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Causes and Consequences of Word Skipping during Reading: Evidence from the Co-Registration of Eye Movements and EEG

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by

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ABSTRACT

Skilled readers skip approximately one third of the words in the text while reading for comprehension (Rayner, 1998). Therefore, a prominent question for decades among reading and language researchers has been how people are able to recognize words and comprehend text without even looking at all of the words. Eye tracking studies have established that some information about an upcoming word in the text can be identified while still looking at the previous word (Rayner, 1975), but it remains an open question whether words that are skipped are thoroughly identified or if skipping decisions are based on shallow heuristic factors, such as low-level visual properties, rough identification of a word's familiarity, and expectations based on context cues. To address this question, two experiments were conducted that manipulated the predictability, familiarity, and subtle spelling errors of upcoming words while recording eye movements and electroencephalography (EEG). Brain responses were measured during fixations on the word that preceded the manipulated target word and trials were split based on whether the target word was skipped or fixated to determine whether skipped words were fully identified in the brain. Results showed that when words are skipped, they *can* be precisely identified while fixating the prior word before skipping. However, this thorough identification depends on having context-based expectations, on the familiarity of the word, and on individual differences in reading strategies.

CHAPTER 1: INTRODUCTION

During skilled reading, the eyes move rapidly across the text through a complex coordination of the oculomotor system and higher-level cognitive processing. A remarkable aspect of the reading process, and language processing more generally, is the incredible speed at which people are able to perform a complex task of (1) identifying the sensory input, (2) decoding abstract symbols, (3) retrieving linguistic and semantic information from memory, and (4) constructing message-level semantic meaning. On average, readers hold fixation on individual words for only around a quarter of a second (Rayner & Pollatsek, 2006) before moving their eyes to the next word. Furthermore, the average skilled reader *skips* (i.e., moves the eyes past a word without ever fixating) approximately one third of all words in a text (Rayner, 1998). Word skipping clearly contributes to reading speed, but an outstanding question is why readers choose to skip certain words and what consequences word skipping has on the accuracy and quality of comprehension. In this dissertation I present evidence that word skipping is indicative of deeper lexical processing of skipped words under certain circumstances, namely when processing of the skipped word is facilitated by sentence constraint. However, the data presented here also suggest that eye movements and higher level cognitive processing are not perfectly coupled and that eye movements across a text during reading are governed by a number of variables that make their interpretation more complex than has previously been assumed. I conclude that eye movement decisions are based on initial judgments about the familiarity and predictability of incoming stimuli, while deeper comprehension and recognition of semantic discrepancies unfolds further downstream after eye movement decisions have been initiated.

Decisions about where to move the eyes (i.e., saccades) and how long to pause the eyes in a given location (i.e., fixations) during reading are assumed to index underlying cognitive processes related to recognizing words and comprehending meaning (see Rayner, 1998). For example, longer fixation durations are assumed to reflect increased difficulty in word identification, regressive eye movements that back-track to an earlier point in the text indicate difficulty in syntactic and semantic integration, and skipping presumably indicates earlier and easier identification of the skipped word. Prominent models of eye movement behavior during reading (e.g., E-Z Reader, Reichle et al., 2006; SWIFT, Engbert, et al., 2005) propose that covert attention can be directed to upcoming words to begin processing them before looking directly at them. These upcoming words fall largely in the *parafoveal* region of the visual field (i.e., the region between 2-5 degrees of visual angle away from the central fixation point of the eyes; it is also characterized by poorer visual quality than the central *foveal* region). These models also assume that the decision of whether to skip or fixate an upcoming word is a function of the amount of lexical (i.e., word level) processing accomplished during this *parafoveal preview*.

However, the exact nature and threshold of the parafoveal pre-processing required to trigger a skipping decision remains an open question. For example, word recognition requires identifying individual letters, recognizing the perceived letter combination as a known word, and retrieving the word's meaning from memory. Some words are more familiar than others and some are more predictable in the context. So, the ease of identification may vary based on the unique combination of such characteristics. Most models of eye movement control assume that eye movement decisions during reading are based on some threshold of partial word identification. However, characterizing or quantifying this threshold that triggers a progressive eye movement proves complicated when so many variables can influence word recognition difficulty and the time course of contributing subprocesses.

A number of linguistic factors are known to influence reading efficiency and, more specifically, word skipping: predictability (i.e., the extent to which supportive context promotes the generation of expectations about upcoming words; Erlich & Rayner, 1981; Rayner & Well, 1996), frequency (i.e., the prevalence of a word in the language, as measured by counting its occurrences in a corpus language sample; Angele et al., 2014; Henderson & Ferriera, 1993), and plausibility (i.e., the extent to which a word fits intelligibly into the meaning of the text; Veldre & Andrews, 2017; Veldre et al., 2020; cf., Abbot & Staub, 2015; Schotter & Jia, 2016). Despite evidence that these properties influence parafoveal processing and the probability of word skipping, there is still quite a bit of unexplained variance in skipping decisions. Sometimes readers still choose to fixate (i.e., *not* skip) parafoveally viewed words that are highly predictable, familiar (i.e., high frequency), and plausible. Alternatively, words that are unpredictable, unfamiliar, and even anomalous (i.e., semantically nonsensical in the context) are sometimes skipped.

It is generally accepted among prominent reading researchers that even "words that are not fixated are clearly processed by the reader" (Rayner, 1998). Because word skipping is quite common, it seems implausible that skipped words are entirely disregarded without contributing to the construction of meaning. Ignoring a substantial portion of the text would likely be counterproductive to the goal of comprehension. However, decisions to move the eyes forward during reading do not necessarily indicate that a word has been *fully* identified. Instead, it has been suggested that eye movements are triggered by a cursory *familiarity check* (Reichle et al., 2006). In other words, a forward eye movement reflects a "hedged bet" (Schotter, 2018) that enough information has been extracted that the reader can reasonably assume that the word's meaning *will be* identified by the time the eyes move, even if semantic memory retrieval lags behind the eyes moving onward.

There is also some evidence that skipped words may not be processed in the same way as fixated words. For example, Eskenazi and Folk (2015b) used an eye tracking during reading session followed by a lexical decision task that contained target words from the reading task to test for repetition priming effects depending on skipping behavior. They found that reaction times in the lexical decision task to skipped words were significantly longer than those to fixated words. They propose that this pattern of reduced repetition priming for skipped words suggests that readers engaged in shallower processing, resulting in shallower memory encoding, relative to words that were fixated.

When it comes to the construction of meaning from language, a broader question is to what extent each word is actually recognized bottom-up (i.e., via processing of the perceptual input from the stimulus). In other words, does language comprehension depend on the identification of each individual letter and each individual word? Or is it better characterized as a rough approximation that is "'good enough' to satisfy the comprehender" (Christianson et al., 2001) regardless of whether the reader's interpretation is a faithful reproduction of the bottom-up input? When a word is skipped, has it truly been fully identified or rather have context cues and a rough familiarity check filled in for clear perceptual input and certainty about the word's identity? On the one hand, it may be that readers skip words because they did achieve bottom-up identification from parafoveal preview alone. On the other hand, skipping may be the result of top-down influences (i.e., representations constructed based on prior knowledge or expectations rather than the perceptual form) and heuristics taking over. It may reflect cases in which the reader 'decides' that scrutinizing and fully identifying the bottom-up input is unnecessary for achieving satisfactory comprehension.

Parafoveal Processing is Critical for Reading Efficiency

Readers can begin bottom-up processing of upcoming words before they even look at them directly (i.e., while they are still in the parafoveal visual field; Rayner, 1975). Studies on eye movements during reading have demonstrated that even this earliest stage of bottom-up word identification is influenced by a word's linguistic properties and semantic fit in a sentence. Whatever processing takes place for skipped words necessarily takes place during this parafoveal preview while the eyes remain on the previous word.

Rayner (1975) introduced an experimental paradigm that redefined the field of reading research, establishing that a substantial amount of word processing can occur before a reader even looks directly at a word. This paradigm employs a gaze-contingent visual display in which a word in a sentence changes depending on whether the reader's eyes are looking at words earlier in the sentence or are looking at the manipulated target word. The paradigm relies on eye tracking to determine the location of the readers' eyes in real time to change a displayed word embedded in a sentence, depending on which word in the display is currently being fixated. Generally, the identity of a particular *target* word in the sentence is manipulated so that a particular parafoveal preview word is displayed prior to a fixation on the target word. That word then changes to the target word as soon as the eye tracker detects that the eyes have crossed an *invisible boundary* located to the left of the space before the target word (see Figure 1). Comparing eye movement behavior in different parafoveal preview conditions allows us to draw inferences about the information that was extracted from the parafoveal preview.

Through the use of this paradigm, it has become clear that readers can pre-process the next word in a sentence while their eyes are still fixated on the preceding word. When the parafoveal preview of an upcoming word is identical to the word that is presented once they fixate it, fixation durations are significantly shorter compared to conditions in which the previewed word was different. This *parafoveal preview benefit* therefore demonstrates that some information about the word was extracted from the parafoveal visual field prior to directly fixating it, and this pre-processing contributes to reading efficiency by allowing the reader to get a head start on word identification while still fixating the preceding word (see Schotter & Rayner, 2012; see Schotter et al., 2013; see Vasilev & Angele, 2017).

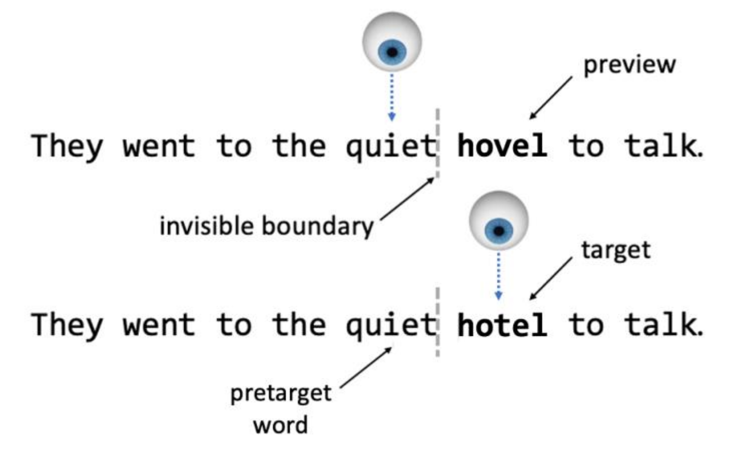

Figure 1

Example of the Gaze Contingent Boundary Paradigm (Devised by Rayner, 1975)

Visual vs. Linguistic Predictors of Word Skipping

To test the extent to which readers are capable of full identification and semantic retrieval during parafoveal processing (which is a necessary precondition for an account of word skipping that is contingent on full word identification), Schotter et al. (2015) manipulated the word's expectancy and semantic relatedness to the preceding context. They used previews that were synonyms of, semantically related to, or semantically unrelated to the target word. The eye movement patterns showed that synonyms of an expected target word, and even implausible but semantically related words, resulted in a significant parafoveal preview benefit compared to a semantically unrelated word. These effects of sentence constraint and semantic fit on the parafoveal preview benefit (i.e., reduced fixation durations on the target word) suggest that semantic activation *can* occur prior to directly fixating an upcoming word. However, full identification of a word's meaning parafoveally may require that some contextual preactivation has taken place. An open question is whether the depth of parafoveal semantic processing is greater still for skipped words.

The fact that readers *can* activate semantic features of a word in parafoveal vision has clear implications when it comes to word skipping. One possible hypothesis for explaining word skipping behavior, which I will refer to as a *thorough identification account*, is that when a word has been sufficiently identified parafoveally (i.e., when a word's semantic features are already being activated) there is no need to expend additional effort and time to get clearer (i.e., foveal) perceptual input. Alternatively, word skipping may not be yoked to extensive lexical or semantic processing and may be better explained by a *shallow heuristic account*. According to this account, skipping may be governed to a larger degree by various lower-level factors, such as visual features, rough familiarity verification, syntactic cues and part-of-speech inferences, as well as simple limitations of the oculomotor system (e.g., optimal saccade distance).

Frequency and Predictability Effects on Word Skipping

Three word properties that tend to reliably influence skipping rates are lexical frequency, predictability, and length (Kliegl, et al., 2004). These properties are critical for efficiency in the earliest stages of parafoveal word recognition and for reaching an activation or familiarity threshold that would allow for a word to be skipped. Predictability and frequency have been reported as having independent, additive effects on skipping rates (i.e., these effects do not interact; cf. Sereno et al., 2018), which has sometimes been interpreted as evidence that they influence separate, staged processes (Staub, 2020). Lexical frequency of a parafoveally viewed word can exert a significant influence on word skipping decisions even in the absence of strong predictions. This is true even when controlling for orthographic familiarity (i.e., the frequency of sub-lexical letter combinations and orthographic patterns within words; White, 2008), suggesting that the familiarity of the holistic lexical representation can be identified parafoveally rapidly enough to affect skipping decisions. Unlike predictability effects (i.e., shorter fixation durations and higher skipping rates in high constraint sentences, in which the context makes a particular word highly predictable), frequency effects in low constraint sentences rely initially on bottom-up decoding of orthographic forms (i.e., the specific combination of letters and their visual form that make up a unique word) to access a holistic lexical representation from memory. The bottom-up form is presumably more easily identified, once initially perceived, based on its representational strength in memory due to more frequent past exposures (Morton, 1969; Smith & Levy, 2013). Therefore, skipping decisions can be influenced both by top-down pre-activation of a word and by factors that contribute to the ease of bottom-up identification. Although eye tracking studies demonstrate that lexical frequency and predictability influence skipping rates, it remains unclear whether this is because (1) they allow for full identification of the parafoveal word or if (2) they serve to trigger skipping decisions regardless of whether the word has been thoroughly identified. An outstanding question, then, is whether the depth of parafoveal processing (e.g., identification of semantic features or prediction violations) varies systematically in association with word skipping decisions. Do instances of word skipping reflect cases of more extensive parafoveal processing? Alternatively, do decisions to fixate an upcoming word indicate less effective parafoveal word identification?

Eye Movement Planning: When vs. Where

As described in the previous section, reliable effects of various linguistic variables (e.g., lexical frequency, predictability, orthographic familiarity) on eye movements make it clear that oculomotor decisions are, at least in part, linguistically driven. Some researchers have argued, however, that although decisions about *how long* to spend fixating a word and *when* to move on are tied to linguistic processing, word skipping and decisions about *where* to move the eyes are largely explained by low-level visual properties of the text. By this account, the actual linguistic content of upcoming words plays a minimal role in these decisions about *how far* to move the eyes once the decision has been made that it is time to move. Some evidence for the proposal that *when* (i.e., fixation durations) and *where* (i.e., saccade distance and direction) decisions are governed by different mechanisms comes from findings that fixation durations on a word and their corresponding saccade amplitudes (both when moving to fixate the word and then moving away to fixate the next word) are not correlated (Rayner & McConkie, 1976). A recent large-scale corpus study investigated the relative variance in fixation durations and word skipping during natural reading that can be explained by word predictability, the availability of parafoveal information, and lower-level features of current fixation position and word length (Heilbron, et al., 2023). Their analyses showed that predictability was a significant predictor of fixation durations, but that variation in skipping behavior was best explained by a simple oculomotor model that took only fixation position and word length into account. These conclusions hearken back to theories dating back to the early 20th century that eye movements are generally controlled by an autonomous control center and that saccade amplitudes are relatively invariable but can be adjusted based on the general difficulty of the text or the task being performed (Huey, 1908; Hochberg, 1976).

Furthermore, it has also been well-established experimentally that word length is the strongest single predictor of skipping probability, with higher skipping rates for shorter words (Brysbaert & Vitu, 1998; Drieghe et al., 2004; Slattery & Yates, 2018). Brysbaert & Vitu (1998) also performed a meta-analysis of all of the studies that had been conducted at that time that manipulated parafoveal word difficulty and found that skipping rates were modulated by approximately 4% based on the frequency of the parafoveal word, 9% based on its predictability, and up to 50% based on word length (ranging from 2 - 9 character words). In a similar vein, Brysbaert and Mitchell (1996) demonstrated that variation in skipping rates can largely be accounted for by the launch position of the saccade away from the previous word (i.e., the location of the fixation on the previous word immediately before initiating the saccade to or past the next word). This effect of launch position prior to a skipping decision suggests that saccades have an optimal length and that words may be skipped simply as a function of their proximity to the previous fixation. Therefore, some existing eye tracking evidence refutes the thorough identification account of word skipping.

However, the influence of close launch position could also be attributed to the higher perceptual quality of the parafoveal preview. Visual acuity is better when the parafoveally perceived word is closer in space to the fixation on the preceding word (i.e., when the eyes have fixated closer to the end of the preceding word and the beginning of the upcoming word). Rayner et al. (1996) demonstrated that close launch position predicts higher skipping rates, but also found that this effect interacts with lexical frequency such that the effect of launch position is greater for high frequency words. This pattern suggests, then, that launch position effects are not purely based on spatial and motor constraints, but also interact with linguistic processing by modulating the perceptibility of the parafoveal preview. Therefore, eye tracking data support the premise that decisions about whether to fixate or skip upcoming words depends to some extent on the spatial distribution of the text in the visual field and the average amplitude of a typical saccade. But, there is also plenty of evidence that linguistic factors (e.g., frequency and predictability) play at least some role in decisions about how far forward to move the eyes (i.e., whether to skip or fixate an upcoming word).

Eye tracking studies have clearly made substantial headway in determining the factors that tend to influence word skipping, and the relative magnitude of their contributions. However, it remains unclear exactly what word skipping indicates about the underlying cognitive processing of the linguistic (and semantic) information that was skipped. If skipping is driven largely by visuospatial and word length properties, what happens when a low frequency or unpredictable word is skipped? Has enough information extracted from parafoveal vision to complete word recognition and semantic integration of that more difficult word? If not, is the missing visual and linguistic input simply filled in with the most likely word to have been there based on context cues and whatever minimal visual information was identified parafoveally? Unfortunately, eye movements alone cannot distinguish between these opposing accounts because they reflect the resulting behavioral decisions, but not necessarily the contributing or ensuing brain processes. Although eye movement data alone may not be sufficient to answer these questions, behavior-contingent neural responses tied to these eye movement decisions may provide the missing link.

The N400 Event-Related Potential Component

Event-related potentials (ERPs; i.e., time-locked brain responses to a stimulus or event extracted from raw electroencaphalogram (EEG) recordings) have advantages over eye movements when it comes to providing a more detailed account of the underlying brain processes that unfold continuously in time (in contrast to the punctate decisions reflected in eye movement measures). For example, the brain activity elicited during parafoveal preview of skipped words can be extracted to reveal whether or not skipped words are thoroughly identified. Skipping behavior is measured as a binary variable, so any graded effects or nuances in the nature of parafoveal processing that contribute to these decisions are not observable based on the eye tracking record alone.

One of the most well-studied language-related ERP effects is the N400 component, a negative-going deflection in the ERP signal that peaks around 400 ms after the presentation of, or start of an eye fixation on, a semantically informative stimulus. In the context of language comprehension, the N400 amplitude is reduced for an expected or contextually appropriate word compared to an unexpected, anomalous, or otherwise inappropriate word given the context (Kutas & Federmeier, 2011). Therefore, the absence or presence of an N400 response to skipped versus fixated parafoveal words can reveal the extent to which the word was identified as being contextually expected and semantically appropriate or not.

Although the N400 is broadly characterized as an index of semantic processing difficulty, some sub-lexical manipulations can also affect this component. For example, N400 effects are reduced for anomalous orthographic neighbors (words that share all but one letter; e.g., *hovel* and *hotel*) of expected words compared to violations that are not orthographic neighbors and are both semantically *and* orthographically unexpected (Laszlo & Federmeier, 2009). This sensitivity to the visual composition of a word suggests that semantic expectations can also feed down to expectations about a word's orthographic form and that the N400 is responsive to both semantic and sub-lexical expectancy. These effects are driven by the presence of expectations because they are not apparent in low constraint sentence contexts (Caliskan, Milligan, & Schotter, 2023). Furthermore, N400 effects of expectancy violation are larger when the sentences are more constraining, and the N400 response is more negative to plausible words in low compared to high constraint contexts (Wlotko & Federmeier, 2012). Therefore, the N400 provides an index of word identification and semantic access that can be used to test the depth of parafoveal word processing when words are skipped.

The N400 effect has been reported for semantic fit manipulations presented in parafoveal vision (Barber et al., 2010, 2013; Milligan, at al., 2023a; Payne, et al., 2019; Schotter, et al., 2023; Stites, et al., 2017), suggesting that readers may be able to access semantics and identify the semantic fit of a word parafoveally. If this is the case, it suggests that semantic access may occur early enough to contribute to saccade planning decisions, including word skipping. However, existing studies of the parafoveal N400 primarily use high constraint sentences (i.e., sentences in which a particular word is rendered highly predictable). Therefore, the observed parafoveally elicited N400 effects may reflect violations of orthographic expectations and not necessarily semantic retrieval for words in parafoveal vision (Nestor et al., in prep). If so, the N400 may instead indicate that parafoveal processing serves primarily as an "expectancy check" and a head-start on processing lower-level features of a word. Identification of an unexpected orthographic form may then inform hedged bets about when and where to move the eyes, even in the absence of semantic access. Full recognition and semantic integration, on the other hand, may depend more heavily on processing that takes place during (and/or following) foveal fixations. One potential way to differentiate whether the parafoveal N400 is semantically or orthographically driven would be to present parafoveal preview words that are orthographically highly similar to an expected word, but semantically anomalous (i.e., an orthographic neighbor).

Co-registration of Eye Tracking and EEG

The field of psycholinguistics and ERPs (in the visual domain) has traditionally relied on rapid serial visual presentation (RSVP; Kornrumpf, et al., 2016), which has advantages and limitations. Because ERPs require timelocking to the onset of an event of interest, RSVP importantly allows for rigorous control over the timing of individual word presentation and timelocking of that event to the neural response. Additionally, eye movements introduce ocular artifacts into the EEG recording from oculomotor and muscular sources that are not part of the brain response. However, as Kornrumpf et al. (2016) point out, the time-invariant serial presentation of single words in a sentence in central vision eliminates key aspects of the reading process, including “parafoveal preprocessing, saccade execution, and the fast changes in attentional processing load occurring from fixation to fixation”. Therefore, while the RSVP method has been quite fruitful for understanding visual language processing in the brain, it is not necessarily reflective of the processes required for natural reading. Because much of the work on brain responses to visual language processing comes from the RSVP paradigm, it is also worth establishing whether these typical ERP effects to sentence-embedded words presented serially, foveally, and at a fixed presentation rate hold up in a more naturalistic scenario where the reader has agency over where to direct attention, how long to view each word, and whether to skip words or regress to previous words in the sentence.

In recent years, methodological and computational advancements have allowed for the simultaneous recording and synchronization of eye movements and ERP responses (see Degno et al., 2021; see Dimigen et al., 2011; see Nikolaev et al., 2016). Combining eye tracking during natural reading and EEG provides a solution to these limitations of the RSVP paradigm and allows for studying visual language comprehension in a more ecologically valid way. Using co-registration, it is possible to use information from the eye movement record to time-lock neural responses to the onset of a fixation on a particular word. Additionally, innovations in computational methods of removing oculomotor artifacts (Dimigen, 2020) and separating overlapping brain responses to temporally proximal fixations (Ehinger & Dimigen, 2019) have provided solutions to previous methodological impediments to measuring ERPs in free-viewing scenarios such as natural reading. Although the simultaneous recording and synchronization of

EEG and high-resolution eye tracking is an emerging technique, a number of studies have already successfully demonstrated that established N400 effects to sentence-embedded manipulations of predictability (Dimigen et al, 2011; Kretschmar et al., 2015), syntactic and semantic contextual fit (Antunez et al., 2022; Metzner et al., 2017), and lexical frequency (Milligan, et al., 2023b) can be detected during natural reading with free eye movements. As such, the co-registration of eye-movements and EEG provides a unique opportunity to reveal both the differential time course and nature of language processing during reading when words are skipped versus fixated, and the relationship between brain and behavior more generally. More specifically, this method has the potential to reveal whether the neural processes associated with word skipping decisions reflect thorough identification during parafoveal processing or shallow heuristically-informed identification.

As described above, the N400 ERP component is assumed to reflect activation of semantic (or sub-lexical) features from long term memory in response to semantically informative stimuli (e.g., words). Therefore, measuring this component time-locked to fixations that precede a decision to either skip or fixate an upcoming word can reveal whether skipping decisions are associated with larger responses to expectancy violations in the parafovea. Comparing trials in which the target word is skipped compared to those in which the manipulated word is ultimately fixated can then distinguish whether skipping is associated with more or less extensive bottom-up parafoveal processing compared to when the reader decides to fixate.

When it comes to behavior-contingent FRP effects, only a single study has yet attempted to tie eye movement decisions to variations in the underlying neuro-linguistic processing. Metzner et al. (2017) manipulated the semantic and syntactic fit of words in natural sentence reading and found differences in the FRP effects to these manipulations based on regressive eye movements. The P600 component, which has been functionally tied to syntactic processing difficulty and structural reanalysis (e.g., Osterhout & Holcomb, 1992), was larger in response to the syntactic anomaly condition on trials in which the reader made a regressive eye movement. Therefore, they demonstrated that differences in eye movement decisions can reflect differences in the underlying brain processes involved in language processing at the individual trial level. In the current experiments, I employ a similar approach to investigate whether skipping decisions reflect distinctly unique scenarios of deeper parafoveal word processing.

Overall, the current investigation is one of the first to attempt to tie behavior to brain responses during reading. One novel contribution of the current studies lies in the ability to connect disparate literatures that have studied language processing using ERPs and eye tracking. In both methodologies, one of the primary questions has been how the representations constructed from the immediate message-level context influence language comprehension (i.e., the role of predictability). Additionally, a key factor of interest when it comes to word recognition has long been the role of an individual's prior experience with a to-be-recognized word (i.e., lexical frequency). When it comes to the field of ERPs and psycholinguistics, limitations of ecological validity have been accepted as a necessary obstacle (due to the use of the RSVP paradigm). In the field of reading research, eye tracking has been an invaluable tool for studying more naturalistic patterns of behavior based on such language characteristics as predictability and lexical frequency. However, eye movement patterns do not necessarily reflect the unfolding of complex brain processes just as ERPs to serially presented single words do not necessarily reflect the full neural processes required for the task of reading. Therefore, in order to bridge these two adjacent and longstanding sub-fields of the psychology of language, the method of co-registering brain responses and eye movement behavior is crucial.

The Current Studies

The experiments in this dissertation seek to contribute a more nuanced understanding of the cognitive processes involved in programming eye movements and processing linguistic content during the complex task of reading. More specifically, the current experiments were designed to test (1) how a word's predictability and familiarity influence parafoveal processing and (2) the extent to which these factors and the underlying brain responses contribute to the reading behavior of word skipping and the comprehension of skipped words.

To achieve a more detailed understanding of the extent of processing that can be achieved parafoveally, and how various levels of representation contribute to behavioral decisions and the depth of language processing, I conducted two experiments that implemented the gaze-contingent boundary display-change paradigm to investigate parafoveal word processing. In Experiment 1, I manipulated the semantic predictability of the word (via a manipulation of sentence constraint) as well as whether the parafoveal preview was the predicted word or was incorrect but orthographically similar to the predicted word. The preview manipulation included an identical expected/plausible condition and a condition in which the preview was an orthographic neighbor (i.e., a real word that differed by a single letter) of an expected/plausible word. In doing so, I intended to test whether parafoveal processing involves roughly matching a perceived low-fidelity stimulus to an expected (or plausible) word or whether readers can in fact perform precise bottom-up word identification parafoveally. By manipulating the target word's predictability, I also tested whether the capacity to perform precise bottom-up word recognition depends on having strong expectations about the upcoming word.

In Experiment 2, I manipulated the lexical frequency of the parafoveally perceived word in high constraint sentences to test whether precise parafoveal word identification depends on the word's familiarity. Here, the sole manipulation was of the identity of the parafoveal preview word as (1) the expected word, (2) an orthographic neighbor anomaly, or (3) the high frequency function word *the*. To maximize the proportion of target word skipping trials and to match the length of *the*, all previews were three letters in length.

In both experiments, I simultaneously recorded eye movements and electroencephalography (EEG) and synchronized these separate data streams to identify differences in brain responses based on skipping behavior as well as the circumstances that contribute to that behavior. Fixation-related potentials (FRPs) were then time-locked to the initiation of eye fixations on the pretarget word (i.e., the word preceding the parafoveal preview manipulation) during natural reading with the goal of better understanding how brain processes involved in language comprehension influence and are modulated based on eye movement behaviors. In order to differentiate the extent of the underlying cognitive processing that accompanies each of these word skipping scenarios, I split trials based on whether the reader chose to skip or fixate the upcoming word to test whether the behavior of word skipping is in fact diagnostic of extensive linguistic processing or is instead the result of lower level cognitive factors such as oculomotor constraints, heuristics based on word length, etc. or top-down "filling-in-the-blank".

CHAPTER 2: SKIPPING-CONTINGENT EFFECTS OF PREDICTABILITY AND SUBTLE FORM VIOLATIONS ON THE PARAFOVEAL N400 (EXPERIMENT 1)

Experiment 1 was designed to test the effect of target word predictability on the depth of parafoveal processing and the interaction between predictability and skipping behavior on the N400 response to subtle orthographic anomalies (which are also semantically implausible). Constraining sentence context and expectations about the identity of an upcoming word can also influence the magnitude of this preview benefit (Balota et al., 1985). For example, Veldre and Andrews (2018) investigated the influence of sentence constraint on parafoveal word processing using a gaze-contingent display change. They observed a significantly larger preview benefit (i.e., reduced fixation durations on the target word when the parafoveal preview was the expected word compared to a different but plausible word) in high constraint compared to low constraint sentences. This pattern suggests that the parafoveal preview benefit can be enhanced by contextually-driven expectations. Furthermore, words can be predicted at various levels of representation. For example, a sentence context could result in the pre-activation of various semantic features of likely upcoming words without a single lexical prediction emerging. If a context is constraining enough, the visual and orthographic features of a specific word may also be pre-activated before it is encountered bottom-up (e.g., DeLong et al., 2021).

Skipping rates have been shown to be modulated by sentence constraint and word predictability (Balota, et al., 1985; Drieghe et al., 2005; Rayner & Well, 1996), which raises the question of whether processing of a bottom-up word form is amplified by the strength of expectations. Depending on a words' predictability then, there may be a number of ways in which prediction could contribute to word recognition efficiency and skipping decisions. For example, it may be the case that strong predictability allows for word skipping through the pre-activation of orthographic form (Laszlo & Federmeier, 2009). This may in turn result in a quick verification process in which the rough bottom-up input extracted from parafoveal vision is compared to these orthographic predictions generated ahead of time. Alternatively, it is possible that strong expectations instead reduce the reliance on bottom-up orthographic decoding, particularly if a parafoveal word form is similar to an expected word. Therefore, skipping of a predictable word may either be reflective of more thorough word identification or may be reflective of the strong top-down representations leading to shallower heuristic-based decisions and "good enough" bottom-up processing.

When a sentence is not constraining enough to generate a singular lexical prediction, semantic features may be pre-activated (e.g., Lai et al., 2023; Schotter & Jia, 2016), but it may be more effortful to map the perceived orthographic form onto a lexical candidate. In these cases, semantically shallower sources of information (e.g., word length, expected syntactic class, or lexical frequency) might serve as heuristics to push the needle of word recognition toward a threshold that would allow for skipping. Additionally, it may be that subtle orthographic anomalies are not detected parafoveally in low constraint sentences and that the lack of expectations results in less precise bottom up processing, but that the reader can fill in the skipped word based on some information about the orthographic form and semantic retrieval of a plausible word that roughly matches the perceived form. In this case, a subtle orthographic anomaly may not elicit an increased N400 response based on the poor semantic fit of the parafoveal preview.

To test these alternative explanations, the current experiment uses the N400 response to the parafoveal word form as an index of the precision of bottom-up word recognition. If strong sentence context results in a larger parafoveal N400 effect to a subtle orthographic violation, it would suggest that sentence constraint facilitates precise bottom-up word recognition rather than reducing sensitivity to a subtle violation in lieu of shallower context-driven processing. Furthermore, if this effect is larger when a word is skipped, it would provide evidence that skipping behavior for highly predictable words is driven by the reader having achieved more extensive word identification parafoveally. A reduced N400 effect when a word is skipped in a low constraint context might also suggest that word skipping is driven by a fundamentally different process when readers skip an unpredictable word. For example, in high constraint contexts, skipping may be a good index that extensive lexical processing took place, while in low constraint, skipping may be more reflective of lower-level factors such as optimal saccade length or word familiarity, while not necessarily being indicative of fully identifying the word's orthographic form or semantic fit in the sentence.

Hypotheses

1. The N400 response to a parafoveal orthographic/semantic anomaly will be larger in high compared to low constraint sentences.
2. The N400 response will be larger when a word is skipped.
3. The N400 response will be largest in the high constraint sentences AND the word is skipped (i.e., there will be an interaction between constraint and skipping on the N400 response).

Method

Participants

Seventy-three participants were recruited from the Psychology Department's SONA subject pool at the University of South Florida and compensated with course credit or recruited through flyers and mailing lists and paid $16/hour for their time. All participants were right-handed native English speakers between ages 18 and 35 with normal or corrected-to-normal vision and no history of reading, learning, or neurological disorders. Participants provided informed consent via an online consent form approved by the University of South Florida. Data from 56 participants are reported in the final analyses; 4 participants were excluded due to synchronization issues with eye-tracking and EEG files, 3 participants did not finish the experimental procedure due to excessive EEG artifacts and/or disconnected electrodes during recording, and an additional 6 were excluded after data processing because of EEG artifact exclusions for at least 30% of trials, and 4 were excluded due to eye tracker/display change errors on at least 20% of trials. All retained participants had at least 6 observations in all conditions for both EEG and eye tracking (mean = 18.32, SD = 4.45).

Stimuli and Design

The experimental stimuli, taken from Milligan & Schotter (2024) consisted of 112 unique target words presented in a 2 (Sentence Context: High Constraint vs. Low Constraint) x 2 (Preview Type: Identical, Orthographically Similar Anomaly)[1] factorial design; see (1a) and (1b) for examples of high and low constraint sentences, respectively, with the two preview conditions in parentheses. The experimental conditions were counterbalanced across sentence items and presented in a random order. Participants saw each target word in both the high and low sentence constraint conditions, but the counterbalancing was such that participants never saw a given target word in the same preview condition. The full experimental stimulus set can be found at https://osf.io/xcq28/. Additionally, there were 58 filler sentences to obscure the design of the

[1] The full experiment included a third preview condition, which was a homophone of the target word. This condition was excluded for the purposes of this dissertation but the information about the stimulus characteristics and results can be found in the published version of this study, Milligan et al. (2024)

study, which were all low constraint and contained a lexical frequency manipulation (taken from Schotter & Leinenger, 2016).

(1a) The boy bought his crush a single red (**rose/road**) rose for Valentine's Day.

(1b) The thoughtful man bought a beautiful (**rose/road**) rose for his wife.

The lexical characteristics for the target and preview words are reported in Table 1. The pretarget words were also roughly matched on length and frequency between the two constraint conditions; high constraint pretarget words were, on average, 6.2 characters long (SD = 2.3) and had a lexical frequency of 3.1 (SD = 2.3) and low constraint pretarget words were 6.2 characters (SD = 1.9) with a frequency of 3.2 (SD = 1.9).

Table 1

Descriptive Statistics of Lexical Characteristics for Target and Anomalous Preview Words

	Target Word	Anomalous Preview
Length (characters)	4.4 (0.8)	4.4 (0.8)
Frequency	3.00 (0.91)	2.98 (0.86)
Orthographic Similarity to Target (Van Orden Index)	–	0.52 (0.10)

Note. Means are reported with standard deviations in parentheses. Target and preview words were always matched on length. Frequencies are log SUBTLWF (Retrieved from the English Lexicon Project (https://elexicon.wustl.edu/index.html); Balota, et al., 2007).

As described in Milligan and Schotter (2024), sentence stimuli were normed for sentence constraint (i.e., cloze probability for the target word; Taylor, 1953) and plausibility (i.e., a 7-point Likert scale from 1, Very Poorly Written to 7, Very Well Written). The proportion of times the target word was produced in the cloze task was, on average, .75 (SD = 0.18) in the high constraint sentences, and .02 (SD = .04) in the low constraint sentences. The average plausibility ratings on a scale of 1 (very poorly written) to 7 (very well written) in the high constraint sentences and low constraint sentences respectively, were 5.36 (SD = 0.51) and 5.29 (SD = 0.61) for the target word and 3.22 (SD = 0.54) and 3.23 (SD = 0.64) for the orthographic anomaly.

Apparatus and Recording

EEG was recorded from 32 Ag/AgCl active electrodes (extended 10/20-system) using an actiCAP/actiCHamp electrode cap and amplifier system (Brain Products) with a 500 Hz online sampling rate. No online frequency filters were used during recording. Horizontal and vertical electrooculogram (EOG) was recorded from two pairs (bipolar reference) of passive electrodes placed on the outer canthi of each eye and above and below the right eye. The scalp electrode signal was referenced online to the left mastoid and re-referenced offline to the algebraic mean of the right and left mastoids. Impedance values were reduced to 10 kΩ or lower at all electrode sites prior to recording.

Eye movements were recorded using an SR Research Ltd. Eyelink 1000 Plus eye tracking camera in remote desktop mode (sampling rate of 500 Hz). Viewing was binocular, but eye movements were recorded from the right eye. A three-point calibration was used at the beginning of the experiment and calibration accuracy had to fall within .3° of visual angle at each point to be accepted. Re-calibration was performed periodically throughout the experiment if accuracy dropped below this level, as determined by an inter-trial drift check.

Procedure

Participants were seated at a viewing distance of 60 cm from a BENQ XL2540 model LCD monitor with a 240 Hz refresh rate and screen resolution of 1920 x 1080 pixels. Participants were instructed to read the sentences normally for comprehension. They were given 5 practice trials to acclimate them to the task. The sentence text appeared on the screen in black

12-point Courier New (monospaced) font on a light gray background. Both experimental and filler sentences were followed by yes/no comprehension questions on 25% of trials, with equal numbers of yes and no correct responses, to ensure that participants read the sentences for meaning. Each trial was initiated by the experimenter after a drift check of the eye tracker. To trigger the presentation of the sentence, the participant had to make a fixation in a black box on the left side of the screen at the location of the beginning of the sentence. Participants were instructed to look at a target sticker on the right edge of the monitor (off screen) once they finished reading for comprehension and the trial was terminated by the participant via a manual button press when they had finished reading.

The gaze-contingent boundary paradigm (Rayner, 1975) was used to present the manipulation of sublexical information only in parafoveal vision; readers therefore only ever fixated on semantically correct words and were less likely to notice the manipulation and alter their behavior or neural processes for strategic reasons. An invisible boundary was placed immediately after the last letter of the pretarget word, before the space before the target word; prior to fixating the target word, the preview word was visible (one of the Preview Type conditions). The target word replaced the preview within approximately 5-10 ms of the eye tracker detecting that the boundary had been crossed. After the experiment, participants were asked whether they noticed anything unusual about the sentence display. Three participants reported noticing a specific word change. If they did not report noticing anything unusual, we then asked if they noticed words flickering or changing. When prompted, 24 participants said they noticed some flickering on between 1 and 10 of the trials.

Data Cleaning and Preprocessing

Eye-tracking data were cleaned using the DataViewer program (SR Research Ltd., version 4.3.1) and fixations in any of the predefined interest areas were merged with a neighboring fixation if their duration was below 80 ms and they were within 0.3° horizontally. Trials were excluded from analyses due to eye tracking data loss, display change errors, pretarget word skipping, and first-pass refixations on the pretarget word (i.e., were not single fixations). The total number of trials before other exclusions was 12526 (out of 12544 total trials presented; the 18 missing trials were from either the participant or experimenter manually terminating a trial accidentally before the sentence was presented. Of these 12526 trials, 8646 had single fixations on the pretarget word. Of these 8646 trials, 230 were excluded due to: j-hooks (i.e., oculomotor error in which the saccade overshoots the fixation point and triggers the display change but returns back to the pretarget word prior to fixating), fixations near the right edge of the pretarget region in which a sample that crossed the boundary triggered the display change (despite the fixation being identified as within the pretarget region), unstable calibrations, and any other erroneous early triggering of the display change. These trials were identified based on manual inspection of all eye tracking trials using the eye movement/fixation visualization application in Data Viewer, leaving 8416. EEG epochs were extracted by identifying fixations in the pretarget region of interest that were not preceded within 600 ms by another pretarget fixation and that were followed within 600 ms by a fixation on either the target word (target fixated trials) or by a fixation on the end of sentence region (target skipped trials). After merging the eye tracking data with the EEG data, 7270 total trials were retained that met these criteria. Of these 7270 trials, 1115 trials were excluded due to EEG artifacts, leaving 6155 trials. Finally, trials were excluded if the target word was fixated but followed by a regression out of the target region rather than a forward saccade, resulting in a total of 5937 trials retained for the pretarget time-locked FRP analysis.

EEG data preprocessing was performed using the EEGLAB (v2019.0/v.2021.0; Delorme & Makeig, 2004), ERPLAB (v8.02; Lopez-Calderon & Luck, 2014) and EYE-EEG (v0.85; Dimigen, et al., 2011) toolboxes in Matlab. The EEG was re-referenced offline to an algebraic mean of the right and left mastoids and band-pass filtered from 0.1-50 Hz (-6dB), with 0.2 - 32.8 Hz half-power (-3dB) cutoffs, using an IIR Butterworth filter. Ocular artifacts were removed from the EEG using optimized independent components analysis (OPTICAT, version 2020-01-28), following the procedures and recommendations described in Dimigen (2020). The ICA was trained using band-pass filtered (with a passband edge of 3 Hz) training data that over-weighted spike potentials by a factor of 1. Ocular artifact components were automatically flagged and removed using eye tracker-guided eye artifact component identification (Plöchl, Ossandón & König, 2012), using a variance ratio threshold of 1.1. EEG was epoched into segments from 200 ms before to 1000 ms after the start of fixations on the pretarget and target words and baseline corrected by subtracting the mean voltage from -200 to 0 ms for each channel. Epochs containing artifacts were flagged for removal using a moving window peak-to-peak threshold automatic artifact detection algorithm, rejecting epochs with voltage changes of greater than 100 μV within a 200 ms time span, with a 50 ms window-step. The epoched data were also inspected manually to confirm that artifact-contaminated epochs were removed. The resulting dependent variables from the eye tracking and EEG data were exported from their respective processing softwares and were merged at the trial-level for confirmatory analyses in R.

Results

The primary dependent variable was the parafoveal N400 FRP (i.e., the amplitude averaged across a centroparietal ROI (C3, C4, Cz, CP1, CP2) from 300 - 500 ms post-fixation time-locked to single fixations on the pretarget word (i.e., the time point at which the preview was visible parafoveally). The ROI was selected a priori to include a representative selection of electrodes surrounding Cz and including centro-parietal sites because the N400 has typically been described as being maximal centro-parietally (e.g., see Kutas & Federmeier, 2011). In order to understand these responses in the context of eye movement behaviors, we also analyzed pretarget single fixation durations (to assess whether the preview had any effect on pre-target word fixations) and target word skipping rates (see Table 2 for descriptive statistics). In order to ensure that the eye tracking skipping analysis aligned as closely as possible with FRP analyses, target skipping rates were only assessed for trials with single fixations on the pretarget word and trials in which first pass fixations on the pretarget and target words were followed by forward saccades (i.e., excluding trials with regressions out of the pretarget or target words).

All analyses were performed using (generalized) linear mixed-effects regression models via the glmer() function (i.e., with a logit link for the binary outcome measure of skipping) and the lmer() function (i.e., for the FRP measures) from the lme4 package (version 1.1-12; Bates et al., 2015) within the R Environment for Statistical Computing (version 3.3.1). The fixed effects contained main effects for parafoveal preview condition (Identical, Orthographically Similar Anomaly) and sentence constraint (High vs. Low), as well as their interactions. Preview condition was coded as a sum-to-zero contrast, comparing the identical to the anomalous preview. Sentence constraint was entered as a treatment contrast, with the high constraint condition as the baseline so that the main effects of the preview and skipping contrasts represent the main effects at the level of high constraint. For the FRP analyses splitting by skipping behavior, skipping was entered as a treatment contrast with target skipped trials as the baseline. All models initially included the maximal random effects structure, but in cases of non-convergence, random effects were removed in a stepwise fashion, starting with interaction slopes, followed by main effect intercepts in the order of least amount of variance accounted for, until the models converged.

Table 2

Descriptive Statistics of Eye Movement Measures: Means (SDs)

	High Constraint		Low Constraint	
	Identical Preview	Orthographic Anomaly Preview	Identical Preview	Orthographic Anomaly Preview
Pretarget Skipping Rate	.25 (.11)	.22 (.11)	.21 (.11)	.22 (.12)
Pretarget SFD	249 (34)	253 (34)	258 (33)	256 (42)
Target Skipping Rate	.45 (.24)	.41 (.21)	.43 (.23)	.41 (.22)
Target SFD	240 (38)	272 (45)	265 (47)	292 (42)
Target GZD	246 (41)	279 (35)	275 (53)	302 (46)

Note. All means and SDs are computed based on subject-level aggregated data.

Pretarget Word Single Fixation Duration

The analysis of SFD for the pretarget word revealed a significant main effect of sentence constraint ($b = 6.42$, $t = 3.22$, $p < .05$), with shorter fixation durations in high compared to low constraint sentences. Note that this main effect reflects the differences between the sentence contexts themselves, not anything about the preview. A word preceding an expected target word in a high constraint sentence is likely to be more predictable than an analogous pretarget word in a low constraint sentence. Therefore, these effects likely reflect more global effects of the constraint manipulation as expectancy builds across the sentence. There were no significant main effects of preview condition nor were there any significant interactions between preview condition and sentence constraint. I also performed a follow-up analysis predicting pretarget SFD by target word skipping behavior, constraint, preview, and their interactions to assess whether the presence of parafoveal-on-foveal effects depended on target skipping behavior and we still found no main effects or interactions of preview condition on pretarget SFD. This lack of significant preview effects are advantageous for our FRP analyses because they indicate that differences in the timing of saccades away from the pretarget word (and consequently the timing of the initiation of fixations on the target or post target words) are unlikely to explain any substantial differences between the preview conditions with respect to fixation timing jitter impacting averaged neural responses.

Target Word Skipping Rate

To maintain consistency between the eye movement and FRP data included in analyses based on skipping, the data included in the skipping rate analyses and figures includes only trials with single fixations on the pretarget word and forward saccades (i.e., excluding trials with regressions out of the pretarget or target regions on the first pass). The main effect of sentence constraint was not a significant predictor of target word skipping. In the high sentence constraint condition (baseline in the model), there was a significant effect for preview condition, with higher skipping for the identical preview. The interaction between preview condition and sentence constraint was not significant (see Figure 2, Table 3).

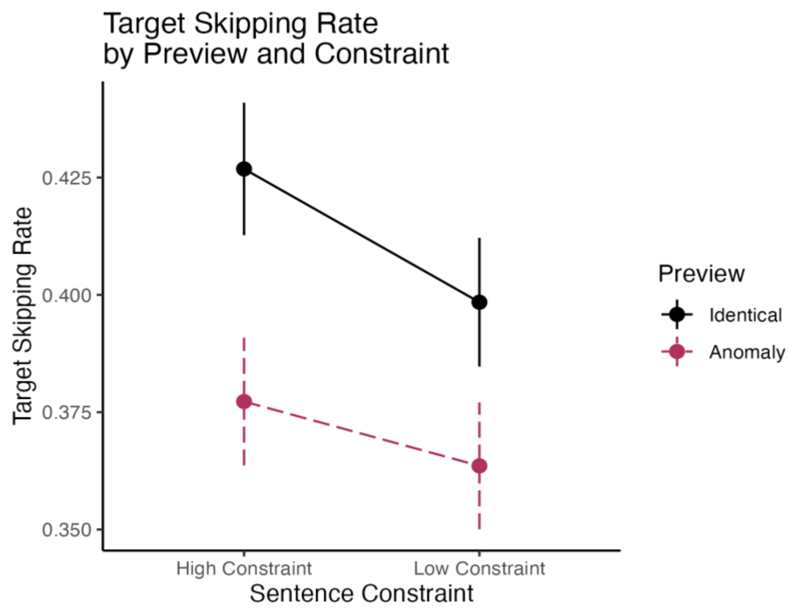

Figure 2

Mean Skipping Rate on the Target Word by Preview Condition and Sentence Constraint

Table 3

Results of Linear Mixed Effects Regression Models Predicting Target Word Skipping Rate by Sentence Constraint and Preview Condition

	Target Skipping Rate			
Predictors	*Est.*	*SE*	*z*	*p*
(Intercept)	0.63	0.10	-2.85	**0.004**
Constraint (High vs. Low)	0.87	0.08	-1.48	0.138
Preview (Identical vs. Anomaly)	0.80	0.08	-2.34	**0.019**
Constraint x Preview	1.01	0.14	0.11	0.916
Observations	5040			

Note. The skipping rate estimate is reported as the odds ratio from the glmer() analysis. This analysis includes only trials with single fixations on the pretarget word and forward saccades from the pretarget word to either the target word or end of sentence region.

N400 FRP Effects Time-locked to Pretarget Fixations

As expected, the N400 amplitude was significantly more negative in low constraint compared to high constraint sentences (collapsing across preview condition; Table 4). In the high constraint sentences in which the reader skipped the target, there was a significant N400 effect (i.e., more negative N400 amplitude) for the orthographic anomaly preview compared to the plausible/expected preview. There was no main effect of target skipping on the N400 amplitude (collapsing across preview conditions in high constraint sentences). For the anomaly compared to the identical preview comparison, there were significant two-way interactions between preview and constraint and preview and skipping; the N400 effect of the orthographic violation was larger in high constraint sentences and was larger when the reader skipped the target word. There was also a three-way interaction between constraint, preview, and skipping such that the effect of preview on the N400 was largest in high constraint sentences when the target word was skipped.

To better characterize the three-way interaction between preview condition, sentence constraint, and target skipping, I conducted follow-up analyses split by target skipping (Table 5). Two separate analyses were conducted for trials in which the target word was skipped and trials in which the target word was fixated, predicting the N400 amplitude by preview condition and sentence constraint. These follow-up analyses used the same contrasts as the primary analysis.

Table 4

Results of Linear Mixed Effects Regression Models Predicting N400 Amplitude Time-locked to the Pretarget Word by Sentence Constraint, Preview Condition, and Target Fixation Behavior

	Pretarget N400			
Predictors	*Est.*	*SE*	*t*	*p*
(Intercept)	-1.11	0.32	-3.44	**0.001**
Constraint (High vs. Low)	-1.24	0.40	-3.10	**0.002**
Preview (Identical vs. Anomaly)	-1.98	0.57	-3.50	**<0.001**
Target Skipping (Skipped vs. Fixated)	0.29	0.38	0.77	0.439
Constraint x Preview	2.00	0.75	2.69	**0.007**
Constraint x Skipping	-0.05	0.52	-0.10	0.917
Preview x Skipping	1.65	0.76	2.17	**0.030**
Constraint x Preview x Skipping	-2.66	0.98	-2.71	**0.007**
Observations	3959			

Table 5

Results of Linear Mixed Effects Regression Analyses Predicting N400 Amplitude Time-locked to the Pretarget Word by Sentence Constraint and Preview Condition Split by Target Skipping

	N400 Target Skipped				**N400 Target Fixated**			
Predictors	*Est.*	*SE*	*t*	*p*	*Est.*	*SE*	*t*	*p*
(Intercept)	-1.16	0.31	-3.71	**<0.001**	-0.82	0.27	-3.00	**0.003**
Constraint (High vs. Low)	-1.19	0.38	-3.13	**0.002**	-1.29	0.31	-4.11	**<0.001**
Preview (Identical vs. Anomaly)	-1.97	0.57	-3.44	**0.001**	-0.35	0.47	-0.75	0.454
Constraint x Preview	2.03	0.76	2.68	**0.007**	-0.61	0.63	-0.96	0.335
Observations	1670				2289			

Pretarget FRPs for Target Skipped Trials

Mirroring the main analysis, there was a significant effect of sentence constraint collapsing across preview conditions (more negative amplitudes for low compared to high constraint). The preview condition effect was also significant for skipping trials, but as reflected in the primary analysis. The interaction between the anomalous preview effect and sentence constraint was also significant, demonstrating a larger effect of the preview manipulation on the N400 amplitude (more negative for the anomaly compared to the plausible/expected preview in high compared to low constraint sentences (see Figure 3 for waveforms and Figure 5 for topographic scalp maps).

Pretarget FRPs for Target Fixated Trials

In contrast with the target skipped trials, in the target fixated analysis the only significant effect on the N400 amplitude was sentence constraint (collapsed across preview condition). There was neither a significant preview nor any interaction between preview condition and sentence constraint. Therefore, this experiment revealed no effect of the parafoveal preview word on the N400 neural response when readers decide not to skip the target word, regardless of sentence constraint (presumably because a decision to fixate the target word indicates shallower lexical processing of the parafoveal word form; see Figure 4 for waveforms and Figure 5 for topographic scalp maps).

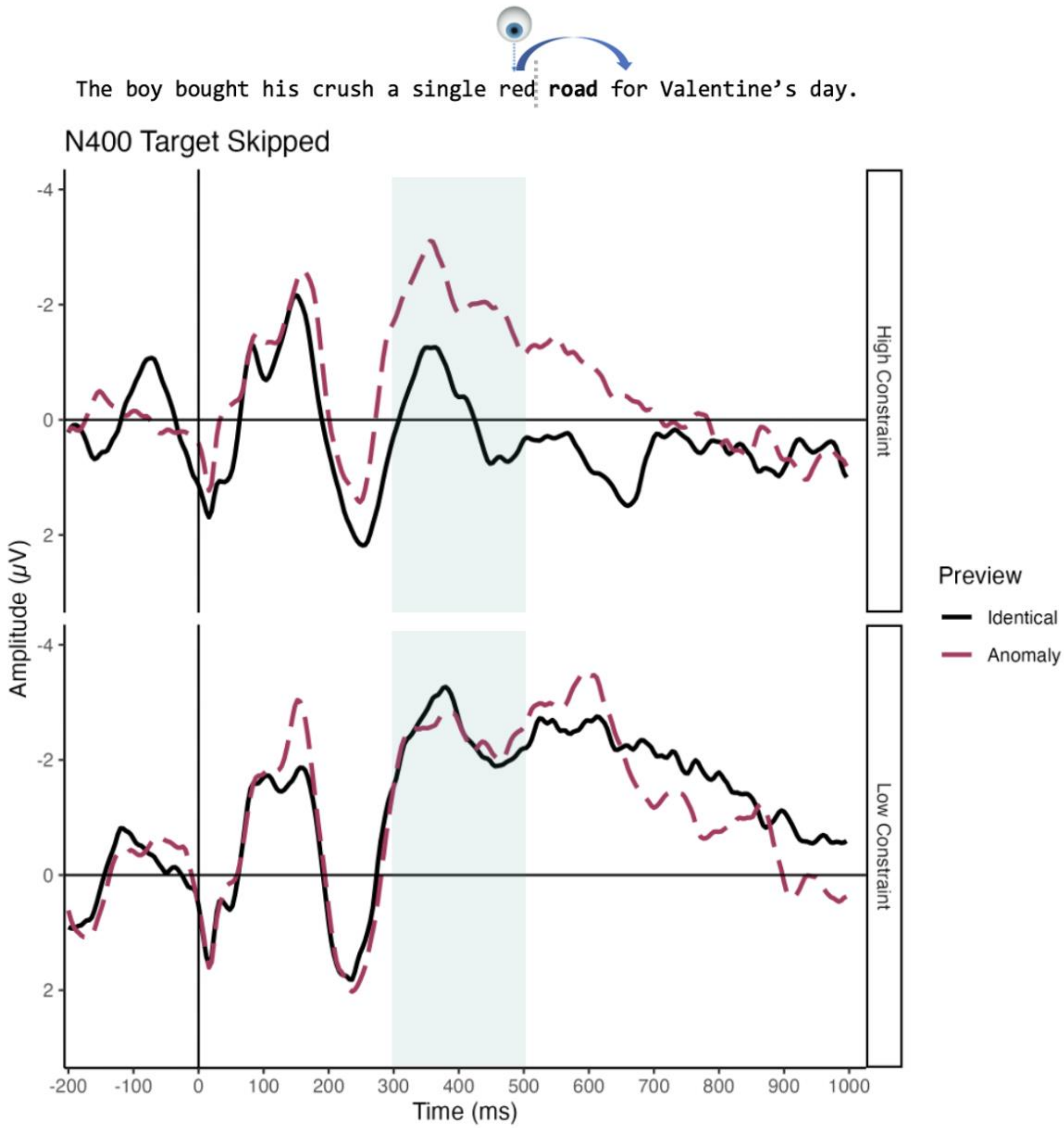

Figure 3

FRP Waveforms at Centroparietal ROI for the N400 Effect of Parafoveal Preview Condition Split by Sentence Constraint and Target Word Skipping Time-locked to the Pretarget Fixation

Note. Shaded boxes indicate analysis time windows. The sentence example represents the preview display; the anomalous word is never directly fixated or visible once the invisible boundary is crossed.

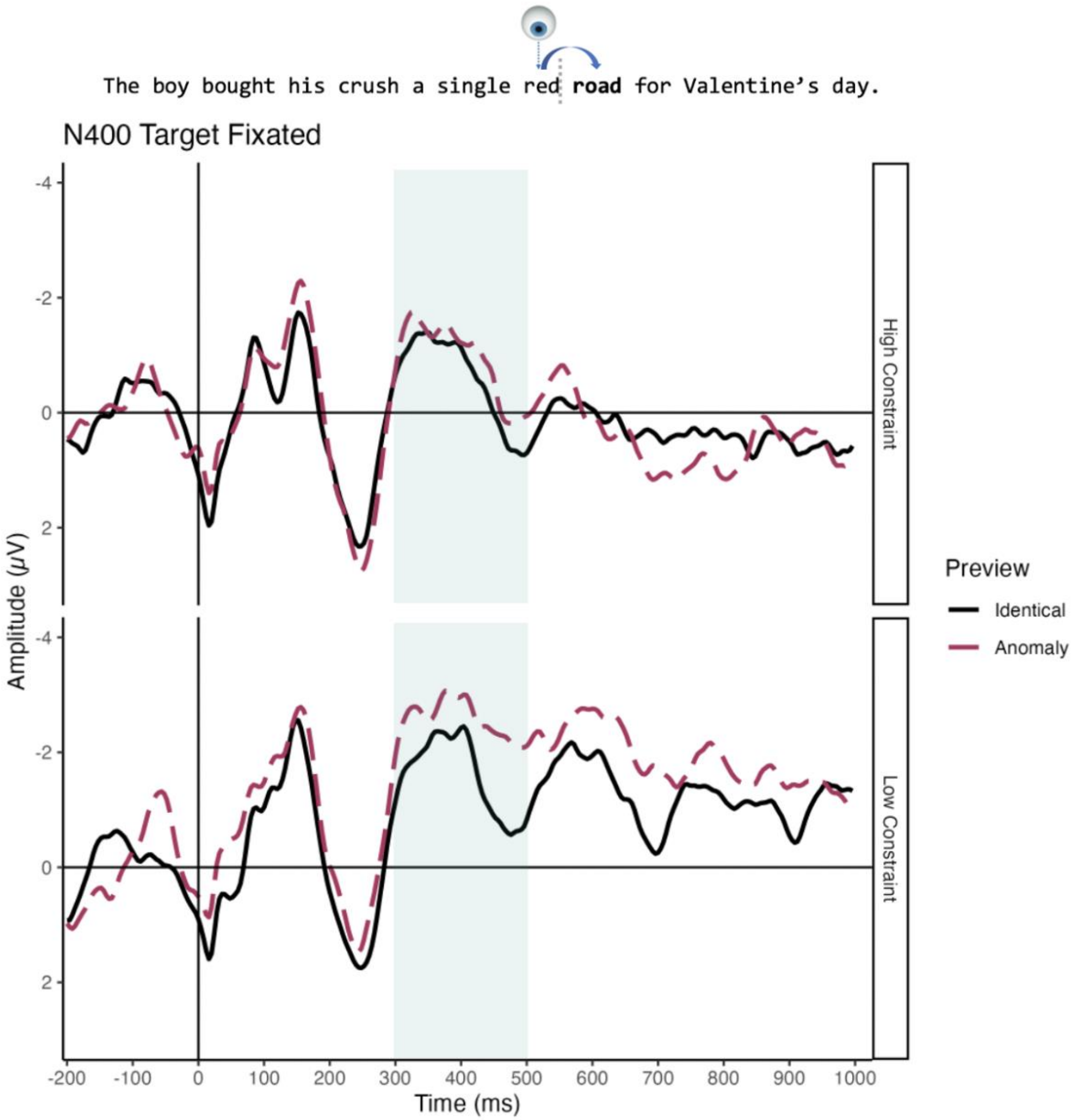

Figure 4

FRP Waveforms at Centroparietal ROI for the N400 Effect of Parafoveal Preview Condition Split by Sentence Constraint when the Target Word was Fixated Time-locked to the Pretarget Fixation

Note. Shaded boxes indicate analysis time windows. The sentence example represents the preview display; the anomalous word is never directly fixated or visible once the invisible boundary is crossed.

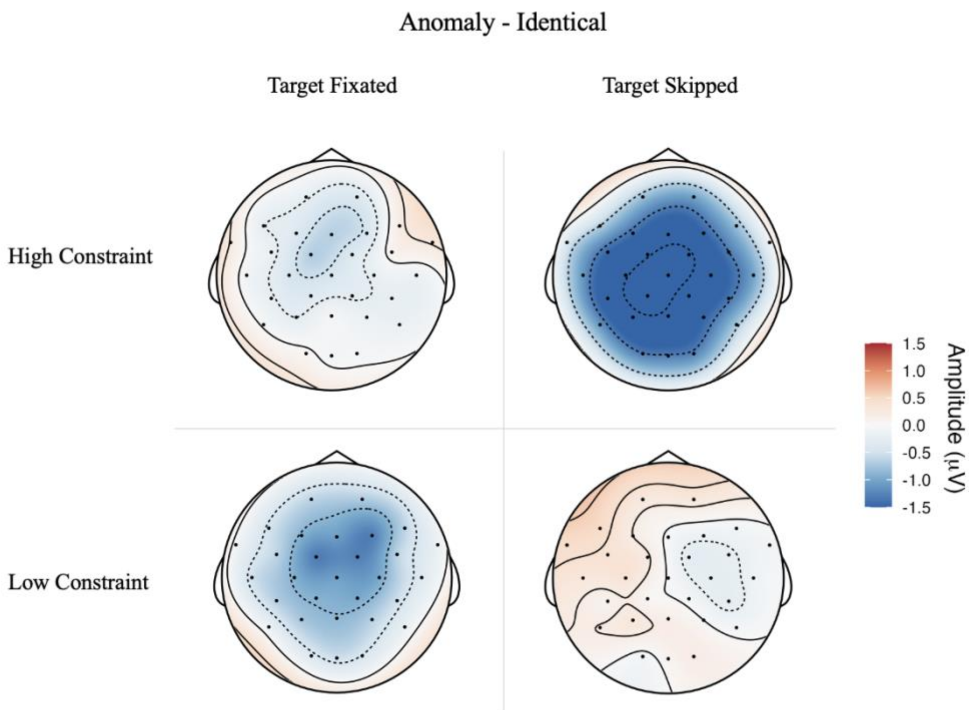

Figure 5

Topographic Scalp Maps of Pretarget Time-locked N400 Effects (Anomaly minus Identical Preview) by Constraint Condition and Target Fixation Behavior

Summary and Discussion

In Experiment 1, I manipulated sentence constraint and the orthographic form of a parafoveally previewed word using the gaze-contingent display change paradigm (Rayner, 1975). Eye movement and EEG recordings were co-registered to extract FRPs time-locked to fixations on a pretarget word during parafoveal preview of the manipulated target words. I used a novel approach of splitting trials based on the reader's decision to either skip or fixate the previewed target word. The N400 component was significantly modulated by the plausibility of the parafoveal preview, but only in highly constraining sentences when the reader decided to skip the previewed word. The results of this experiment suggest that the ability to identify a word's fine-grained orthographic form depends on whether the reader has expectations about the identity of the upcoming word. This data pattern suggests that word skipping is not only determined by low-level visual and oculomotor constraints but is also associated with deeper lexical processing of upcoming words in parafoveal vision.

However, although the brain responses demonstrate that, on trials in which the target word was skipped, identification of the parafoveal preview was more precise, the identification of a parafoveal anomaly did not result in a disruption to the forward progress of the eye movements. Based on general assumptions in reading research that difficulty in comprehension results in less skipping, longer fixations, and increased regressive eye movements (see Rayner & Pollatsek, 2006; see Clifton et al., 2016), it might be expected that the identification of an anomalous word would be associated with decisions not to skip. However, the current study reveals a nuanced account of the relationship between parafoveal linguistic processing and eye movement decisions. The fact that skipping is associated with larger brain responses to the contextually incompatible preview word indicates that word skipping is sometimes determined by achieving substantial progress toward identifying the to-be-skipped word, but also suggests that skipping decisions precede full semantic retrieval and contextual integration. The current study also contributes to our understanding of the limits of parafoveal processing more generally. When a sentence context allows for relatively strong predictions about likely upcoming words, bottom-up parafoveal word identification can be quite precise, as evidenced by brain responses that show discrimination between an expected word and a visually similar implausible word.

A remaining question that is not fully resolved by this study is how word identification unfolds in the case of low constraint sentences when a word is skipped but not precisely identified. The null N400 effect in low constraint sentences indicates that the skipped word was not fully identified parafoveally. Skipping rates were numerically lowest for the orthographic anomaly preview in low constraint sentences, but they were still skipped around 40% of the time. Therefore, in these cases, skipping decisions were not determined by thorough identification of the parafoveal word and appear to align more closely with the shallow heuristic account of word skipping. More work is needed to determine the specific causes of word skipping in such circumstances where the skipped word does not appear to have been accurately identified. Furthermore, I plan to conduct future exploratory analyses of the current dataset to investigate whether skipping of words that were not fully identified on the first pass (i.e., in low constraint sentences) is associated with downstream compensatory strategies, such as regressive eye movements or slower reading of the post-target region of the sentence. It may also be the case that in the absence of strong expectations, individual words are simply not encoded as deeply as when an expectation is satisfied or violated.

CHAPTER 3: SKIPPING-CONTINGENT EFFECTS OF ORTHOGRAPHIC EXPECTANCY AND LEXICAL FREQUENCY ON PARAFOVEAL WORD IDENTIFICATION (EXPERIMENT 2)

As demonstrated in Experiment 1, predictability influences parafoveal processing and skipping decisions by improving the precision and efficiency of bottom-up word identification. The familiarity of a word (i.e., lexical frequency) has also been demonstrated in previous eye tracking experiments to influence skipping rates (Angele et al., 2014; Henderson & Ferriera, 1993). When it comes to lexical frequency, it has been argued that the identification threshold of more familiar words is lower, giving them “priority access” (Taft & Forster, 1976), which could also reduce the perceptual quality threshold for word identification of a parafoveal word. Similarly, it has been proposed that high frequency words may have a higher resting state level of activation, which makes their meanings easier to access (Coltheart et al., 2001). In either case, one might predict that this relative ease of identification would allow for deeper processing of high frequency words parafoveally. A recent co-registration study that manipulated parafoveal word frequency did in fact show that more extensive processing of high frequency words was achieved parafoveally, as indexed by modulation of the subsequent foveal N400 (Milligan et al., 2023).

Models of eye movement control during reading have also proposed that eye movement decisions are not based on full word identification, but rather on a cursory “familiarity check” (Reichle et al., 2006). Based on this account, lexical frequency would clearly play a role in identifying an upcoming stimulus as familiar, making it easier to identify parafoveal words.

Another lexical characteristic that has been identified as contributing to skipping decisions is word length. People often skip short words and this is true even when controlling for lexical frequency (which is correlated with length; shorter words tend to be higher frequency; Kliegl et al., 2004). Eye movement control and saccade initiation are assumed to be driven to some degree by a cursory familiarity check, however, word length, which is more visuospatial than linguistic, is an even stronger predictor of skipping probability (Brysbaert & Vitu, 1998). Therefore, while skipping is clearly influenced by a word's predictability and familiarity, other spatial oculomotor constraints are clearly at play as well. So, if an unfamiliar or unpredictable short word is skipped, does this scenario represent a case in which word skipping is driven primarily by oculomotor constraints rather than lexical processing?

It may be more difficult for the eyes to program very short saccades to a small upcoming target word. Higher skipping rates of short words may simply be due to the limitations of the oculomotor system and to oculomotor error, or *mislocated fixations* (i.e., unintended fixations on the following word when the reader intended to fixate the short word; Nuthmann, et al., 2005). Another possibility when it comes to word length is that the brain is finely tuned to statistical probabilities. Short words are more likely to be function words that contain minimal semantic information, so skipping of short words may be the result of such probabilistic heuristics in the service of efficiency. Short function words (e.g., articles) also tend to be skipped more frequently than short content words (e.g., nouns, verbs), suggesting that there is some sensitivity of the oculomotor system to grammatical characteristics and the expected amount of semantic content of an upcoming word (Gautier, et al., 2000; Just & Carpenter, 1983; O'Reagan, 1979; cf. Staub, 2023). Therefore, it may be that the brain utilizes experience-based statistical probabilities of very short words containing sparse semantic content to make hedged bets on whether a word is less crucial for comprehension and worth skipping. Even if the bottom-up form is not fully identified parafoveally, the brain may be able to mentally "fill in the gaps" of skipped function words with whatever word was most likely to be present based on syntactic context cues.

A question raised by Angele and Rayner (2013) about the nature of skipping and lexical processing of short articles is whether these short, semantically shallow function words are more or less *automatically* skipped regardless of their semantic or syntactic fit in the sentence. They used the word *the*, which is the most frequent word in the English language (Balota, et al., 2007), as a test case to see if infelicitous (i.e., syntactically and semantically anomalous) instances of the word *the* were still frequently skipped. They found that when the parafoveal preview of a three-letter verb was replaced with the (semantically and syntactically implausible) word *the*, it was still skipped *more frequently* than when the correct verb preview was presented. In a follow-up study, Abbott et al. (2015) also tested the effect of sentence constraint on infelicitous *the* skipping and replicated the finding of higher skipping rates in low constraint sentences, but also reported an additive effect of constraint, resulting in still higher skipping rates of *the* in high constraint sentences. Therefore, having strong expectations that were violated did not disrupt the tendency to skip the anomalous function word. They only presented 10 items per condition, however, so it is possible they did not have sufficient statistical power to test this interaction between constraint and the preview condition. Nevertheless, they did replicate the phenomenon of higher skipping rates for the high frequency article *the* even when it made no sense in the sentence context, was a syntactic violation, and even when a different word was highly predictable.

Therefore, it appears as though skipping decisions are sometimes driven by low-level lexical characteristics rather than higher level semantic processing or contextual fit. In the case of extremely high frequency words, the word's familiarity, and potentially its relative lack of semantic content, can drive skipping decisions regardless of whether the word is incomprehensible based on the sentence context. The language processing system has clearly adapted in some way to deal with the fact that high frequency articles are regularly skipped. Therefore, it may be that syntactic cues allow the reader to "fill in the blank" with the word that makes the most sense, potentially disregarding the lexical input from the bottom-up parafoveal preview altogether.

The current experiment seeks to determine whether extremely high frequency words such as articles are processed and integrated into the syntactic and semantic representation of the sentence, in a bottom-up fashion, when they are skipped. Alternatively, top-down heuristics alone may guide the higher-level construction of meaning, without requiring scrutiny of the actual bottom-up input when the parafoveal preview is identified as a highly frequent function word. Furthermore, the proposed study includes a subtle orthographic violation to serve as a replication of Experiment 1, but for shorter, three-letter words. The current study, therefore, also allows for the comparison of skipping behavior and brain responses to very short anomalous words that are either (1) content words without any specific frequency manipulation or (2) a very high frequency function word, *the*. Because Experiment 1 demonstrated that effects of parafoveal anomalies on the N400 were more pronounced in high constraint sentences, and because Abbott et al. (2015) did not report a significant interaction between sentence constraint and *the* skipping rates, the current experiment used only high constraint sentence frames. Furthermore, from a practical standpoint, I chose to use high constraint sentences and short words to promote higher overall skipping rates with the aim of achieving a roughly equivalent number of observations for each eye movement behavior (i.e., skipping vs. non-skipping).

Hypotheses

1. I expected to replicate the orthographic anomaly preview effects from Experiment 1, with larger N400 amplitudes for the anomaly compared to the expected/identical condition when the target word is skipped but not when it is fixated.
2. Regarding the anomalous *the* and identical preview comparison:
    a. I also expected to find a larger N400 amplitude for the anomalous *the* preview condition compared to the expected word, which would demonstrate that even high frequency function words are semantically processed parafoveally. However, because the function word *the* is very high frequency and contains little semantic content, I expected that this effect might be numerically smaller compared to the orthographic anomaly effect.
    b. Alternatively, it is possible that high frequency function words are generally not deeply processed for semantic and syntactic fit, which could explain why they are so frequently skipped. If this is the case, and the anomalous *the* does not elicit an N400 effect compared to the expected word, it would indicate that high frequency articles are largely ignored during the reading process.
3. Regarding the interaction between the anomalous *the* preview effect and skipping behavior:
    a. I hypothesized that, like the orthographic anomaly effect, the anomalous *the* preview effect would be larger on skipping trials, indicating deeper processing and more thorough identification of skipped words.
    b. However, if high frequency function words are skipped automatically (Angele & Rayner, 2013) and not processed for semantic content, there may be no N400

effect for the anomalous *the* condition regardless of skipping behavior. Alternatively, if there is a main effect of the anomalous *the* preview (i.e., larger N400 amplitude compared to the identical condition) but no interaction with skipping behavior, would indicate that high frequency articles are easily and quickly identified but that skipping of these function words is determined by additional factors besides thorough identification.

Method

Participants

Sixty-nine participants were recruited from the Psychology Department's SONA subject pool at the University of South Florida and compensated with course credit or recruited through flyers and mailing lists and paid $16/hour for their time. As in Experiment 1, all participants included in analyses were right-handed native English speakers between ages 18 and 35 with normal or corrected-to-normal vision and no history of reading, learning, or neurological disorders. Participants provided informed consent via an online consent form approved by the University of South Florida.

Because I was uncertain what effect sizes to expect for the parafoveal N400 effects, I conducted a sensitivity analysis based on 48 participants using PANGEA (v0.2; https://jakewestfall.shinyapps.io/pangea/). This initial value was selected because a previous co-registration study conducted in our lab that found significant effects of a parafoveal preview manipulation included 45 participants (Milligan et al., 2023a) and I expected that the magnitude of effects to subtle spelling errors and a high frequency function word in the current study might be slightly smaller. The sensitivity analysis showed that with 48 participants and 20 items per condition (assuming that approximately two thirds of trials would meet the inclusion and behavioral criteria) per skipping behavior (assuming a roughly even split between target skipping and fixating trials), I would be able to detect an interaction effect between the parafoveal word manipulations and skipping behavior with a small effect size (Cohen's d = 0.24) at a power of .80. Therefore, based on this acceptable probability of a type II error with even a small effect size and ~33% trial loss, the target sample size selected for this study is 48 usable participants.

Five participants were excluded because it was determined after data collection that they had not been appropriately screened to verify that they met the inclusion criteria. Seven were excluded because of poor quality EEG data (e.g., excessive muscle noise, disconnected electrodes, drifting, etc.) and 1 was excluded because of poor eye tracker calibration. Three participants were dismissed prior to completing the experiment due to inability to sufficiently reduce impedances during capping. Two were excluded due to experimenter error in recording the EEG data. Three participants were excluded after data processing because they had fewer than 15 trials (75% data loss) retained per condition after trial exclusions based on faulty display changes, eye tracker data loss, EEG artifacts, and behavioral criteria (i.e., must have single fixations on the pretarget word followed by a forward saccade). In total, 21 of the 69 participants were excluded from analysis, resulting in a final sample of 48 usable participants (i.e., the a priori determined target sample size).

Stimuli and Design

Sentence stimuli consisted of 180 high constraint sentences that made a 3-letter target word predictable. The parafoveal preview was manipulated using the gaze-contingent display change paradigm (see Figure 1), with three preview conditions: an identical predictable word (i.e., no display change between preview and target), an orthographic neighbor of the predictable target word, and the high frequency function word *the* (see Example Sentences below). The foveally fixated (or skipped) target word that was displayed after the eyes crossed the invisible boundary (located immediately after the last character in the pretarget word) was always a predictable, plausible word. Preview condition was counterbalanced across sentence items in three separate lists so that each sentence was presented in every preview condition across the three lists. Each participant saw one list, with each sentence item presented in only one of the preview conditions, resulting in each participant seeing 60 items per preview condition.

Example Sentences (parafoveal preview conditions in parentheses):

(1) When Baxter saw his treats, his tail would always (***wag/sag/the***) **wag** side to side.

(2) The unmarried man lived in a bachelor (***pad/pat/the***) **pad** in the thriving city.

The anomalous preview and target words were roughly matched, on average across items, on lexical frequency, orthographic neighborhood size (i.e., the number of real words that share all but one letter with a given word), and semantic diversity (i.e., a measure of the diversity of different contexts in which a word tends to appear in the language; see Table 6) because these variables have been previously shown to influence eye movements and ERP responses. The letter that differed between the expected target word and the orthographic neighbor preview was also evenly distributed across letter position (i.e., even number of first, middle, and final letter position substitutions).

Sentence Norming

Sentence stimuli were subjected to identical normative procedures as described in Experiment 1 to verify the predictability of the target word and the (im)plausibility of the target and preview words. The mean cloze probability (i.e., proportion of responses that matched the intended target word) was .74 (SD = .23), verifying that the sentence stimuli were at least moderately constraining toward the target word.

Table 6

Descriptive Statistics of Lexical Characteristics for Expected Target and Anomalous Orthographic Neighbor Preview Words

	Expected Target Word	Orthographic Anomaly Preview
Frequency	3.2 (0.8)	3.8 (1.0)
Orthographic Neighborhood Size	18.2 (5.9)	20.0 (5.2)
Semantic Diversity	1.7 (.3)	2.0 (0.3)

Note. Means are reported with standard deviations in parentheses. Frequencies are log SUBTLWF (Retrieved from the English Lexicon Project (https://elexicon.wustl.edu/index.html); Balota, et al., 2007).

The mean plausibility rating (on a Likert scale from 1(highly implausible) - 7 (highly plausible)) for the expected target word was 5.6 (SD = .55) and for the orthographic neighbor anomaly was 3.0 (SD = .46). I did not collect normative data for the anomalous *the* condition out of concern that presenting sentences in a norming study in which the word *the* repeatedly appeared anomalously might produce unusual judgments from either heightened or dampened sensitivity to the error. However, *the* always replaced a content word and, based on part of speech alone, was always erroneous in the sentence.

Procedure

The procedure, task, and display parameters were identical to those described in Experiment 1.

Data Cleaning and Preprocessing

EEG and eye tracking data processing procedures were identical to those described in Experiment 1. After synchronizing and merging the EEG and eye tracking data, 5423 trials were retained that had single fixations on the pretarget word. Of those trials, 271 were excluded because the pretarget fixation was followed by a regressive, rather than forward, saccade, leaving 5152 trials. Of these, 115 trials were flagged for eye tracking or display issues, including premature or delayed display changes, track loss, or calibration issues, which were identified via manual inspection of the eye tracking data. Of the remaining 5037 trials, 578 trials were flagged for EEG artifacts, resulting in 4459 trials retained for analyses. The average number of trials retained per subject was 32.0 (SD = 7.4) in the identical condition, 31.1 (SD = 7.3) in the orthographic anomaly condition, and 29.8 (SD = 6.8) in the anomalous *the* condition.

Results

Analyses followed the same procedures and methods (i.e., linear mixed effects regression) described in Experiment 1. The primary dependent variable of the N400 time-locked to the pretarget fixation was also defined using the same ROI and time window. For all analyses, preview condition was coded as a successive differences contrast comparing the orthographic anomaly condition to the identical preview condition and the identical preview to the anomalous *the* condition. For the skipping contingent FRP analysis, skipping behavior was entered as a treatment contrast (0, 1), with target skipping as the baseline.

Skipping Rates and Fixation Durations of (Fixated) Target Words

Target word skipping probability did not differ significantly between the identical preview condition (mean = 46%, SD = 16%; see Table 7 for analysis results) and the orthographic anomaly condition (mean = 49%, SD = 18%). However, skipping rates in the anomalous *the* preview condition (mean = 67%, SD = 17%) were significantly higher than the identical condition, replicating the findings from Angele and Rayner (2013) and Abbott et al., (2015) that skipping of the high frequency function word *the,* even when it is implausible in the sentence context, is more frequent than skipping of plausible or expected words (see Figure 6A).

Table 7

Results of Generalized Linear Mixed Effects Models Predicting Target Word Skipping Rate and Single Fixation Duration by Preview Condition

	Target Skipping Rate				**Target Single Fixation Duration**			
Predictors	*Est.*	*SE*	*t*	*p*	*Est.*	*SE*	*t*	*p*
(Intercept)	1.21	0.13	1.73	0.083	251.65	5.85	43.02	**<0.001**
Preview (Anomaly vs. Identical)	1.11	0.09	1.25	0.210	-34.83	5.08	-6.86	**<0.001**
Preview (Identical vs. The)	2.47	0.24	9.50	**<0.001**	46.62	6.94	6.72	**<0.001**
Observations	5507				2459			

Note. The skipping rate estimate is reported as the odds ratio from the glmer() analysis.

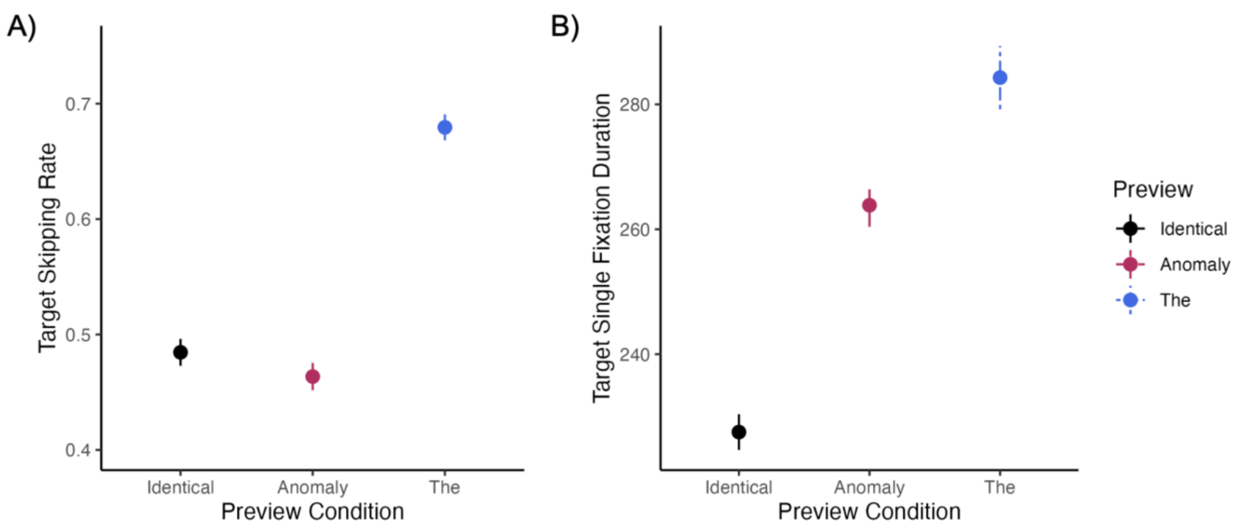

Figure 6

Average Skipping Rates (Panel A) and Single Fixation Durations (Panel B) of the Target Word by Parafoveal Preview Condition

Note. Error bars represent standard error.

Interestingly, when the target word was fixated, there were longer fixation durations for the orthographic anomaly and *the* preview conditions compared to the identical (Table 7). Although skipping rates were higher for *the*, downstream effects on fixation durations (for trials without target word skipping) demonstrate a substantial disruption from the anomalous high frequency preview (See Figure 6B).

Skipping Contingent Parafoveal N400 Effects

For the anomalous *the* preview effect, however, the N400 effect did not differ significantly as a function of skipping behavior. Topographic maps of these N400 effects by preview condition and skipping behavior (Figure 9) exhibit a canonical centro-parietal scalp distribution for these responses.

Table 8

Results of Linear Mixed Effects Regression Predicting Pretarget Time-locked N400 Amplitude by Preview Condition and Skipping Behavior

	Pretarget N400			
Predictors	*Est.*	*SE*	*t*	*p*
(Intercept)	-0.96	0.21	-4.64	**<0.001**
Preview (Anomaly vs. Identical)	1.32	0.40	3.27	**0.001**
Preview (Identical vs. The)	-0.78	0.36	-2.20	**0.028**
Target Skipping (Skipped vs. Fixated)	0.58	0.23	2.56	**0.010**
Preview (A vs. I) x Skipping	-1.07	0.53	-2.03	**0.042**
Preview (I vs. T) x Skipping	-0.30	0.55	-0.55	0.582
Observations	4456			

To better characterize the two-way interaction between preview condition and skipping behavior, I also conducted two follow-up analyses predicting the N400 by preview condition for the skipping and fixating trials separately (Table 9). This analysis showed a significant effect of the anomaly compared to identical preview only for target skipped trials, but a significant effect for *the* compared to the identical for both skipped and fixated trials.

Table 9

Results of Linear Mixed Effects Regressions Predicting Parafoveal N400 Amplitude by Preview Condition Split by Skipping Behavior

	N400 - Target Skipped				**N400 - Target Fixated**			
Predictors	*Est.*	*SE*	*t*	*p*	*Est.*	*SE*	*t*	*p*
(Intercept)	-1.01	0.20	-4.95	**<0.001**	-0.55	0.19	-2.84	**0.004**
Preview (Anomaly vs. Identical)	1.38	0.45	3.04	**0.002**	0.28	0.36	0.79	0.428
Preview (Identical vs. The)	-0.76	0.34	-2.20	**0.028**	-1.04	0.42	-2.50	**0.012**
Observations	2832				2331			

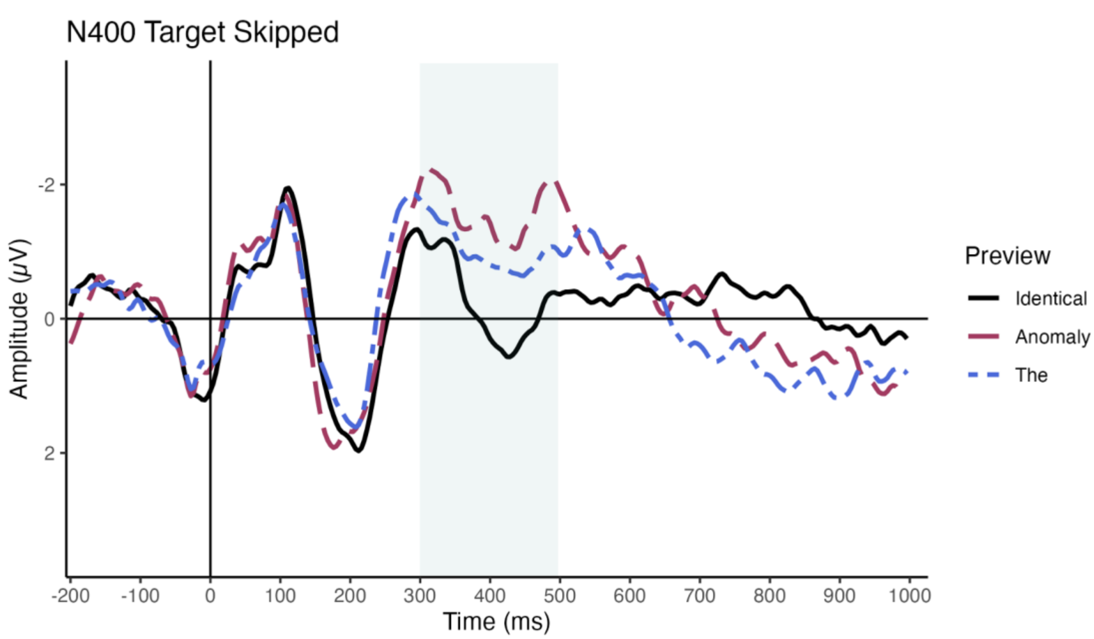

Figure 7

N400 Waveforms by Preview Condition at Centroparietal ROI for Target Skipping Trials

Note. Shaded boxes indicate analysis time windows.

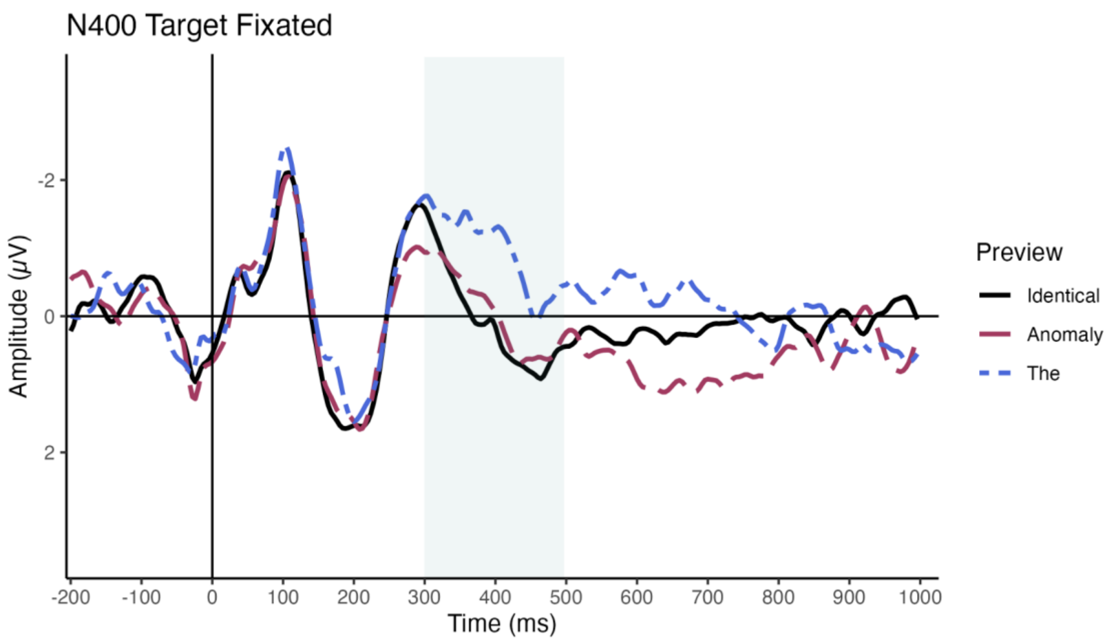

Figure 8

N400 Waveforms by Preview Condition at Centroparietal ROI for Target Fixating Trials

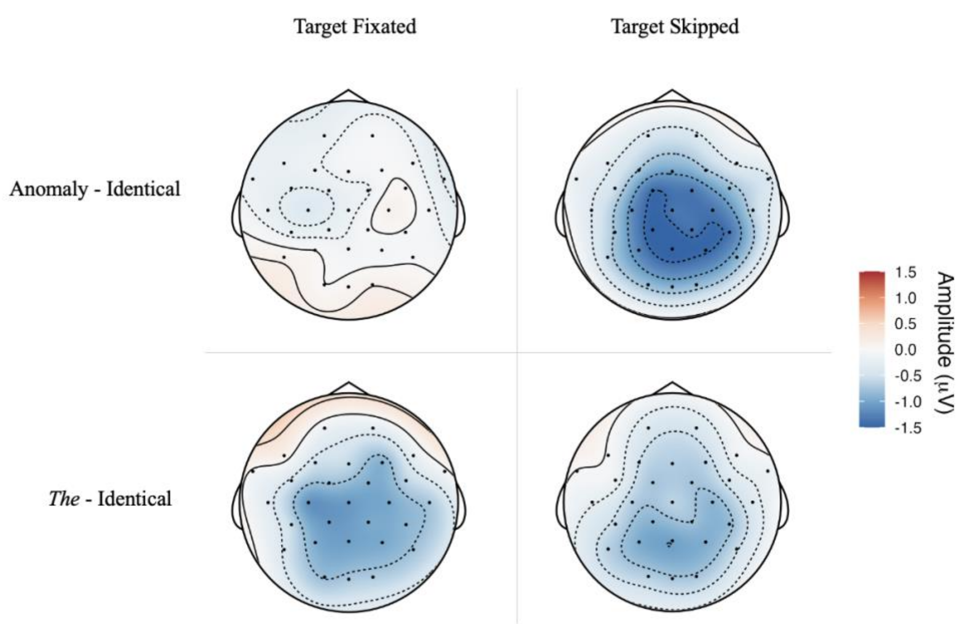

Figure 9

Topographic Scalp Maps of N400 Preview Effects (Anomaly Minus Identical and The Minus Identical) Split by Target Skipping Behavior

Exploratory Analyses of Individual Differences in Parafoveal Processing based on Participant-level Skipping Rates

Because the a priori analyses were based on relationships between trial-level skipping behavior and neural responses that collapsed across individuals, I also conducted an exploratory follow-up analysis to assess whether the observed patterns might be driven by differences between individual participants. The range of average skipping behavior was relatively broad across participants even for the expected identical condition (range = 10% - 82%, mean = 46%, SD = 16%; see Figure 10 for a histogram of the distribution). I hypothesized that individuals who skipped most target words might have qualitatively different strategies and depth of word identification with regard to skipping behavior relative to those who almost always fixated the target word.

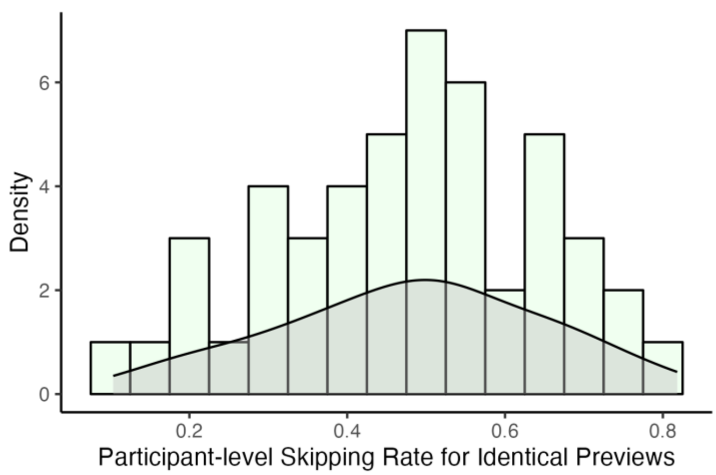

Figure 10

Distribution of Mean Skipping Rates Across Participants for the Identical Preview Condition

To investigate these potential individual differences based on participants' skipping tendencies, I calculated the mean skipping rate for each participant in the identical condition (to reflect only cases in which the preview of the skipped word was expected and plausible). I then used a linear mixed effects regression to predict mean participant N400 amplitude by preview condition, skipping behavior, and average participant-level skipping rates for the identical condition, as well as the interactions between these variables (Table 10). Contrasts for the target skipping effect (skipped as the baseline) and preview condition (successive differences) were identical to confirmatory analyses. Participant skipping rate was entered as a continuous centered variable. Preview condition was entered as a random intercept for subjects.

Table 10

Results of Linear Mixed Effects Regression Predicting N400 Amplitude (Participant-level Mean) by Preview Condition, Participant-level Skipping Rates (Identical Preview), and Skipping Behavior

	Pretarget N400			
Predictors	*Est.*	*SE*	*t*	*p*
(Intercept)	-0.98	0.21	-4.72	**<0.001**
Preview (Anomaly vs. Identical)	1.42	0.48	2.98	**0.003**
Preview (Identical vs. The)	-0.88	0.46	-1.91	0.057
Participant Skip Rate	0.48	0.26	1.84	0.067
Target Skipping (Skipped vs. Fixated)	-0.06	0.21	-0.28	0.780
Preview (A vs. I) x Target Skip	-1.29	0.63	-2.03	**0.044**
Preview (I vs. T) x Target Skip	-0.26	0.63	-0.41	0.683
Preview (A vs. I) x Skip Rate	-0.14	0.48	-0.30	0.765
Preview (I vs. T) x Skip Rate	0.65	0.46	1.41	0.159
Target Skip x Skip Rate	-0.22	0.26	-0.85	0.396
Preview (A vs. I) x Target Skip x Skip Rate	0.32	0.64	0.51	0.614
Preview (I vs. T) x Target Skip x Skip Rate	-1.25	0.64	-1.97	0.050

Results from this analysis aligned with the results of the primary analysis (Table 8), with a significant main effect of the anomaly compared to identical preview (for skipped trials) as well as a significant interaction of this comparison with skipping behavior, and a marginally significant ($p = .06$) main effect for the identical compared to *the* preview comparison. As far as the effect of participant-level skipping rates, the only interaction with preview condition and skipping behavior that reached near significance ($p = .05$) was the three-way interaction between the identical and anomalous *the* preview comparison and skipping behavior. This interaction was characterized by opposite effects of skipping behavior on the N400 effect of the identical versus anomalous *the* preview comparison for individuals with higher versus lower overall skipping rates (see Figure 11). Individuals with a higher tendency to skip the three-letter target word (in the identical preview condition) exhibited an N400 response to the anomalous *the* preview on trials in which they fixated the target word, which was eliminated for skipping trials. Alternatively, individuals with low skipping tendencies showed an N400 effect only on trials in which they skipped the target word. Therefore, the lack of a skipping interaction for the identical versus *the* comparison in the primary analysis appears to be due to opposite patterns for different participants averaging out when collapsing across individuals.

In contrast, the pattern of N400 effects for the orthographic anomaly preview (i.e., larger N400 effect on skipped trials compared to fixated trials) appears to be more consistent across participants and did not differ significantly based on participant-level skipping tendencies. These individual differences effects and their implications are discussed in further detail in the Summary and Discussion section below.

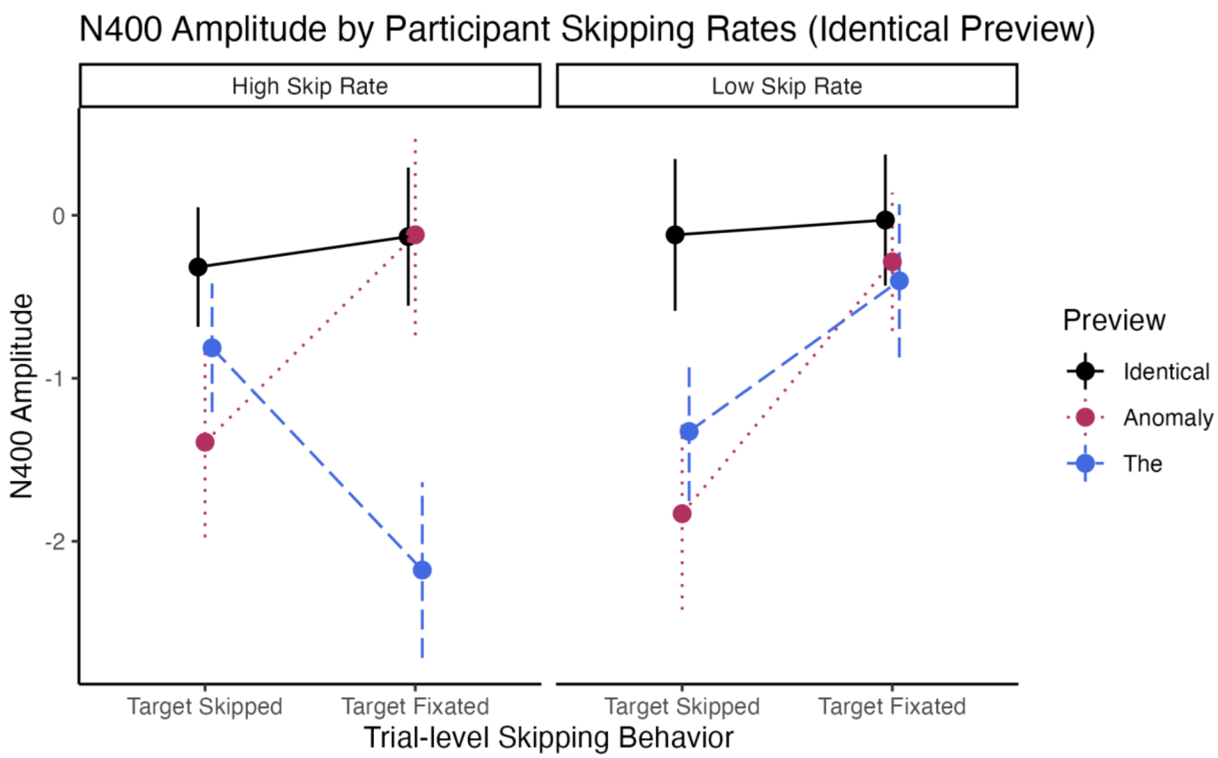

Figure 11

Individual Differences in the Skipping-Contingent N400 Effect to Preview Condition Based on Participants' Average Skipping Rates (for the Identical Condition)

Summary and Discussion

The current experiment tested whether skipping behavior is reflective of more extensive and precise parafoveal processing of a skipped word. The design tested both whether readers are able to detect subtle orthographic errors and anomalous high frequency function words during parafoveal preview (of short three-letter words) and whether identification of a word's orthographic form or familiarity is associated with the ensuing eye movement behavior. The N400 responses to these manipulations show that readers can identify both subtle spelling errors and contextually incompatible function words based on parafoveal preview alone. When it comes to more moderate frequency content words, particularly those that share visual features with an expected word, the interaction with skipping behavior demonstrates that word skipping is associated with thorough identification of the word parafoveally. However, in the case of the anomalous *the* previews, the N400 effect was not significantly reduced on trials in which the reader decided to fixate the target word. The N400 effect to this parafoveal error was present regardless of the nature of subsequent eye movement decisions.

Based on high skipping rates of an anomalous *the*, Angele and Rayner (2013) proposed that short, high frequency articles are skipped automatically, regardless of their contribution (or lack thereof) to a higher level semantic representation. The current study replicates their findings in eye movement behavior. Skipping rates of *the* have been consistently shown to be quite high, as demonstrated in the current experiment (i.e., almost 70% of the time). Based on the primary analyses (Table 7) predicting the parafoveal N400 amplitude by preview condition and skipping behavior (and their interactions), the word *the* appears to have been identified as anomalous (eliciting an N400 response) irrespective of eye movement behavior. On the surface, the lack of an interaction between preview and skipping indicates that parafoveal identification of high frequency function words is relatively ubiquitous. Because recognition of the anomaly (as indexed by the N400 effect) did not differ based on behavior, it appears as though shallow heuristics, rather than the depth of word identification, might determine skipping decisions for frequent function words.

The Role of Individual Differences in Skipping Tendencies

Although the average patterns indicate that skipping behavior for high frequency articles is not explained by the extent to which they are identified, the exploratory analysis I conducted to assess the role of individual differences tells a more nuanced story. This analysis revealed that this apparent lack of an interaction was due to participant-level differences in the direction of this interaction which were obscured by collapsing across individuals. Individuals with higher skipping rates for short, plausible, and expected words (i.e., the identical condition) showed an N400 effect only in cases when they chose to fixate the target word. In contrast, individuals with a higher tendency to fixate each word (i.e., lower overall skipping rates) showed an N400 effect only when they chose to skip. I propose that these different patterns may be due to individual differences in the threshold of word identification that determines a given reader's skipping decisions.

Based on the data patterns, frequent skippers may tend to use shallow heuristic processing for highly frequent words to trigger skipping decisions. This strategy might also explain why they tend to skip more frequently overall. They may engage in a somewhat risky skipping strategy that allows for skipping based on an initial familiarity check even when they have not fully determined the semantic fit of the word being skipped. Therefore, when they skip an anomalous *the* based on its extreme familiarity, they might not fully register the semantic violation. Instead, they might use context cues to make sense of the sentence as a whole when they encounter an unexpected function word, resulting in a diminished parafoveal N400 response. On the other hand, I hypothesize that the fact that an N400 is elicited only in the rarer cases in which they fixate the target word (for the anomalous *the* condition) reflects that occasionally they do thoroughly identify its meaning, detect a semantic violation, and experience a disruption in comprehension. This deeper semantic processing then results in the decision to slow down and fixate the word in question, while also eliciting an N400 response.

Although these frequent skippers showed a reversal in the skipping contingent N400 pattern for the anomalous *the* condition, they demonstrated the average pattern reported in both experiments 1 & 2 for the orthographic anomaly. Therefore, frequent skippers, specifically, appear to engage in qualitatively different processes for high frequency function words compared to relatively lower frequency function words. If the initial familiarity check does not reach a sufficient threshold for skipping, they may still be able to achieve enough bottom-up orthographic processing, especially in high constraint sentences to achieve a predictability check. A previous eye tracking study by Slattery & Yates (2018) demonstrated that spelling ability is a significant predictor of individual differences in skipping rates. Individuals who are better spellers and are more cognizant of precise orthographic forms have higher overall skipping rates. Additionally, skipping rates are positively associated with print exposure (assumed to be an implicit measure of reading experience as measured by a task in which participants are asked to identify names of real famous authors; Faber et al., 2020) Therefore, frequent skippers may be more practiced readers and more skilled at precise word identification. These readers may be able to achieve this predictability check faster than less frequent skippers, allowing them to make skipping decisions based on more thorough identification more often. If enough identification is achieved for them to verify that the orthography roughly matches an expected word, a skip could be triggered and an N400 elicited downstream once they have fully registered that the parafoveal word had an orthographic error.

Alternatively, for readers who progress through the text more deliberately and skip less frequently, it may be that they rely more on foveal processing to precisely identify each word. This may be partially due to the fact that they are less capable of extracting information from parafoveal preview and less willing to "hedge their bets" that they will be able to identify the word if they skip it. Therefore, the lack of an N400 response to the parafoveally anomalous article when they choose to fixate may be due to the fact that they were not able to accomplish a familiarity check before making an eye movement decision. On the other hand, the rarer cases in which they did skip may reflect a subset of cases in which they did sufficiently identify the familiarity of the word parafoveally in time to make a skipping decision. Therefore, the presence of an N400 effect when they skip would indicate cases of more successful parafoveal processing, resulting in the decision to skip, while also resulting in the downstream recognition of a semantic fit violation.

CHAPTER 4: GENERAL DISCUSSION

Causes of Word Skipping: Thorough Identification vs. Shallow Heuristics

The goal of the experiments in the current dissertation was to expand our understanding of the relationship between behavior and language processing in the brain during natural reading. If decisions to progress past a word in a text are closely tied to successful identification and comprehension (i.e., the *thorough identification account*), skipping should not occur unless a word has been fully recognized parafoveally. Alternatively, if eye movements are only loosely associated with successful word identification and are governed by partial linguistic processing and heuristics (i.e., the *shallow heuristic account*), skipping could occur in the absence of complete word recognition. Although reading researchers have previously used skipping behavior to infer that words can sometimes be fully recognized based on parafoveal preview alone (e.g., Drieghe et al., 2005; Fitzsimmons & Drieghe, 2013), the experiments in this dissertation are the first to demonstrate using online neural responses that word identification in the brain does in fact occur when words are skipped.

Based on the results of the experiments presented here, a hybrid account that accommodates both thorough identification and shallow heuristic-based processing as contributors to skipping behavior is necessary. Precise identification of the presented word's orthographic form was apparent in highly constrained sentence contexts when the word was skipped but this precision was not evident in the absence of expectations (see Experiment 1). Therefore, in scenarios where the reader has expectations about an upcoming word, skipping behavior does appear to be diagnostic of thorough bottom-up identification. However, when the message being communicated was more vague (i.e., in low constraint sentences), skipping occurred even when precise parafoveal word identification had not been achieved. In these cases where comprehension was more effortful and the message being communicated was not readily apparent based on context, the threshold for skipping appears to have been relaxed. Skipping took place even when the subtle orthographic violation that rendered the parafoveal word nonsensical was not identified. The lack of an N400 effect to the violation suggests that without the support of expectations to facilitate parafoveal processing, the preview word may have been incorrectly identified as the visually similar plausible word. The anomalous word that actually appeared on the screen was never truly recognized. Instead, the skipped word was assumed to be its plausible orthographic neighbor, resulting in no difference in N400 amplitude between the identical and anomalous previews.

Alternatively, when word identification was arguably easiest, when the parafoveal word was a high frequency article and the sentence promoted predictions of a different word, the word *the* was thoroughly identified (as evidenced by the N400 response to its anomalous presentation) both when it was skipped and when it was fixated (which occurred far less frequently; see Experiment 2). Replicating the previous eye tracking studies (Angele & Rayner, 2013; Abbott et al., 2015), skipping rates of the anomalous *the* preview in Experiment 2 were quite high (almost 70%), even though the brain responses indicated that the word was recognized as anomalous in the sentence context. Therefore, highly frequent articles may be skipped relatively automatically, as proposed by Angele & Rayner (2013). Based on the combined patterns of eye movement behavior and neural response data, lexical frequency and part-of-speech serve as heuristics that promote skipping of high frequency articles on a time course that precedes identification of expectancy violations or semantic (and syntactic) fit. In general, the extreme familiarity of function words such as *the*, and perhaps their relatively shallower semantic content, allow them to be easily and rapidly identified parafoveally, eliminating the need for subsequent foveal processing.

Individual Differences in Skipping-Contingent Linguistic Processing during Reading

Qualifying the findings from Experiment 2, I also found evidence that the relationship between skipping behavior and linguistic processing varies across individuals. The presence of an N400 effect to the anomalous *the* in both target skipping and fixating scenarios appears to be due to the fact that some people had a larger N400 response for skipped trials and some people had a larger N400 response for fixated trials. This variability across individuals was significantly explained by variability in participants' general skipping tendencies. I argue that the data patterns suggest that more frequent skippers may use shallow heuristics and familiarity checks to skip high frequency words, while also being more efficient at recognizing the orthographic form of a parafoveal word to engage in predictability checks for lower frequency words. On the other hand, less frequent skippers may engage in skipping only when they are more confident about the word's identity (i.e., in cases of more thorough identification; e.g., Eskenazi & Folk, 2015a), resulting in the presence of parafoveal N400 effects to anomalous and unexpected words only when words are skipped.

Experiment 2 was not designed to test the effects of individual differences on the relationship between skipping behavior and parafoveal linguistic processing, so future studies should be conducted to more rigorously test the hypotheses proposed above. Previous eye tracking studies have reported that individual differences in skipping rates are related to spelling ability (Yates & Slattery, 2018) and print exposure (Faber et al., 2020). Therefore, including such assessments in future co-registration studies designed to test skipping-contingent N400 effects would further our understanding of how language processing and eye movement behavior during reading might vary depending on an individual's language skills and reading strategies.

Furthermore, using tasks during sentence reading experiments that are more diagnostic of online reading comprehension could allow us to determine whether an individual's tendency to skip, and their skipping-contingent brain responses, are associated with successful comprehension. The answers to such questions may have implications for identifying brain and behavioral patterns in struggling readers and better understanding how reading interventions might allow struggling readers to be more successful.

As a whole, the results of the Experiments presented here support the conclusion that skipping is determined by thorough identification *sometimes*. The interplay between visual and linguistic properties as determiners of word skipping behavior has been a prominent topic of discussion among reading and eye movement researchers and some accounts have come down more strongly on the side of skipping being primarily determined by lower level visual factors Brysbaert & Vitu (1998), while other accounts have proposed that, especially when readers have strong predictions, skipping reflects full recognition of the parafoveal word (Drieghe, et al., 2005). The current findings largely align with the latter account (Drieghe, et al., 2005) by demonstrating that word skipping is consistently associated with precise bottom-up processing of upcoming content words when context-driven expectations facilitate and provide useful constraints on word identification. However, when precise parafoveal processing is particularly difficult (i.e., in the absence of expectations when the parafoveal word is only subtly incorrect) *or* when it is particularly easy (i.e., in the presence of strong expectations with an easily identified high frequency parafoveal word), skipping appears to be driven more often by heuristics, familiarity checks, and "good enough" processing. The complexity of these patterns therefore demands a nuanced theoretical interpretation of the causes of word skipping and further work is necessary to get a clearer picture of situational and person-level factors that determine word skipping decisions, particularly in the absence of very strong expectations.

Defining Comprehension in the Context of Reading Goals

A key motivation for investigating the depth of language processing associated with the particular reading behavior of skipping was to determine the extent to which readers precisely identify each individual word during reading. Word skipping is an interesting curiosity in itself, but it also provides a useful test case for identifying the cognitive mechanisms that drive eye movement decisions more generally. If words are skipped without being fully identified, it would suggest that successful reading does not require precise and laborious word identification. Alternatively, if skipping decisions did require precise word identification, it would suggest that (1) the brain is incredibly good at identifying words extremely rapidly to allow for skipping to occur at all and (2) that language comprehension relies on precise processing and decoding of each unit of linguistic information. However, the present results demonstrate that eye movement behavior can be flexible and that decisions can be adjusted based on the difficulty of language processing in a given scenario.

To explain this flexibility, I believe it is necessary to look at reading from a broader perspective as a cognitive task with a goal. We assume that the goal of reading is comprehension, however, reading can be a quite variable process depending on the motivation of the reader (e.g., Bråten et al, 2017; Treptow et al., 2007; Goldhammer et al., 2014). Furthermore, it is worth thinking about comprehension as a continuum as well. For example, if the reader's current goal is searching for a specific piece of information in a text, presumably to accomplish some external goal, the depth of processing may be quite shallow until they encounter a portion of the text that seems contextually relevant to the information being sought (Cole et al., 2011; White et al., 2015). If, on the other hand, the goal is to proofread for spelling errors, bottom-up word identification may instead be quite meticulous and precise (Schotter et al., 2014; Kaakinen et al., 2010). If, as in the current study, the goal is simply general comprehension to answer relatively straightforward comprehension questions (without any long term goal for information retention), the precision of bottom-up word identification may fall somewhere in the middle. To emphasize this point for the need for flexibility in reading behavior, take for example the scenario of encountering a never-before-seen word while reading with the motivation of deep comprehension. If it were the case that reading comprehension and the progression of eye movements through the text required full recognition and comprehension of each individual word, the eyes would be stuck forever on the unknown word. Clearly, then, it is beneficial for the reader to weigh the desire for accurate comprehension against the need to continue on with the task when making eye movement decisions, based on the assumption that comprehension will generally be achieved to a satisfactory degree given the task at hand.

If eye movement behavior was determined by a rigid set of parameters (e.g., skipping behavior always requiring precise word identification, or always resulting from shallow, heuristically driven decisions, the behavior of reading would not be capable of adjusting to the situational demands and goals of the reader. Therefore, situating the current study in the broader context of reading as a goal-oriented behavior, I argue that eye movement decisions are governed by a combination of factors including top-down predictions, high-level linguistic comprehension, low-level visual factors, and heuristics based on lexical familiarity and syntactic cues. The threshold that determines a skipping decision is based on a situationally-determined equilibrium between efficiency and precision of comprehension (Duggan & Payne, 2011; Kruger et al, 2022; Rayner et al., 2016), which must flexibly adjust to the immediate task demands. As demonstrated by the results of the experiments presented here, sentence constraint and lexical frequency both influence the difficulty of identifying a parafoveal word and when parafoveal word processing is relatively easy, skipping behavior increases and *can* be indicative of more precise and efficient bottom-up word processing.

When people have expectations about what is going to happen or what is going to be communicated, they are already entering the process of comprehending what comes next with a deeper understanding of the higher-level message being communicated and an investment in that expectation being born out. One plausible hypothesis about the effect of context-based expectations on the precision of word identification is that expectations might result in shallow processing of the next piece of information because of existing biases taking over, but this does not appear to be the case. Instead, it appears as though expectations allow readers to invest more attentional resources to deeply process the bottom-up stimulus. In the experiments presented here, when the context was highly informative, processing of the subtle anomalies in the text was more thorough, precise, and efficient than when the sentence context did not lend itself to pre-generating expectations about the upcoming textual content.

Increasingly, with people spending vast amounts of time consuming information and interacting with each other through text on their computer screens (e.g., reading news articles, emails, comments on social media, etc.), much of our engagement with language takes place through reading and visual language processing. Therefore, it is critical for understanding the consumption of information, the comprehension of text-based communication, and the human experience more broadly, for us to better understand how people make decisions about where to allocate their attention during reading and how these behavioral decisions impact understanding.

Conclusions

Word skipping is an example of a behavior that results from a drive for efficiency in comprehending information. I propose that this behavior is flexible and that the threshold that determines whether to spend more time to look directly at a word, to be certain of its identity and meaning, depends on the motivational and contextual factors. When readers are uncertain about the message being communicated and when they have minimal expectations about what the next piece of information will be, they are willing to engage more in *shallow heuristic* processing. Alternatively, when they have strong expectations about the message being communicated, their behavioral decisions are more reflective of, and determined by, precise and *thorough identification* of each new piece of information (i.e., each upcoming word in a sentence).

Identifying the factors that determine word skipping and reading behavior has implications for the relationship between perceptual processing, higher-level cognition, and behavior more generally. Reading is a complex cognitive process that takes place quite rapidly. Results from the experiments presented here support a hybrid account of information processing in the brain in which rapid behavioral decisions and accurate comprehension must compromise to reach a satisfactory equilibrium based on the specific demands of the scenario. When text comprehension is supported by useful context-based expectations, attentional resources may be freed up for rapid processing of an upcoming word. Contextual pre-activation of semantic and form-level features can promote efficient and precise bottom-up identification. This successful and efficient processing then promotes decisions to move the eyes forward based on complete word identification. Alternatively, when the context is vague and identification of a parafoveal word is more difficult, readers still engage in word skipping, but these decisions are not necessarily reflective of thorough word identification. Therefore, maintaining efficiency by skipping words appears to win out sometimes even when thorough word identification cannot be completed rapidly enough during parafoveal preview.

REFERENCES

Abbott, M. J., Angele, B., Ahn, Y. D., & Rayner, K. (2015). Skipping syntactically illegal the previews: The role of predictability. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 41*(6), 1703.

Abbott, M. J., & Staub, A. (2015). The effect of plausibility on eye movements in reading: Testing EZ Reader's null predictions. *Journal of Memory and Language, 85,* 76-87.

Angele, B., & Rayner, K. (2013). Processing the in the parafovea: Are articles skipped automatically?. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 39*(2), 649.

Angele, B., Laishley, A. E., Rayner, K., & Liversedge, S. P. (2014). The effect of high-and low-frequency previews and sentential fit on word skipping during reading. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 40*(4), 1181.

Antúnez, M., Milligan, S., Hernández-Cabrera, J. A., Barber, H. A., & Schotter, E. R. (2022). Semantic parafoveal processing in natural reading: Insight from fixation-related potentials & eye movements. *Psychophysiology, 59*(4), e13986.

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

Balota, D.A., Yap, M.J., Cortese, M.J., Hutchison, K.A., Kessler, B., Loftis, B., Neely, J.H., Nelson, D.L., Simpson, G.B., & Treiman, R. (2007). The English Lexicon Project. *Behavior Research Methods, 39,* 445-459.

Bråten, I., Johansen, R. P., & Strømsø, H. I. (2017). Effects of different ways of introducing a reading task on intrinsic motivation and comprehension. *Journal of Research in Reading, 40*(1), 17-36.

Brysbaert, M., & Vitu, F. (1998). Word skipping: Implications for theories of eye movement control in reading. In *Eye guidance in Reading and Scene Perception* (pp. 125-147). Elsevier Science Ltd.

Christianson, K., Hollingworth, A., Halliwell, J. F., & Ferreira, F. (2001). Thematic roles assigned along the garden path linger. *Cognitive Psychology, 42*(4), 368-407.

Clifton Jr, C., Ferreira, F., Henderson, J. M., Inhoff, A. W., Liversedge, S. P., Reichle, E. D., & Schotter, E. R. (2016). Eye movements in reading and information processing: Keith Rayner's 40 year legacy. *Journal of Memory and Language, 86*, 1-19.

Cole, M. J., Gwizdka, J., Liu, C., Bierig, R., Belkin, N. J., & Zhang, X. (2011). Task and user effects on reading patterns in information search. *Interacting with Computers, 23*(4), 346-362.

Coltheart, M., Rastle, K., Perry, C., Langdon, R., & Ziegler, J. (2001). DRC: a dual route cascaded model of visual word recognition and reading aloud. *Psychological Review, 108*(1), 204.

Degno, F., Loberg, O., & Liversedge, S. P. (2021). Co-Registration of Eye movements and fixation—related potentials in natural Reading: Practical issues of experimental design and data analysis. *Collabra: Psychology, 7*(1), 18032.

DeLong, K. A., Chan, W. H., & Kutas, M. (2021). Testing limits: ERP evidence for word form preactivation during speeded sentence reading. *Psychophysiology, 58*(2), e13720.

Dimigen, O. (2020). Optimizing the ICA-based removal of ocular EEG artifacts from free viewing experiments. *NeuroImage, 207*, 116117.

Dimigen, O., Sommer, W., Hohlfeld, A., Jacobs, A. M., & Kliegl, R. (2011). Coregistration of eye movements and EEG in natural reading: analyses and review. *Journal of Experimental Psychology: General, 140*(4), 552.

Drieghe, D., Rayner, K., & Pollatsek, A. (2005). Eye movements and word skipping during reading revisited. *Journal of Experimental Psychology: Human Perception and Performance, 31*(5), 954.

Duggan, G. B., & Payne, S. J. (2011, May). Skim reading by satisficing: evidence from eye tracking. In *Proceedings of the SIGCHI conference on human factors in computing systems* (pp. 1141-1150).

Ehinger, B. V., & Dimigen, O. (2019). Unfold: an integrated toolbox for overlap correction, non-linear modeling, and regression-based EEG analysis. *PeerJ, 7,* e7838.

Engbert, R., Nuthmann, A., Richter, E. M., & Kliegl, R. (2005). SWIFT: a dynamical model of saccade generation during reading. *Psychological Review, 112*(4), 777.

Ehrlich, S. F., & Rayner, K. (1981). Contextual effects on word perception and eye movements during reading. *Journal of Verbal Learning and Verbal Behavior*, *20*(6), 641-655.

Eskenazi, M. A., & Folk, J. R. (2015a). Reading skill and word skipping: Implications for visual and linguistic accounts of word skipping. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 41*(6), 1923.

Eskenazi, M. A., & Folk, J. R. (2015b). Skipped words and fixated words are processed differently during reading. *Psychonomic Bulletin & Review, 22*, 537-542.

Faber, M., Mak, M., & Willems, R. M. (2020). Word skipping as an indicator of individual reading style during literary reading. Journal of Eye Movement Research, 13(3).

Fitzsimmons, G., & Drieghe, D. (2013). How fast can predictability influence word skipping during reading?. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 39*(4), 1054.

Gautier, V., O’Regan, J. K., & Le Gargasson, J. F. (2000). ‘The-skipping’revisited in French: programming saccades to skip the article ‘les. *Vision Research, 40*(18), 2517-2531.

Goldhammer, F., Naumann, J., Stelter, A., Tóth, K., Rölke, H., & Klieme, E. (2014). The time on task effect in reading and problem solving is moderated by task difficulty and skill: Insights from a computer-based large-scale assessment. *Journal of Educational Psychology, 106*(3), 608.

Heilbron, M., van Haren, J., Hagoort, P., & de Lange, F. P. (2023). Lexical processing strongly affects reading times but not skipping during natural reading. *Open Mind, 7*, 757-783.

Henderson, J. M., & Ferreira, F. (2013). Eye movement control during reading: Fixation measures reflect foveal but not parafoveal processing difficulty. In *Reading and Language Processing* (pp. 73-93). Psychology Press.

Hochberg, J. (1976). Toward a speech-plan eye-movement model of reading. *Eye Movements and Psychological Processes*, 397-416.

Huey, E. B. (1908). The psychology and pedagogy of reading: With a review of the history of reading and writing and of methods, texts, and hygiene in reading.

Just, M. A., & Carpenter, P. A. (1992). A capacity theory of comprehension: individual differences in working memory. *Psychological Review, 99*(1), 122.

Kaakinen, J. K., & Hyönä, J. (2010). Task effects on eye movements during reading. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 36*(6), 1561.

Kliegl, R., Grabner, E., Rolfs, M., & Engbert, R. (2004). Length, frequency, and predictability effects of words on eye movements in reading. *European Journal of Cognitive Psychology, 16*(1-2), 262-284.

Kornrumpf, B., Niefind, F., Sommer, W., & Dimigen, O. (2016). Neural correlates of word recognition: A systematic comparison of natural reading and rapid serial visual presentation. *Journal of Cognitive Neuroscience, 28*(9), 1374-1391.

Kretzschmar, F., Schlesewsky, M., & Staub, A. (2015). Dissociating word frequency and predictability effects in reading: Evidence from coregistration of eye movements and EEG. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 41*(6), 1648.

Kruger, J. L., Wisniewska, N., & Liao, S. (2022). Why subtitle speed matters: Evidence from word skipping and rereading. *Applied Psycholinguistics, 43*(1), 211-236.

Lai, M. K., Payne, B. R., & Federmeier, K. D. (2023). Graded and ungraded expectation patterns: Prediction dynamics during active comprehension. *Psychophysiology*, e14424.

Laszlo, S., & Federmeier, K. D. (2009). A Beautiful Day in the Neighborhood: An Event-Related Potential Study of Lexical Relationships and Prediction in Context. *Journal of Memory and Language*, *61*(3), 326–338.

Metzner, P., Von Der Malsburg, T., Vasishth, S., & Rösler, F. (2017). The importance of reading naturally: Evidence from combined recordings of eye movements and electric brain potentials. *Cognitive Science, 41*, 1232-1263.

Milligan, S., Nestor, B., Antúnez, M., & Schotter, E. R. (2023a). Out of sight, out of mind: Foveal processing is necessary for semantic integration of words into sentence context. *Journal of Experimental Psychology: Human Perception and Performance, 49*(5), 687.

Milligan, S., Antúnez, M., Barber, H. A., & Schotter, E. R. (2023b). Are eye movements and EEG on the same page?: A coregistration study on parafoveal preview and lexical frequency. Journal of Experimental Psychology: General, 152(1), 188.

Milligan, S., & Schotter, E. R. (2024). Do readers here what they sea?: Effects of lexicality, predictability, and individual differences on the phonological preview benefit. *Journal of Memory and Language*, *135*, 104480.

Morton, J. (1969). Interaction of information in word recognition. *Psychological Review*, *76(*2), 165.

Nikolaev, A. R., Meghanathan, R. N., & van Leeuwen, C. (2016). Combining EEG and eye movement recording in free viewing: Pitfalls and possibilities. *Brain and Cognition, 107*, 55-83.

O'Reagan, J. K. (1979). Eye guidance in reading: evidence for linguistic control hypothesis. *Perceptual Psychophysics, 25*, 501-509.

Osterhout, L., & Holcomb, P. J. (1992). Event-related brain potentials elicited by syntactic anomaly. *Journal of Memory and Language, 31*(6), 785–806.

Payne, B. R., Stites, M. C., & Federmeier, K. D. (2019). Event-related brain potentials reveal how multiple aspects of semantic processing unfold across parafoveal and foveal vision during sentence reading. *Psychophysiology, 56*(10), e13432.

Rayner, K. (1975). The perceptual span and peripheral cues in reading. *Cognitive Psychology, 7*(1), 65-81.

Rayner, K. (1998). Eye movements in reading and information processing: 20 years of research. *Psychological Bulletin, 124*(3), 372.

Rayner, K., & McConkie, G. W. (1976). What guides a reader's eye movements?. *Vision Research, 16*(8), 829-837.

Rayner, K., & Pollatsek, A. (2006). Eye-movement control in reading. In *Handbook of Psycholinguistics* (pp. 613-657). Academic Press.

Rayner, K., Schotter, E. R., Masson, M. E., Potter, M. C., & Treiman, R. (2016). So much to read, so little time: How do we read, and can speed reading help?. *Psychological Science in the Public Interest, 17*(1), 4-34.

Rayner, K., & Well, A. D. (1996). Effects of contextual constraint on eye movements in reading: A further examination. *Psychonomic Bulletin & Review, 3*(4), 504-509.

Reichle, E. D., Pollatsek, A., Fisher, D. L., & Rayner, K. (1998). Toward a model of eye movement control in reading. *Psychological Review, 105*(1), 125–157.

Reichle, E. D., Pollatsek, A., & Rayner, K. (2006). E–Z Reader: A cognitive-control, serial-attention model of eye-movement behavior during reading. *Cognitive Systems Research, 7*(1), 4-22.

Sereno, S. C., Hand, C. J., Shahid, A., Yao, B., & O’Donnell, P. J. (2018). Testing the limits of contextual constraint: Interactions with word frequency and parafoveal preview during fluent reading. *Quarterly Journal of Experimental Psychology, 71*(1), 302-313.

Schotter, E.R., (2018). Reading ahead by hedging our bets on seeing the future: Eye tracking and electrophysiology evidence for parafoveal lexical processing and saccadic control by partial word recognition. *Psychology of Learning and Motivation, 68,* 263-298.

Schotter, E. R., Angele, B., & Rayner, K. (2012). Parafoveal processing in reading. *Attention, Perception, & Psychophysics, 74*, 5-35.

Schotter, E. R., Bicknell, K., Howard, I., Levy, R., & Rayner, K. (2014). Task effects reveal cognitive flexibility responding to frequency and predictability: Evidence from eye movements in reading and proofreading. *Cognition, 131*(1), 1-27.

Schotter, E. R., & Jia, A. (2016). Semantic and plausibility preview benefit effects in English: Evidence from eye movements. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 42*(12), 1839.

Schotter, E. R., Lee, M., Reiderman, M., & Rayner, K. (2015). The effect of contextual constraint on parafoveal processing in reading. *Journal of Memory and Language, 83*, 118-139.

Schotter, E. R., Leinenger, M., & von der Malsburg, T. (2018). When your mind skips what your eyes fixate: How forced fixations lead to comprehension illusions in reading. *Psychonomic Bulletin & Review, 25*, 1884-1890.

Schotter, E. R., Milligan, S., & Estevez, V. M. (2023). Event-related potentials show that parafoveal vision is insufficient for semantic integration. *Psychophysiology*, e14246.

Schotter, E. R., & Rayner, K. (2012). Eye movements and word recognition during reading. In *Visual Word Recognition Volume 2* (pp. 73-101). Psychology Press.

Slattery, T. J., & Yates, M. (2018). Word skipping: Effects of word length, predictability, spelling and reading skill. *Quarterly Journal of Experimental Psychology*, *71*(1), 250-259.

Smith, N. J., & Levy, R. (2013). The effect of word predictability on reading time is logarithmic. *Cognition, 128*(3), 302-319.

Staub, A. (2020). Do effects of visual contrast and font difficulty on readers' eye movements interact with effects of word frequency or predictability?. *Journal of Experimental Psychology: Human Perception and Performance, 46*(11), 1235.

Staub, A. (2023). The function/content word distinction and eye movements in reading. *Journal of Experimental Psychology: Learning, Memory, and Cognition*.

Stites, M. C., Payne, B. R., & Federmeier, K. D. (2017). Getting ahead of yourself: Parafoveal word expectancy modulates the N400 during sentence reading. *Cognitive, Affective, & Behavioral Neuroscience, 17*, 475-490.

Taft, M., & Forster, K. I. (1976). Lexical storage and retrieval of polymorphemic and polysyllabic words. *Journal of Verbal Learning and Verbal Behavior, 15*(6), 607-620.

Taylor, W. L. (1953). "Cloze Procedure": A New Tool for Measuring Readability. *Journalism Quarterly, 30*(4), 415–433.

Treptow, M. A., Burns, M. K., & McComas, J. J. (2007). Reading at the frustration, instructional, and independent levels: The effects on students' reading comprehension and time on task. *School Psychology Review, 36*(1), 159-166.

Veldre, A., & Andrews, S. (2017). Parafoveal preview benefit in sentence reading: Independent effects of plausibility and orthographic relatedness. *Psychonomic Bulletin & Review, 24*, 519-528.

Veldre, A., & Andrews, S. (2018). Parafoveal preview effects depend on both preview plausibility and target predictability. *Quarterly Journal of Experimental Psychology, 71*(1), 64-74.

Veldre, A., Reichle, E. D., Wong, R., & Andrews, S. (2020). The effect of contextual plausibility on word skipping during reading. *Cognition, 197*, 104184.

White, S. J. (2008). Eye movement control during reading: Effects of word frequency and orthographic familiarity. *Journal of Experimental Psychology: Human Perception and Performance, 34*(1), 205.

White, S. J., Warrington, K. L., McGowan, V. A., & Paterson, K. B. (2015). Eye movements during reading and topic scanning: Effects of word frequency. *Journal of Experimental Psychology: Human Perception and Performance, 41*(1), 233.