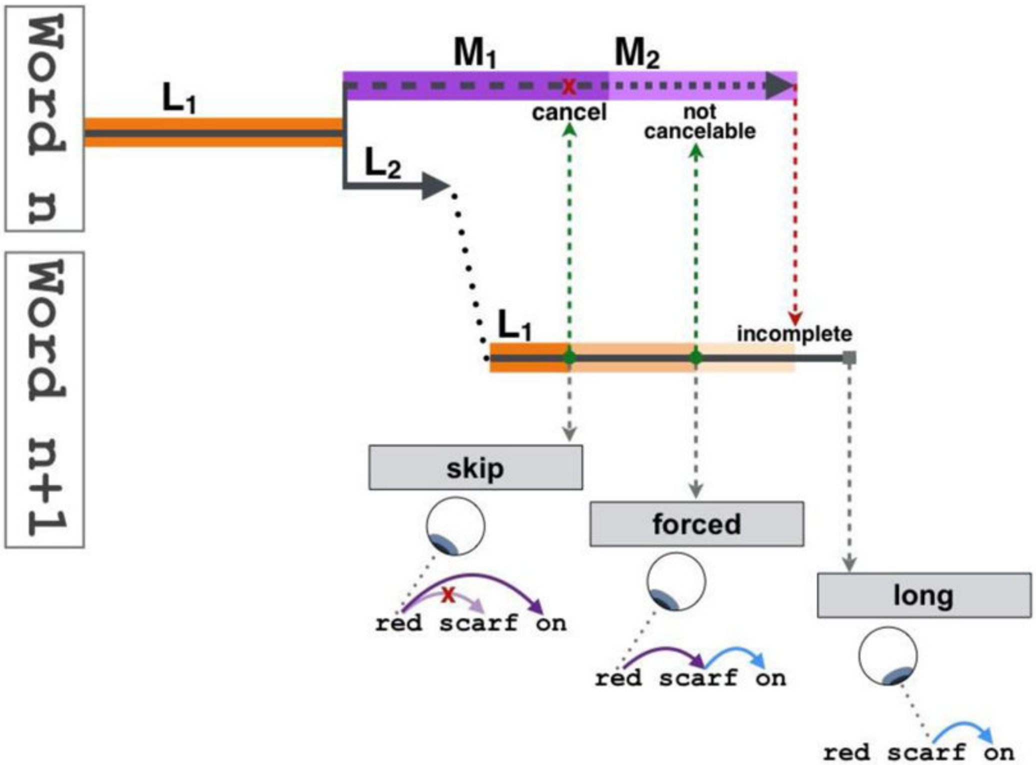

Figure 11.
Schematic diagram of processing stages for two consecutive words (*n* and *n+1*) in three fixation behavior scenarios from the E-Z Reader model. Time progresses horizontally from left to right and space progresses vertically from top to bottom. Whether one of the three scenarios (represented by the type in the grey box and the diagram of the eye and saccade sequences at the bottom) is observed depends on when the L_1 stage of word identification for word *n+1* completes relative to the saccade planning stages for the saccade from word *n* to word *n+1*. If it completes during the labile stage of saccade planning (M_1) toward word *n +1*, the first saccade will be cancelled and a different one be programmed to word *n+2* (i.e., a skip). If it completes during the non-labile stage (M_2) two saccades will be programmed with a short intervening fixation on word *n+1* (i.e., a forced fixation). If it does not complete by the time the eyes move to word *n+1* a saccade will not be planned until sufficient foveal information from word *n+1* is obtained (i.e., a long fixation).

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Table 1

Summary statistics for target/preview words in Experiment 1.

	High Frequency				Low Frequency			
	M	***SD***	***Min.***	***Max.***	***M***	***SD***	***Min.***	***Max.***
Log HAL Frequency/400 mil	10.50	1.05	8.21	13.25	6.81	1.20	2.83	8.9
Raw Frequency per million	159	208	9	1414	4	4	0	18
Length	5.88	0.83	4	9	5.88	0.83	4	9
Cloze predictability	0.04	0.11	0	0.8	0.01	0.04	0	0.5
Sentence acceptability	5.34	0.74	3	6.7	5.35	0.78	2	6.7

Table 2

Means and standard errors, aggregated by subject, for reading time measures in Experiment 1.

Target Word Frequency	**High**		**Low**	
Preview Word Frequency	**High**	**Low**	**High**	**Low**
First Fixation Duration	222 (6.6)	239 (7.4)	237 (8.8)	243 (8.2)
Single Fixation Duration	227 (7.8)	248 (9.0)	243 (11)	250 (9.7)
Gaze Duration	244 (8.3)	265 (9.2)	267 (12)	275 (11)
Go-Past Time	278 (10)	300 (14)	309 (17)	310 (16)
Total Time	292 (12)	334 (15)	345 (22)	327 (19)
Fixation Probability	0.90 (.02)	0.92 (.03)	0.89 (.03)	0.90 (.02)
Regressions out	0.08 (.01)	0.09 (.02)	0.08 (.01)	0.08 (.01)
Regressions in	0.12 (.02)	0.20 (.02)	0.20 (.02)	0.14 (.02)

Table 3

Results of linear mixed effects models for reading time measures on the target in Experiment 1 from models with the high frequency target (left columns) or low frequency target as the baseline (right columns). The intercept represents the mean duration for the baseline target frequency averaged across display type and the effect of target frequency is the difference between target frequency conditions averaged across display type. The effects of target frequency and the interaction should be identical (with reversed sign) between the two models but the numerical values differ slightly when the random effects were different between the two models (see Footnote [4]). Significant effects are indicated by boldface.

Measure	Contrast	Model with High Frequency Baseline			Model with Low Frequency Baseline		
		b	SE	|t|	b	SE	|t|
First Fixation Duration							
	Intercept	**230.24**	**6.99**	**32.95**	**239.87**	**8.51**	**28.19**
	Target frequency effect	**9.63**	**2.84**	**3.39**	**−9.63**	**2.84**	**3.39**
	Display type for baseline	**16.53**	**3.24**	**5.11**	−5.89	3.67	1.61
	Display type * frequency	**−22.42**	**4.92**	**4.56**	**22.42**	**4.92**	**4.56**
Single Fixation Duration							
	Intercept	**237.29**	**8.37**	**28.37**	**247.03**	**10.24**	**24.14**
	Target frequency effect	**9.82**	**3.21**	**3.06**	**−9.86**	**3.24**	**3.04**
	Display type for baseline	**21.34**	**3.69**	**5.79**	−6.93	4.75	1.46
	Display type * frequency	**−28.29**	**6.40**	**4.42**	**27.94**	**6.40**	**4.36**
Gaze Duration							
	Intercept	**254.13**	**8.69**	**29.25**	**270.60**	**11.96**	**22.62**
	Target frequency effect	**16.31**	**4.58**	**3.57**	**−16.50**	**4.57**	**3.61**
	Display type for baseline	**20.96**	**3.94**	**5.32**	−8.87	4.93	1.80
	Display type * frequency	**−30.04**	**6.48**	**4.64**	**30.00**	**6.44**	**4.66**
Go-Past Time							
	Intercept	**288.48**	**11.80**	**24.45**	**308.55**	**16.24**	**19.00**
	Target frequency effect	**20.02**	**7.58**	**2.64**	**−20.03**	**7.46**	**2.69**
	Display type for baseline	**22.34**	**7.42**	**3.01**	−2.44	6.40	0.38
	Display type * frequency	**−25.08**	**10.17**	**2.47**	**23.93**	**9.74**	**2.46**
Total Time							
	Intercept	**312.11**	**13.05**	**23.92**	**335.75**	**20.14**	**16.67**
	Target frequency effect	**23.56**	**9.37**	**2.52**	**−23.58**	**9.32**	**2.53**

Measure	Contrast	Model with High Frequency Baseline			Model with Low Frequency Baseline		
		b	**SE**	**|t|**	**b**	**SE**	**|t|**
	Display type for baseline	**42.63**	**7.88**	**5.41**	**18.80**	**7.78**	**2.42**
	Display type * frequency	**−23.82**	**8.74**	**2.73**	**23.96**	**9.19**	**2.61**

Table 4

Results of the logistic regression models for fixation probability measures across condition in Experiment 1. For fixation probability the intercept represents the mean of the high and low frequency preview conditions and the contrasts represents the difference between them. For regression probability models contrasts are specified similarly to the fixation duration models with the high frequency baseline. Significant effects are indicated by boldface.

Measure	Contrast	Overall Preview Benefit		
		b	**|z|**	**p**
Fixation probability				
	Intercept	**3.15**	**9.18**	**< .001**
	Preview frequency effect	0.29	1.58	.11
Regression out probability				
	Intercept	**−2.72**	**15.12**	**< .001**
	Target frequency effect	−0.14	0.92	0.36
	Display type for HF target	0.02	0.12	0.90
	Display type * frequency	0.04	0.12	0.90
Regression in probability				
	Intercept	**−1.93**	**12.48**	**< .001**
	Target frequency effect	0.08	0.75	0.45
	Display type for HF target	**0.78**	**5.20**	**< .001**
	Display type * frequency	−0.26	1.32	0.19

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Table 5

Results of the quantile regression analysis for the effect of preview frequency, target frequency, and their interaction at each of 10 Vincentiles in Experiment 1. Significant effects are indicated by boldface.

Vincentile	Intercept			Preview Frequency			Target Frequency			Interaction		
	b	**|t|**	**p**	**b**	**|t|**	**p**	**b**	**|t|**	**p**	**b**	**|t|**	**p**
0–.09	**151**	**154.54**	**< .001**	**9**	**4.34**	**< .001**	1	0.26	.80	1	0.26	.80
.1–.19	**171**	**178.07**	**< .001**	**13**	**6.77**	**< .001**	−2	1.04	.30	−2	0.52	.60
.2–.29	**188**	**150.69**	**< .001**	**16**	**6.41**	**< .001**	−1	0.40	.69	−6	1.20	.23
.3–.39	**205**	**152.33**	**< .001**	**19**	**6.87**	**< .001**	−1	0.19	.85	−9	1.67	.10
.4–.49	**224**	**144.51**	**< .001**	**16**	**5.16**	**< .001**	4	1.29	.20	−8	1.29	.20
.5–.59	**242**	**157.59**	**< .001**	**17**	**5.54**	**< .001**	**9**	**2.93**	**< .005**	−8	1.30	.19
.6–.69	**265**	**141.28**	**< .001**	**19**	**4.93**	**< .001**	**16**	**4.13**	**< .001**	**−17**	**2.26**	**< .05**
.7–.79	**296**	**125.39**	**< .001**	**13**	**2.75**	**< .01**	**22**	**4.66**	**< .001**	**−26**	**2.75**	**< .01**
.8–.89	**343**	**100.72**	**< .001**	13	1.83	.07	**31**	**4.48**	**< .001**	−23	1.69	.09
.9–.99	**560**	**37.93**	**< .001**	32	1.08	.27	**61**	**2.07**	**< .05**	2	0.97	.97

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Table 6

Means and standard errors, aggregated by subject, for reading time measures in Experiment 2.

Target Nonword	**Legal**		**Illegal**	
Preview Word Frequency	**High**	**Low**	**High**	**Low**
First Fixation Duration	251 (8.7)	265 (9.2)	248 (9.0)	266 (9.4)
Single Fixation Duration	254 (9.6)	273 (10)	256 (10)	278 (11)
Gaze Duration	300 (13)	315 (15)	289 (12)	313 (13)
Go-Past Time	335 (19)	360 (21)	321 (15)	350 (17)
Total Time	415 (27)	418 (26)	363 (22)	381 (21)
Fixation Probability	0.89 (.02)	0.92 (.02)	0.89 (.02)	0.93 (.02)
Regressions out	0.07 (.02)	0.10 (.02)	0.07 (.01)	0.09 (.02)
Regressions in	0.29 (.04)	0.25 (.03)	0.19 (.03)	0.16 (.03)

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Table 7

Results of the linear mixed effects models for reading time measures on the target across conditions in Experiment 2. The intercept represents the overall mean across all conditions, the first contrast tests for the effect of preview word frequency (averaged across target condition), the second contrast tests for the effect of target (legal vs. illegal; averaged across preview frequency), and the third contrast tests for the interaction between the effect of target type and preview frequency (i.e., non-significant interactions suggest additive effects). Significant effects are indicated by boldface.

Measure	Contrast	b	SE	|t|
First Fixation Duration				
	Intercept	**257.38**	**8.59**	**29.96**
	Preview frequency	**15.95**	**4.38**	**3.64**
	Target type	−0.85	3.22	0.26
	Preview * Target	4.70	6.59	0.71
Single Fixation Duration				
	Intercept	**265.13**	**9.83**	**26.96**
	Preview frequency	**19.87**	**5.53**	**3.59**
	Target type	3.75	3.39	1.11
	Preview * Target	4.06	6.58	0.62
Gaze Duration				
	Intercept	**303.98**	**12.80**	**23.74**
	Preview frequency	**19.52**	**5.38**	**3.63**
	Target type	−6.11	5.25	1.16
	Preview * Target	10.09	7.82	1.29
Go-Past Time				
	Intercept	**341.52**	**17.16**	**19.90**
	Preview frequency	**26.37**	**8.66**	**3.05**
	Target type	−11.82	8.37	1.41
	Preview * Target	3.21	10.33	0.31
Total Time				
	Intercept	**394.14**	**23.59**	**16.71**
	Preview frequency	10.98	6.12	1.80
	Target type	**−43.88**	**7.76**	**5.66**
	Preview * Target	15.01	10.80	1.39

Table 8

Results of the generalized linear mixed effects models for fixation probability measures on the target across conditions in Experiment 2. The intercept represents the overall mean across all conditions, the first contrast tests for the effect of preview word frequency (averaged across target condition), the second contrast tests for the effect of target (legal vs. illegal; averaged across preview frequency), and the third contrast tests for the interaction between the effect of preview frequency and target type (i.e., non-significant interactions suggest additive effects). Significant effects are indicated by boldface.

Measure	Contrast	b	|z|	p
Fixation probability				
	Intercept	**2.98**	**11.37**	**< .001**
	Preview frequency	**0.43**	**2.56**	**< .05**
Regression out probability				
	Intercept	**−2.81**	**13.82**	**< .001**
	Preview frequency	**0.41**	**2.74**	**< .01**
	Target type	0.02	0.10	0.92
	Preview * Target	−0.13	0.53	0.59
Regression in probability				
	Intercept	**−1.52**	**8.13**	**< .001**
	Preview frequency	−0.17	1.79	.07
	Target type	**−0.73**	**7.67**	**< .001**
	Preview * Target	0.06	0.35	0.73

Table 9

Means and standard errors, aggregated by subject, for reading time measures in Experiment 3.

Target Word Frequency	**High**		**Low**	
Preview Nonword	**Legal**	**Illegal**	**Legal**	**Illegal**
First Fixation Duration	248 (7.7)	252 (7.3)	252 (7.8)	259 (8.7)
Single Fixation Duration	259 (9.8)	263 (8.7)	266 (10)	271 (10)
Gaze Duration	280 (9.6)	286 (9.2)	289 (10)	296 (9.0)
Go-Past Time	333 (14)	334 (14)	341 (15)	348 (13)
Total Time	344 (12)	347 (11)	361 (14)	366 (13)
Fixation Probability	0.93 (.02)	0.94 (.02)	0.93 (.02)	0.93 (.02)
Regressions out	0.13 (.02)	0.12 (.02)	0.12 (.02)	0.13 (.02)
Regressions in	0.17 (.02)	0.16 (.02)	0.17 (.01)	0.15 (.01)

Table 10

Results of the linear mixed effects models for reading time measures on the target across conditions in Experiment 3. The intercept represents the overall mean across all conditions, the first contrast tests for the effect of word frequency (averaged across preview condition), the second contrast tests for the effect of preview (legal vs. illegal; averaged across target frequency), and the third contrast tests for the interaction between the effect of target frequency and preview type (i.e., non-significant interactions suggest additive effects). Significant effects are indicated by boldface.

Measure	Contrast	b	SE	|t|
First Fixation Duration				
	Intercept	**252.60**	**7.50**	**33.67**
	Preview type	5.03	3.86	1.30
	Target frequency	**5.44**	**2.73**	**1.99**
	Preview * Target	2.41	5.07	0.48
Single Fixation Duration				
	Intercept	**264.68**	**9.41**	**28.13**
	Preview type	4.36	3.53	1.24
	Target frequency	**8.13**	**3.26**	**2.50**
	Preview * Target	2.63	4.55	0.58
Gaze Duration				
	Intercept	**287.79**	**8.98**	**32.05**
	Preview type	6.70	5.13	1.30
	Target frequency	**9.43**	**3.07**	**3.07**
	Preview * Target	1.46	5.96	0.25
Go-Past Time				
	Intercept	**339.01**	**13.24**	**25.61**
	Preview type	5.86	7.24	0.81
	Target frequency	**11.55**	**4.72**	**2.45**
	Preview * Target	5.90	9.17	0.64
Total Time				
	Intercept	**354.34**	**11.69**	**30.31**
	Preview type	4.62	7.04	0.66
	Target frequency	**17.89**	**5.73**	**3.12**
	Preview * Target	3.77	8.60	0.44

Table 11

Results of the generalized linear mixed effects models for fixation probability measures on the target across conditions in Experiment 3. The intercept represents the grand mean across all conditions, the first contrast tests for the effect of word frequency (averaged across preview condition), the second contrast tests for the effect of preview (legal vs. illegal; averaged across target frequency), and the third contrast tests for the interaction between the effect of target frequency and preview type (i.e., non-significant interactions suggest additive effects). Significant effects are indicated by boldface.

Measure	Contrast	b	|z|	p
Fixation probability				
	Intercept	**3.75**	**10.40**	**< .001**
	Preview type	0.21	0.99	0.32
Regression out probability				
	Intercept	**−2.31**	**12.59**	**< .001**
	Preview type	0.07	0.61	0.54
	Target frequency	0.06	0.48	0.63
	Preview * Target	0.10	0.49	0.62
Regression in probability				
	Intercept	**−1.79**	**18.76**	**< .001**
	Preview type	−0.11	1.26	0.21
	Target frequency	0.02	0.23	0.82
	Preview * Target	0.06	0.32	0.75