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

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… the relative position of the visual fixation pause in the total complex can at present be estimated only roughly as somewhere in the middle of the [reading] process, between the pre-fixational vision and the utterance, or appreciation.

- Raymond Dodge (1907)

More succinctly, we do not wait until we look at a word to start reading it, and we are not done by the time we decide to leave. Dodge and his contemporaries had access to only rudimentary empirical methods to study reading, but made incredible theoretical breakthroughs in explaining the process in detail. This paper covers the insights we have gained some 110 years later using advanced empirical methods like high-resolution eye tracking, electroencephalography, and combined recordings of the two. What humbles the modern cognitive scientist is that such advanced equipment only serves to affirm the conclusions those researchers surmised long ago using only logic and simple observation.

Skilled reading progresses at a remarkable speed (i.e., 200-400 words per minute) despite how many complex cognitive processes are involved (e.g., word recognition, sentence parsing, discourse representation, eye-movement control, etc.; Huey, 1908; Rayner, 1998; Rayner, Schotter, Masson, Potter, & Treiman, 2016). This surprising efficiency has led some researchers to insinuate that there is not enough time for language processing to influence moment-to-moment processes in reading (how long the eyes linger before moving – i.e., *fixation durations*; McConkie & Yang, 2003; Vitu, 2003). Despite substantial empirical and computational evidence suggesting that timing of eye movements (i.e., *saccades*, which intervene between fixations) is directly controlled by ongoing language processing (Reingold, Reichle, Glaholt, & Sheridan, 2012), we are still posed with an apparent paradox. How can fixation durations only last, on average, 200 milliseconds when electrophysiology studies suggest that neurocognitive responses to a word's meaning (i.e., the *N400 component*, which peaks around 400 ms; see Kutas & Federmeier, 2011) occur well after that (Rayner & Clifton, 2009)? In this paper, I propose that there are two aspects of the reading process that might help unravel this apparent paradox: (1) *hedging our bets* on word recognition – the triggering of saccades based on partial, rather than complete, word recognition and (2) *seeing the future* words in the sentence – the ability to preview words in parafoveal vision prior to fixating them during natural reading. I argue that these two properties of the reading system contribute to a specialized cognitive architecture that allows for *reading ahead* – allocating attention to words before our eyes reach them. This architecture causes saccade behavior during reading to be composed of several underlying types, which are sometimes determined by a parafoveal preview of a word, and sometimes a combination of both the parafoveal preview and the subsequently foveated information obtained from the word.

The reading speed paradox

Natural reading is not merely serial identification of fixated words, but rather a highly coordinated process in which prior context, foveal information, and parafoveal preview interact to guide the eyes' pursuit of information from the text (i.e., saccades). If we were to speculate about the natural reading process (in which entire sentences or paragraphs are available at all times and readers are able to fixate the words for however long, and in whatever order they please) based solely on results from single word or Rapid Serial Visual Presentation (RSVP) studies, we might arrive at erroneous conclusions about the speed with which readers can identify words and progress through text. For example, *lexical decision latencies* (the time required to judge whether a letter string is a word or nonword and press a corresponding button) last approximately 600 ms. If we were to subtract the time required for other processes (e.g., button press: ~400 ms; Ratcliff, Gomez & McKoon, 2004), we are left with an estimate for the time needed for word recognition around 200ms. Because fixation durations last approximately 250 ms, and saccade programming must be initiated approximately 125 ms before then (Becker & Jurgens, 1979; Rayner, Slowiczek, Clifton, & Bertera, 1983; Rayner, 1998; 2009), reading behavior can only be explained by overlapping processes (e.g., word processing, saccade programming, etc.) that depend on parafoveal preview to maintain efficiency (Reichle & Reingold, 2013; Reingold et al., 2012). Moreover, the timing of the N400 suggests that substantial linguistic information is processed by the brain after a saccade would have moved the eyes away from the word, and well after that saccade plan was initiated.

How can we reconcile these seemingly incompatible timelines? Obviously, one answer to this question is that these measurements (i.e., button press reaction time the lexical decision task, saccade latencies/fixation durations in reading, and N400 peak latencies in ERPs) index different aspects of word recognition. For example, the lexical decision task only requires that the person know whether the stimulus is a word or not to do the task, whereas during reading in eye tracking and ERP experiments the person, presumably, needs to also know *which* word it is. In addition, ERP and eye tracking studies, which presumably measure the same process (i.e., language comprehension), do so in very different ways; ERP studies focus on *time-fixed processes* (i.e., those that occur with a consistent timing in response to a particular event – the onset of the presentation of the word) whereas eye tracking studies focus on *time-variable processes* (i.e., those that cause a saccade to leave a word sooner versus later, or cause the eyes to move forward versus backward). When focusing on the measurement advantage of one of these methodologies we may obscure the strength of the other, losing the precision to detect its signal. In this paper, however, I focus on two other explanations: saccades during reading are initiated by hedging our bets on word recognition and, words are preprocessed before they are fixated during parafoveal preview.

***Hedging our bets*: coordinating eye movements and language processing.**

A simple way to solve this apparent paradox is already a fundamental aspect of the architecture of the reading system, as explained by some current models of saccadic control in reading: word recognition processes initiate saccade plans forward from words, but do so based on partial, rather than complete word recognition. For example, *direct control models* assume that saccades are controlled by ongoing cognitive processing (e.g., Reichle, Pollatsek, Fisher, & Rayner, 1998), which contrasts with *indirect control models* (e.g., McConkie & Yang, 2003) that assume cognition does not, or does only rarely, intervene with a random or autonomous saccadic control mechanism (see Reingold et al., 2012). The clearest evidence for direct control comes from the fact that fixation durations last longer on words that are more difficult to process cognitively or linguistically (e.g., words that are uncommon or unexpected; Rayner, 1998, 2009). This suggests that saccades can be initiated sooner when word recognition is in the process of completing faster. In fact, divergence points from a survival analysis of fixation duration distributions show that the effect of word frequency is observed as early as 145 ms after fixation onset, early enough to affect the majority of fixations (i.e., 91%: Reingold et al., 2012).

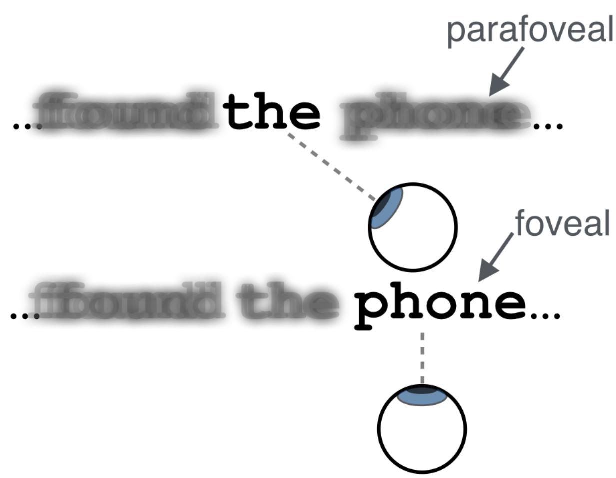
Some of these direct control models (e.g., E-Z Reader: Reichle et al., 1998; Reichle, 2011) posit that word identification involves *two successive stages*, (1) an initial assessment of familiarity after which saccades are triggered, and (2) subsequent retrieval of meaning, pronunciation, etc. (cf. SWIFT: Engbert, Nuthmann, Richter, & Kliegl, 2005; Schad & Engbert, 2012). Because the completion of the first stage of word recognition triggers saccade planning, this architecture implies that readers plan saccades forward from a word *before they have completely identified it*, and consequently before accessing its semantics (i.e., processes that generate the N400). This can explain why readers will skip over a word that makes no sense in the sentence context, provided that it is short and familiar (e.g., in "She was sure she would the all the tests." the underlined word *the* is skipped more often than the correct word, *ace*, and as often as the subsequent felicitous occurrence of *the*; Angele & Rayner, 2013; see also Abbott, Angele, Ahn, & Rayner, 2015; Angele, Laishley, Rayner, & Liversedge, 2014)

Importantly, in order for this aspect of the reading architecture to completely solve the timing issue, readers would have to plan saccades extremely early during fixations. For example, if a fixation were to last 200 ms and saccade plans take approximately 125 ms to execute (Becker & Jürgens, 1979), the plan would have had to have been initiated within the first 75 ms. Given that it takes approximately 60 ms for information about the word to transfer from the retina to the brain (see Reichle & Reingold, 2013), this means that only 15 ms worth of linguistic information would feed into the decision to make a saccade. This seems implausible and too risky to be efficient; therefore, there must be some other source of linguistic information that readers use to determine when they have enough information about a word to make a saccade forward.

***Seeing the future*: obtaining parafoveal preview of upcoming words.**

Reading speed also derives partly from the opportunity to obtain information from a word before directly viewing it, while the word is in parafoveal vision (i.e., during *parafoveal preview*; see Schotter, Angele, & Rayner, 2012 for a review). Parafoveal vision provides poorer perception of the text than direct, *foveal vision* (Figure 1); thus, any linguistic processing of the word that occurs during parafoveal preview is less precise than processing during foveal perception. Although foveal information enters the processing stream with higher perceptual fidelity, parafoveal information enters the processing stream sooner and therefore has potential to influence reading directly. In the same study using divergence point estimates in a survival analysis, mentioned above, Reingold et al. (2012) used a gaze-contingent boundary paradigm, to determine how early the effect of word frequency is observed when the preview is available compared to when it is denied by a parafoveal nonword mask (i.e., when word processing cannot start until direct fixation). That analysis revealed that the effect of word frequency was detectable about 111 ms earlier when preview was available, suggesting that readers had done a substantial amount of word processing based on the parafoveal preview.

Figure 1. Schematic of the visual fidelity of a word (*phone*) when viewed in different areas of the visual field (i.e., the parafovea versus the fovea) on two successive fixations.

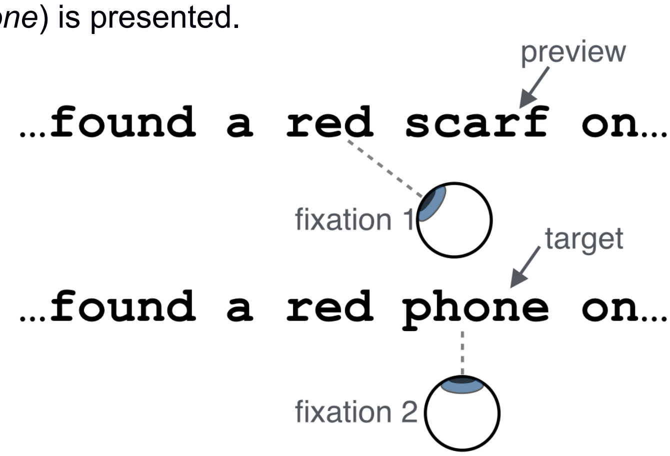


As I discuss in detail below, although it is clear that parafoveal preview allows the reading system to gain a head-start on word processing, it is not entirely clear how such preprocessing is subsequently utilized. For example, is parafoveal information used to facilitate processing on the subsequent fixation (i.e., for *trans-saccadic integration* with foveal information: Rayner, 1975; Pollatsek, Lesch, Morris, & Rayner, 1992; Cutter, Drieghe, & Liversedge, 2015) or independently for saccade planning (i.e., *skipping*: Rayner, 2009 or *forced fixations*: Schotter & Leinenger, 2016) and subsequent word recognition? I argue that both processes operate, and the likelihood of each scenario depends on the ease of lexically processing the parafoveal preview.

***Reading ahead*: Using parafoveal preview to initiate word recognition.**

Studies that investigate parafoveal processing in reading use a *gaze-contingent display change (boundary) paradigm* (Rayner, 1975), in which a parafoveal preview stimulus changes to a different *foveal target* word during the saccade to the target (readers are not consciously aware of this change if it occurs during the saccade, due to saccadic suppression; Matin, 1974). Reading time (e.g., fixation duration on the target) is generally compared between conditions in which the preview is available (i.e., *valid*) compared to when it is masked with a different stimulus (i.e., is *invalid*) and, on average, fixation durations are shorter by about 20-50 ms for valid compared to invalid previews (see Rayner, 2009; Reingold et al., 2012; Schotter et al. 2012; Vasilev & Angele, 2017). However, as discussed below, some recent findings using a different experimental design suggest that the notion of "valid" versus "invalid" preview with respect to the target stimulus may not capture the complete nature of parafoveal preview effects.

Figure 2. A schematic of the gaze-contingent boundary paradigm (Rayner, 1975). The identity of a particular stimulus changes between two successive fixations – on the first fixation, the preview stimulus (*scarf*) is presented and on the second fixation the target stimulus (*phone*) is presented.



The findings from boundary paradigm studies have broader implications for reading because they may explain why readers sometimes misinterpret words that do not change (i.e., because they look like another, more common word – a *higher frequency neighbor* – that would also fit into the sentence). For example, readers sometimes initially misinterpret the word *birth* in the sentence "Mary knew that giving *birch* trees to the park would beautify it." Upon reading the rest of the sentence they would become confused and reread to confirm the correct word meaning (i.e., *birch*; Slattery, 2009; see also Gregg & Inhoff, 2016; Johnson, 2009). Thus, although I suggested that parafoveal preview and saccade planning based on partial word recognition contribute to reading efficiency, there is also potential for these mechanisms to cause inefficiencies if readers incorrectly presume a word's identity based on the parafoveal preview and can only properly identify it by rereading.

Traditional accounts of parafoveal preview: *Trans-saccadic integration*. If parafoveal information is not used to trigger saccades, and a different word is ultimately fixated (i.e., after a display change), what happens to the word recognition process? Traditionally, the preview "validity" effects described above have been explained by trans-saccadic linguistic integration accounts, which posit that parafoveal preview information is merged or compared with foveal target information once directly fixated. On these accounts, processing is easier when preview and target are similar and therefore more easily integrated; consequently, fixation durations are shorter, leading to a *preview benefit* (e.g., Rayner, 1975; Pollatsek et al., 1992; Cutter et al., 2015). An alternative way to conceptualize this effect is that processing is more difficult when preview and target are dissimilar and less easily integrated; consequently, fixation durations are longer, leading to a *preview cost* (e.g., Kliegl, Hohenstein & McDonald, 2013; Marx, Hawelka, Schuster, & Hutzler, 2015). On these accounts, parafoveal information is accessed, but foveal information is required to modify or interact with the information that was pre-activated from the parafovea in order to trigger saccades. This idea was noted by early reading researchers,

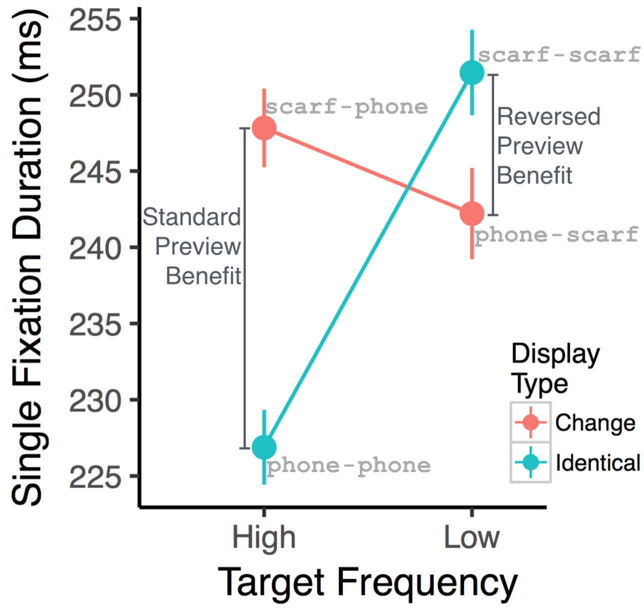
> As in subsequent fixation the peripherally seen word comes to the area of clear vision I conjecture that the inhibitory function of clear perception becomes more prominent, shutting out of the competition all of the residua aroused by the more general peripheral stimulation except those further stimulated by the new, more definite details.
> (Dodge, 1907, p. 57).

An alternative explanation for these effects is an explanation by misidentification, akin to the misidentification effects described via the *birch*/*birth* example above (e.g., Slattery, 2009; see also Gregg & Inhoff, 2016; Johnson, 2009). Parafoveal information may initiate the recognition process, but due to poor parafoveal perception, perceptual units within the word are imprecisely activated. Because sublexical representations of the preview and target are similar, these imprecise activations initiate activation of the target word, even though it is not yet presented. This implies that parafoveal preview activates a set of lexical items, rather than a single one.

Most studies that investigated and found evidence for trans-saccadic integration have used nonwords as invalid previews, which are on their own not recognizable and would not lead to the completion of the first stage of word recognition (i.e., saccade triggering). These “invalid” previews *should* impose a cost on reading efficiency, but it is unclear why: possibly due to a difference from the target (i.e., trans-saccadic integration failure) or possibly due to a lack of recognizability.

Another account of parafoveal preview: *Forced fixations*. Although trans-saccadic integration has successfully accounted for the majority of findings in gaze-contingent studies (see Schotter et al., 2012; Cutter et al., 2015; Vasilev & Angele, 2017), not all findings are compatible with this idea; a recent set of work that has investigated the effect of preview recognizability (i.e., independent of a relationship to the target) found data that cannot be explained by trans-saccadic integration. Schotter and Leinenger (2016) used the boundary paradigm with unrelated high and low frequency target words (e.g., “The boy found a red *phone*/*scarf* on his way to school.”) and previews that were either identical to the target (e.g., *phone* was a preview for *phone* or *scarf* was a preview for *scarf*) or the other member of the pair (i.e., the unrelated higher- or lower-frequency word, *phone* was a preview for *scarf* or *scarf* was a preview for *phone*, respectively). In the high frequency target condition, the unrelated preview led to longer fixation durations on the target than the identical preview—a *standard preview benefit*. However, in the low frequency target condition, the unrelated preview led to shorter fixation durations on the target than the identical preview—a *reversed preview benefit* (Figure 3).

Figure 3. Diagram of the design and results from Schotter and Leinenger (2016, Experiment 1). Single fixation duration on the target word as a function of target frequency, preview frequency, and display type. Example preview-target stimulus pairs are shown next to each condition mean and the comparisons used to show standard preview benefit and reversed preview benefit are noted. Error bars represent +/- 1 SEM. Figure adapted from Schotter and Leinenger (2016).

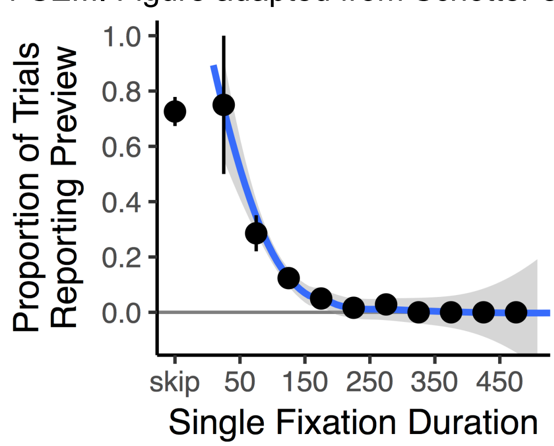


Because trans-saccadic integration accounts assume that target processing is better following similar compared to dissimilar previews, they cannot explain this reversed preview benefit, and likewise cannot explain *preview plausibility benefits*, where readers spend less time on a target when a completely unrelated preview was plausible compared to implausible (e.g., Schotter & Jia, 2016; Veldre & Andrews 2016). In contrast, an alternative account can explain these effects because it posits that the durations of (at least some) fixations are determined by information obtained during parafoveal preview, regardless of the subsequently fixated target information. On this account, previewing a word that is easy to process (i.e., plausible and/or high frequency) can lead the reading system to not only skip over it (Rayner, 2009), but also to make a *forced fixation* on it (Schotter & Leinenger, 2016). In fact, prior modeling work suggests that parafoveal information can sometimes be processed to such a degree that that it reaches the second stage of word identification based on the preview (i.e., semantic processing is initiated and saccades away from the word are initiated: Schotter, Reichle, & Rayner, 2014). Again, this idea is not new,

Unquestionably, the peripheral vision is sometimes satisfactory enough in itself without demanding clearer vision. Such is undoubtedly the case in reading for zones bordering on the macula [i.e., the parafovea].
(Dodge, 1907, pp. 58-59)

Forced fixations are short single fixations on the word before moving forward, even when the subsequently fixated target word is completely unrelated to the preview. More precisely, forced fixations are cases in which the system would otherwise skip the word – because it seemed easy to recognize – but the skipping decision was made too late, at a point when the saccade toward the to-be-skipped word could not be cancelled (see Becker & Jürgens, 1979; Rayner et al., 1983). During forced fixations, the reader should be insensitive to properties of the fixated word because attention has already shifted to the subsequent one (Morrison, 1984). Schotter, Leinenger, and von der Malsburg (2018) tested this prediction, by explicitly probing the reader's encoding of the text with two-alternative forced choice questions with the preview and target word as response options (see also Schotter & Jia, 2016). Readers reported reading the target word the majority of the time, except when they skipped over it or fixated it for less than 100 ms and did not reread (Figure 4). If the reader had reread the target word, they were extremely likely to report the target (i.e., rather than the preview), regardless of initial skipping or fixation duration because the re-encounter with the target word overrode the initial representation (Booth & Weger, 2013; Schotter, Tran, & Rayner, 2014).

Figure 4. Results from Schotter et al. (2018). Probability of reporting the preview as a function of fixation behavior (skipping or 50-ms bins of single fixation duration) as a function of which word was reported in response to the probe question for trials in which the target was not reread. The blue line represents a loess smoothed fit line for non-binned data and the grey envelope represents a 95% confidence interval, error bars on binned data represent ± 1 SEM. Figure adapted from Schotter et al. (2018).

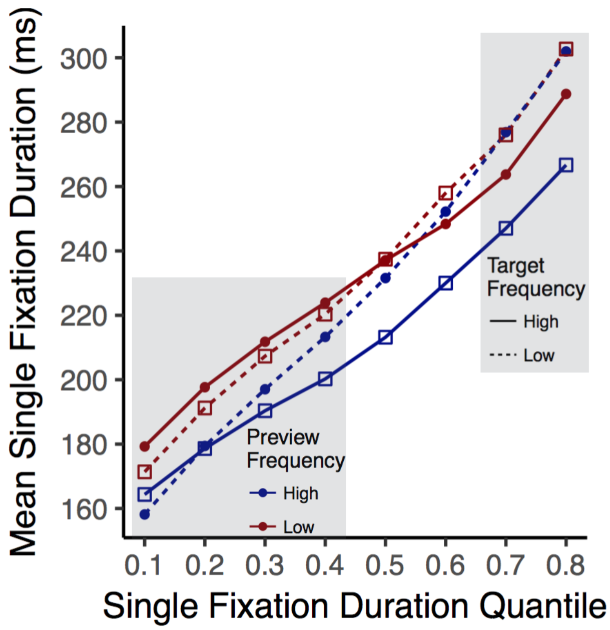


As Schotter et al. (2018) noted, during forced fixations on the target it appears as if readers did not encode the word they fixated - they *fixated it with their eyes but skipped it with their minds*. Importantly, in contrast to indirect control theories of reading (e.g., McConkie & Yang, 2003; Vitu, 2003), the likelihood and duration of forced fixations are determined by lexical properties, specifically the ease of lexically processing the parafoveal preview. Forced fixations are more likely when the parafoveal preview is easy to process (e.g., high frequency and/or plausible) than when it is not, and the saccade should be initiated sooner with increasing ease of recognition.

A hybrid account of parafoveal preview effects. As mentioned above, neither account is sufficient to explain the variety of parafoveal preview effects reported in the literature. Only trans-saccadic integration can account for standard preview benefit effects observed for parafoveal nonword previews that are orthographically similar (Rayner, 1975) or phonologically similar (Miellet & Sparrow, 2004) to the target; because nonword previews are not easy to recognize they would not lead to skips or forced fixations. Thus, preview benefits from nonwords that are linguistically related to the target suggest that sub-lexical information is obtained from the preview and, in some way, is used to facilitate processing once the target is fixated, perhaps via trans-saccadic linguistic integration or perhaps because the nonword preview was mistaken for the target word, due to their similarity. In contrast, only forced fixations can account for fixations that are relatively short on the target (i.e., those that would otherwise be skips) when the preview and target are substantially different. Because trans-saccadic integration relies on similarity these types of trials should lead to particularly long fixations, but when the preview is a plausible higher frequency word that is unrelated to the target, as in the *phone-scarf* example above (Schotter & Leinenger, 2016), fixation durations are shorter than when the preview and target are identical. Thus, there are multiple ways in which a parafoveal preview affects saccade triggering in reading, either independent of the target (i.e., via forced fixations) or in combination with it (i.e., via trans-saccadic integration). Importantly, these two mechanisms regard the relationship between word identification and saccadic control, and do not require differing underlying word recognition processes – the difference is a matter of speed or efficiency.

Using a quantile regression analysis, we demonstrated that fixations of different durations show different effects of the preview, target, or comparison thereof (Figure 5). Short fixations showed an influence of preview word frequency but not target word frequency whereas long fixations showed an influence of target word frequency but not preview word frequency. Lastly, intermediate quantiles showed an interaction (i.e., an effect of display change). These data suggest that, even within a single distribution of fixations obtained within a single study, there is evidence for different populations of fixations that are influenced by different linguistic properties.

Figure 5. Diagram of the results of the quantile regression from Schotter and Leinenger (2016). Mean single fixation duration as a function of fixation duration quantile, preview frequency, and target frequency. Figure adapted from Schotter and Leinenger (2016)



This variety of preview effects may be explained by a hybrid mechanism of saccade triggering (Reingold et al., 2012) that includes both forced fixations and trans-saccadic integration (Schotter & Leinenger, 2016). On this hybrid account, forced fixations reflect one saccade triggering mechanism that is engaged when the preview is easy to process, whereas preview costs reflect another mechanism that intervenes when trans-saccadic integration failure occurs (i.e., a lack of similarity between the preview and target). Phenomenologically, forced fixations are short fixations followed by progressive saccades whereas fixations that are influenced by trans-saccadic integration failure are relatively longer and/or followed by refixations or regressions. Because forced fixations are relatively short, there is little to no time for the foveal target information to enter the system (e.g., due to the retina-brain lag; Reichle & Reingold, 2013) by the time the progressive saccade leaving that word is executed, and therefore little influence of the target on the duration or likelihood of these progressive saccades. If trans-saccadic integration fails, it may only affect subsequent fixations and saccades (i.e., on the post-target word). When forced fixations do not occur (i.e., when the preview is difficult to process), fixations on the target are longer and there is more opportunity to obtain foveal information from it; these fixation durations are influenced exclusively by the frequency of the target (longest quantiles), or by the lack of similarity between the preview and target (intermediate quantiles: Figure 5).

Subsequent work by Schotter, von der Malsburg, and Leinenger, (2018) found a differential time course of regressions in response to trans-saccadic integration based on preview frequency. Their data suggest that it may not be the case that all short fixations show no effect of trans-saccadic integration failure, but rather the effect may not occur early enough to influence fixation durations on, or saccades out of, the target word. To test whether trans-saccadic integration (or failure thereof) depends on the likelihood of forced fixations (i.e., preview frequency), they manipulated a *probe region* at the end of the sentence that caused one, neither, or both words to become implausible, and inserted a *buffer region* between it and the preview/target region – in which both words remained plausible – to distinguish regressions due to trans-saccadic integration failure from those due to implausibility. Regressions due to trans-saccadic integration failure occurred earlier (i.e., from the target region) when the preview was low frequency, and later (i.e., from the buffer region) when the preview was high frequency. These findings align with the quantile regression analysis reported by Schotter and Leinenger (2016; see also Figure 5, above) showing a different time course of effects that depends on preview word properties (i.e., frequency). In contrast, regressions out of the probe region (for trials in which there were not already regressions out of prior regions – due to trans-saccadic integration failure) were only influenced by the plausibility of the target word, not properties of the preview or the display change. This finding aligns with the analysis reported by Schotter, Leinenger, et al. (2018) showing that, most of the time, the completion of word recognition is primarily based on information obtained during direct fixation on a word.

Prior debates about parafoveal processing: *Serial vs. parallel lexical processing*

The above hybrid account of parafoveal processing is a relatively new idea (although, as noted, it echoes conjectures made by researchers over a century ago), which considers parafoveal preview in a different way than much of the research that preceded it. The majority of prior research focused on the implications of parafoveal processing for models of saccadic control in reading, particularly the theoretical debate between models that assume that word identification occurs serially across words (e.g., *E-Z Reader*: Reichle et al., 1998; see Reichle, Liversedge, Pollatsek, & Rayner, 2009) or in parallel (e.g., *SWIFT*: Engbert et al., 2005; Schad & Engbert, 2012). These debates have primarily focused on two issues: (1) whether readers obtain semantic information during parafoveal preview (i.e., *semantic preview benefit*) and (2) whether lexical processing of the parafoveal word affects fixation durations on the preceding word (i.e., *parafoveal-on-foveal effects*). These are important theoretical questions, but it may be that the debates, as currently characterized, are ill-formed by setting up alternatives that are too strongly dichotomized. In fact, the framework I have laid out above suggests that these two issues may not tease the models apart because an overlap in linguistic processing of the upcoming word and the fixation on the current word is possible within the architecture of a serial lexical processing model. These two issues have captured the attention and focus of electrophysiology studies of parafoveal preview (see electrophysiological evidence sections below), but in doing so have limited the potential for those studies to fully explore the relationship between cognitive-linguistic processing and saccadic control in reading.

Semantic preview benefit. Because semantic processing of words is presumed to occur after processing of other properties (e.g., orthography and phonology), researchers have argued that evidence for semantic processing during parafoveal preview would be more compatible with parallel lexical processing models (e.g., Engbert et al., 2005; Reilly & Radach, 2006) than serial lexical processing models (e.g., Reichle et al., 1998). Early studies did not find evidence for semantic preview benefit by comparing preview words that were semantically related and unrelated to the subsequently fixated target word (Altarriba, Kambe, Pollatsek, & Rayner, 2001; Hyönä & Häikiö, 2005; Rayner, Balota, & Pollatsek, 1986, Rayner, Schotter, & Drieghe, 2014).

However, subsequent studies did find evidence for semantic preview benefit using similar experimental designs (Hohenstein & Kliegl, 2014; Hohenstein, Laubrock, & Kliegl, 2010; Yan, Richter, Shu, & Kliegl, 2009; Yan, Zhou, Shu, & Kliegl, 2012; Yang, 2013; Yang et al., 2012). Initially, these differences were explained cross-linguistically; semantic preview benefit might be more likely in orthographically shallow languages like German, or languages for which there is a more direct connection between orthography and semantics like Chinese, than it is in an orthographically deep alphabetic language like English (Laubrock & Hohenstein, 2012; Schotter et al., 2012). However, subsequent work revealed that semantic preview benefit occurs even in English (e.g., for synonymous preview; Schotter, 2013) and the presence depends on whether the initial letter is capitalized (i.e., draws attention to the preview: Rayner & Schotter, 2014), the sentence is constraining (Schotter, Lee, Reiderman, & Rayner, 2015), and, most importantly, whether the preview is plausible in the sentence context (Schotter & Jia, 2016; Veldre & Andrews, 2016a,b; cf. Yang, Wang, Slattery, & Rayner, 2014 for similar effects in Chinese). This latter finding aligns with the idea of forced fixations, described above; to the extent that the parafoveal preview is easy to process (i.e., plausible), it can lead to shorter fixation durations, potentially irrespective of a relationship to the target. As discussed above, this latter explanation is not necessarily incompatible with a serial account because simulations of the data from Schotter (2013) showed that the E-Z Reader model had reached the presumed semantic activation (i.e., second) stage of word recognition based on the parafoveal preview, and consequently had initiated saccade programming (Schotter, Reichle, et al., 2014).

Parafoveal-on-foveal effects. While the above literature focuses on whether semantic information can be accessed from the parafovea to influence subsequent fixations on the target, the core of the theoretical debate surrounding parafoveal-on-foveal (PoF) effects regards whether lexical (and semantic) information accessed in the parafovea influences reading of the previously fixated word (see Drieghe, 2011; Hyönä, 2011; Schotter et al., 2012). Models that assume words are processed serially would not predict lexical properties of the upcoming word to affect saccade decisions for the preceding word, but parallel models should, in theory. Note that parallel models do not explicitly have a mechanism to implement PoF effects; for example, the most prominent of these models (i.e., the SWIFT model; Engbert et al., 2005) only includes a mechanism for *foveal* influences on saccade timing, not *parafoveal* influences (cf. Schad & Engbert, 2012).

Most evidence for PoF effects comes from non-reading tasks. For example, some researchers suggest PoF effects occur when participants make lexical or semantic decisions about a centrally presented word with related or unrelated flankers (Bradshaw, 1974), but these effects did not hold when fixation position was monitored to ensure that subjects did not move their eyes to the flanker words (Inhoff and Rayner, 1980; Inhoff, 1982).

In a reading context, most positive evidence for lexical PoF effects comes from corpus analyses (Kennedy, 1998; Kennedy & Pynte, 2005; Kliegl, 2007; Kliegl et al., 2006), which lack tight experimental control that allows for causative inference. In contrast, experimentally controlled studies have not found evidence for lexical PoF effects (Angele & Rayner, 2011; Angele et al., 2008; Carpenter & Just, 1983; Henderson & Ferreira, 1993; Inhoff, Starr, & Shindler, 2000; Rayner, Juhasz, & Brown, 2007; Staub, Rayner, Pollatsek, Hyönä, and Majewski, 2007). Importantly, in a study that combined a corpus analysis and an experimental manipulation of word frequency and of access to the word in parafoveal vision via a moving parafoveal mask, small lexical PoF effects (i.e., 1 ms effects) were observed both when the parafoveal preview was visible and when it was masked (Angele, Schotter, Slattery, Tenenbaum, Bicknell, & Rayner, 2015). These data suggest that evidence for lexical PoF effects observed in corpus analyses should be judged with skepticism, because they may not be due to parafoveal lexical information influencing incoming saccade decisions, but rather something about the structure of the sentence (i.e., a property of the currently fixated word is correlated with the frequency of the upcoming word).

An important thing to note about PoF effects is that the debate regarding the models centers on whether parafoveal processing of the word affects *fixation durations* on the prior word. Some ERP studies, which are reviewed below, expand the definition of these effects beyond fixation durations and interpret ERP components relating to the parafoveal word as PoF effects. However, such evidence of parafoveal processing is not necessarily incompatible with a serial attention shift model (i.e., if it occurs after the lexical processing for the fixated word; see Schotter, Reichle, and Rayner, 2014) and therefore should be considered a parafoveal preview effect rather than a PoF effect. More specifically, those effects reflect the type of processing implied by forced fixations, rather than trans-saccadic integration. That is, parafoveal processing progresses so far as to cause skipping or pre-initiated saccades away from the parafoveal word, and sometimes to higher level word processing (e.g., the kind reflected in the N400).

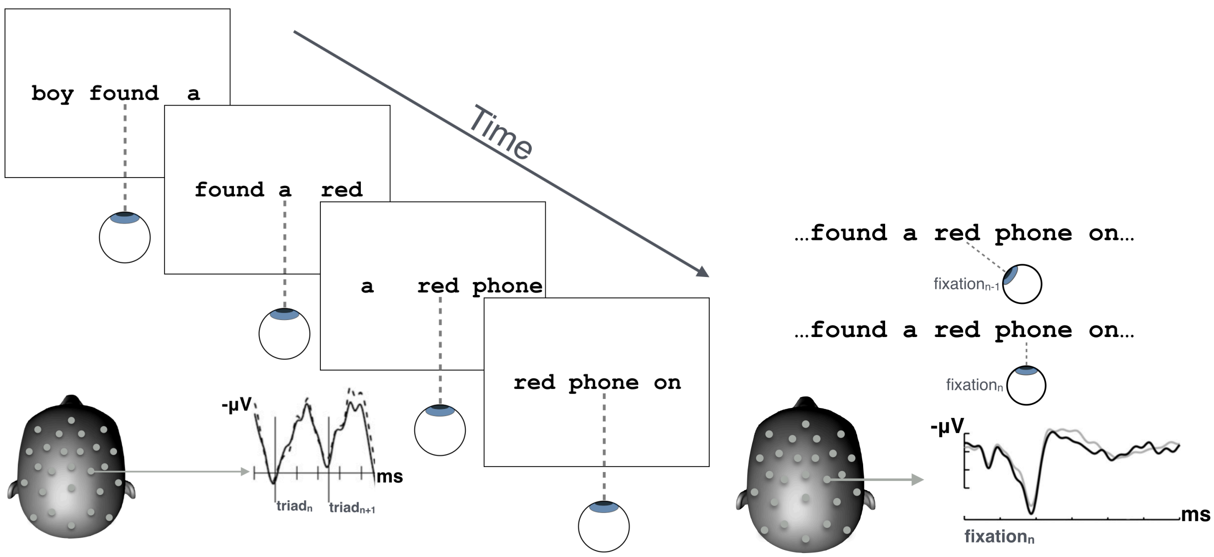
Evidence for parafoveal processing from electrophysiology studies

As mentioned at the beginning of this article, there is an apparent paradox posed by comparisons between eye tracking and ERP studies with respect to the timing of word recognition. Lexical information about words influences eye movements as early as the decision to skip them (i.e., *before* they are fixated), but also affects ERP components that peak sometimes as late as 400 ms after the word is presented. Rayner and Clifton (2009) suggested that this discrepancy may be explained by methodological differences, for example (1) the presentation rate of the RSVP stream in ERP research tends to be much slower than the timing of natural reading, (2) RSVP studies traditionally have presented only one word at a time, eliminating the possibility of parafoveal preview, and (3) ERP research has focused on the N400 component, but there may be earlier, smaller components that reflect effects analogous to those observed in the eye movement record. As will be clear from much of the review that follows, I doubt the first explanation, but the combination of the second and third is quite similar to the hypothesis proposed above - mainly that single word RSVP studies haven't allowed for parafoveal preview, and saccade latencies and ERPs (or at least the N400) measure different aspects of the reading process.

Tests of the assumptions of saccadic control models of reading with ERPs. Sereno, Rayner, and Posner (1998) compared the timelines of the effects of lexical properties (i.e., word frequency, and orthographic regularity) using the same stimuli in both a reading task with eye tracking and a lexical decision task using ERPs (see also Dambacher & Kliegl, 2007). They found an early effect of word frequency in the ERP record and proposed a timeline of lexical access during reading that overlapped with (but was not complete by) the time that the saccade program was initiated (see also Sereno & Rayner, 2003). This conclusion is based on deduction and comparisons between independent measurements of eye movements and ERPs, but has also been tested directly by measuring ERPs in the time window leading up to a saccade (Reichle, Tokowicz, Liu, & Perfetti, 2011). Reichle et al.'s participants made lexical decisions to simultaneously presented but spatially separated pairs of letter strings, one at fixation and one in the periphery, such that they had to fixate each word sequentially and make lexical decisions to each one. To investigate the neurocognitive processes that led to the decision to move the eyes, they time-locked the ERP waveform to the onset of the saccade away from the first word and examined the ERP components that occurred prior to it. They included a frequency manipulation to see whether it had an influence on such neurocognitive processes and found an effect of word frequency as early as 125-150 ms before saccade onset, which is consistent with saccade planning time estimates (e.g., Becker & Jürgens, 1979; Rayner et al., 1983) and with the assumptions of a model in which there are two stages of word recognition and the completion of the first one initiates saccade programs (e.g., the E-Z Reader model).

A recent review of ERP evidence of the neurophysiological constraints on the eye-mind link (i.e., the coordination of cognitive processing and saccadic control) suggested that "the temporal constraints are too severe to permit direct lexical control of eye movements without a significant amount of parafoveal processing" (Reichle & Reingold, 2013, p. 1). However, as mentioned by Rayner and Clifton (2009), most ERP studies have not allowed parafoveal preview due to the use of single word RSVP. Since Rayner and Clifton's paper, several new studies have been published that address these limitations, and start to bridge the gap between reading research using eye movements and ERPs. In general, these studies take two approaches: (1) use an *RSVP with flankers paradigm* to measure ERPs in the canonical way (i.e., using RSVP to ensure tight experimental control) and provide parafoveal preview via parafoveal flankers or (2) use a *Fixation Related Potentials (FRPs) paradigm* to measure ERPs during natural reading with saccades and correct for artifacts in the EEG record afterward (Figure 6). These studies have revealed evidence of parafoveal lexical processing, but as mentioned above, it is unclear whether such processing occurs during or after lexical processing of the fixated word, and therefore whether these data are compatible or incompatible with a serial model of lexical identification. Moreover, many of these studies have not used a reading for comprehension task, so it may be unclear whether the results generalize to reading scenarios. Nonetheless, these studies provide important preliminary data for future work that may directly test these theories.

Figure 6. Schematic diagram of the RSVP with flankers paradigm (left) and the Fixation Related Potentials paradigm (right).



RSVP with flanker paradigm. Barber, Doñamayor, Kutas, and Münte (2010) tested whether the brain registers semantic information from parafoveal words using a modification to the traditional ERP paradigm. German readers read sentences in which the words were presented via RSVP in triads such that the centrally fixated word was flanked two degrees (i.e., in the parafovea) bilaterally by the preceding and succeeding word. On the critical trials, the rightward parafoveal word was either the appropriate word in the sentence, or was replaced with a semantically incongruent word. They found that the incongruence elicited an N400 effect, suggesting that the readers had begun to process the word's meaning prior to it being directly fixated. Barber, Ben-Zvi, Bentin, and Kutas (2011) conducted a similar paradigm in which the flanker strings were pseudowords except for the third triad of each sentence, which was flanked either by two pseudowords, or by a pseudoword/word combination in which the word randomly appeared on the left or right, and was either semantically congruent or incongruent with the sentence. They compared native readers of English and Hebrew, reading in their respective languages, to assess whether any parafoveal effects they observe were related to canonical reading direction. In studies of eye movements in reading, these two languages lead to different asymmetries of the allocation of parafoveal attention: parafoveal processing extends further to the right in English (and other languages that are read from left-to-right) and extends further to the left in Hebrew and Arabic, which are read from right-to-left (Pollatsek, Bolozky, Well, & Rayner, 1981; see also Jordan et al., 2014). In the ERP study, parafoveally presented incongruent words elicited larger P2 amplitudes than congruent words and this effect was observed only when the word was in the rightward parafovea for English readers and only when the word was presented in the leftward parafovea for Hebrew readers (Barber et al., 2011). Thus, these data suggest that ERP evidence for parafoveal processing in this paradigm is related to the parafoveal allocation of attention that is generally part of reading.

In subsequent work, Barber, Meij, and Kutas (2013) tested whether the degree to which readers access semantic information parafoveally depends on the sentence context. Akin to the idea that foveal load decreases the amount of parafoveal preview (i.e., because processing of the currently fixated word is more attention-consuming; Henderson & Ferreira, 1990), they found larger responses to parafoveally presented incongruous words when the fixated word was predictable, thereby allowing more cognitive resources to be allocated parafoveally. Similar effects were observed by Payne, Stites, and Federmeier (2016); the brain's response to the orthographic legality of the upcoming parafoveal word was modulated by the semantic predictability of the fixated word. Zhang, Li, Wang, and Wang (2015) replicated these findings and found that the effect was observed even when the word that created the congruity was read earlier in the sentence, suggesting that the effects were due to sentence-level integration processes, rather than word-level semantic priming. Thus, these studies suggest that parafoveal processing indicates semantic processing of upcoming words and is modulated by the difficulty of foveal processing. These findings alone do not distinguish between serial and parallel lexical processing models in reading without knowing more about the time course of the parafoveal processing relative to the foveal processing. If foveal load affects parafoveal processing by delaying the time at which it can start, even a serial model can account for foveal load effects (Schotter, Reichle, & Rayner, 2014).

Stites, Payne, and Federmeier (2017) found that readers' brain responses demonstrated graded responses to the parafoveal words' semantic fit into the sentence (i.e., not only an effect of congruous versus incongruous words, but an effect of plausibility or *degree* of expectedness). In contrast, responses to foveal words showed only an effect of anomaly, suggesting that they had done a substantial amount of word processing from the parafovea and therefore needed to allocate less cognitive effort to unexpected, but not anomalous, when they subsequently fixated them. Simultaneous work showed that the processing of words across the visual field differs for older readers: they showed both a graded effect of semantic fit in response to words viewed both parafoveally and foveally (Payne & Federmeier, 2017), suggesting that older readers process words parafoveally, but perhaps do not complete the processing then and therefore require more foveal processing than younger adults. These data may be compatible with the idea of trans-saccadic integration, but because there were no manipulations of "preview validity" (i.e., the identity of the words did not change between when they were presented parafoveally and foveally) such conclusions are premature.

Only a few studies have addressed the question of whether parafoveal information is integrated with subsequent foveal information. Barber et al. (2013) also manipulated the congruity of the word when it was presented in foveal vision, which allows for two important comparisons. First, they were able to directly compare foveal and parafoveal responses to semantic incongruity, which were clearly larger for foveally presented words (i.e., there was a greater amplitude difference between the congruent and incongruent conditions). Second, they were able to test whether similarity between the parafoveal and foveal stimulus had an effect on the brain's response, and it seems as if it did not. Barber et al. (2013) suggested that this lack of an effect is difficult to explain, but as discussed earlier, trans-saccadic integration is not the sole mechanism for parafoveal preview effects. Subsequent work by Li, Niefind, Wang, Sommer, and Dimigen (2015) on Chinese readers did find an effect of similarity between the parafoveal and foveal stimulus, in that valid previews elicited a more positive N1 component once the word was view foveally than did invalid previews. Clearly more work is needed to determine the conditions under which such trans-saccadic integration can be observed. However, we may not expect all findings in the eye movement literature to have analogous findings in the ERP literature because many aspects of the reading architecture may change during RSVP.

The previously reviewed studies suggest that parafoveal lexical/semantic processing does occur, which is an important demonstration that this paradigm works, but does not address the theoretical debates, or the new theoretical framework I laid out above. One question about the generalizability of these studies is whether, during natural reading, the foveal words in these triads *would have been fixated*. Words tend to be skipped when they are predictable (see Staub, 2015), short and/or high frequency (see Drieghe, Brysbaert, Desmet, & De Baecke, 2004); in the RSVP with flankers paradigm, forcing a reader to fixate a word they might otherwise not have, or for longer than they normally would have if they had fixated it, might encourage parafoveal processing and therefore over-estimate the degree of it relative to natural reading.

Together, these studies align well with much of the research reviewed above: readers are able to access semantic information from upcoming words when reading for comprehension, especially when the word is upcoming (i.e., to the right for readers of German and English, or to the left for readers of Hebrew) and when the fixated word easy to process (i.e., highly expected). As mentioned, it is unclear whether the tight experimental control over the presentation of the words caused more parafoveal processing than readers might otherwise take advantage of (i.e., they may have already moved their eyes to fixate the word before the transition to the next word triad).

Fixation Related Potentials (FRPs) paradigm. The theoretical framework I laid out above specifically regards how parafoveal linguistic processing relates to saccadic control during reading. One of the limitations to the RSVP with flankers paradigm is that participants are required to hold fixation, so any aspect of the reading process that relates to attention shifting to the upcoming word prior to the saccade may be diminished or eliminated. In fact, Kornrumpf, Niefind, Sommer and Dimigen (2016) found that electrophysiological measures of parafoveal processing (e.g., an effect they termed the N1 preview effect) were smaller in the RSVP with flankers paradigm than in FRP paradigm when participants were “reading” word lists. Similar findings were reported by Niefind and Dimigen (2016), who replicated the study (i.e., compared the FRP and RSVP with flankers paradigms when subjects were “reading” word lists) and also incorporated a preview validity manipulation. They orthogonally manipulated preview word frequency and validity much like Schotter and Leinenger (2016; see also Risse & Kliegl, 2014); they found effects of parafoveal word frequency during the fixation on the previous word in the FRP paradigm, but not the ERP with flankers paradigm, perhaps because the participants were less likely to shift attention to the parafovea when they were not making saccades. These findings also contrast with the parafoveal N400 effects in the RSVP with flankers paradigm studies reported above, perhaps because “reading” word lists reduces lexical parafoveal processing; this could be because the stimuli reduced the benefit of prior semantic/syntactic context, or because the task introduced cognitive load associated with doing something other than understanding (i.e., making a decision about whether one of the words in the list was an animal). In fact, Kornrumpf et al. (2016) reported that foveal load reduced parafoveal effects in both eye movements and electrophysiological measures.

Baccino and Manunta (2005), who introduced the method of time-locking brain activity and saccades (i.e., FRPs), investigated PoF effects (i.e., effects of parafoveal word properties during fixation on the previous word) while participants made semantic decisions about word pairs that they needed to make saccades between. They found little evidence for semantic PoF effects, but did find effects of parafoveal word status (i.e., whether the parafoveal stimulus was a word or nonword). As noted above, such sub-lexical PoF effects do not distinguish between serial and parallel models of word identification. Moreover, they only investigated early FRP components (i.e., those within the time window of the fixation) so it is unclear whether there was any evidence for semantic processing, as other studies have shown that parafoveal semantic effects are observed in the N400 component (see review, above). López-Peréz, Dampuré, Hernández-Cabrera, and Barber (2016) replicated Baccino and Manunta (2005) but used a larger time window (i.e., included the N400) and incorporated a display change to investigate preview validity effects. They found a parafoveal N400 effect in the FRPs, but no PoF effect in the eye movements. Such differences in these findings suggest that parafoveal N400 effects should not be considered PoF effects, but rather parafoveal preview effects (see discussion in the PoF effects section, above).

Dimigen, Kliegl, and Sommer (2012) used the boundary paradigm and measured

FRPs while subjects "read" word lists to investigate trans-saccadic integration. They reported a *preview positivity* that peaked approximately 200-280 ms after fixation on the target word that only differentiated the identical condition from display change conditions but did not differentiate semantically related from unrelated conditions. This preview positivity might indicate trans-saccadic integration (failure), and the timeline is within a reasonable fixation duration for it to cause increased fixation durations or regressions observed in the eye movement record. This contrasts with a later timing of preview validity effects reported by López-Peréz et al. (2016), which may have been due to a task difference (i.e., two words versus longer lists of words) or a difference in stimuli. Given how few studies have been conducted on preview validity effects in FRPs, more work needs to be done to determine which components are most reflective of trans-saccadic integration processes.

All the studies on FRPs reported here have not used a reading for comprehension task, but rather a task in which subjects are required to make saccades between words and make some sort of decision. Such a task has methodological advantages in that it makes it more likely that subjects will fixate each word, and will be likely to do so only once, which reduces data loss (e.g., due to skipping) and makes data processing and analysis more akin to traditional ERP studies. However, such tasks are not completely analogous to reading for comprehension and it is not entirely clear how such a task change affects the underlying cognitive processes involved. It is clear that task changes not only affect saccadic control (e.g., proofreading leads to less skipping and longer fixations than reading), but also cognitive processing associated with word identification (e.g., word frequency, and sometimes predictability, effects are larger in proofreading than in reading for comprehension; Kaakinen & Hyona, 2010; Schotter, Bicknell, et al., 2014). The only study, published to date, which investigated parafoveal processing using FRPs in a naturalistic reading task was reported by Kretzschmar, Bornkessel-Schlesewsky, and Schlesewsky (2009). They had subjects read sentences that were manipulated such that a particular word was highly expected (i.e., "The opposite of black is ____") and either presented the predicted word (i.e., *white*), a related word (i.e., *yellow*) or unrelated word (i.e., *nice*). They found a foveal N400 effect (i.e., once the word was fixated) that differentiated the predicted from either unpredicted word, and a parafoveal N400 effect (i.e., during the last fixation prior to landing on the target) that differentiated the unrelated from both the expected and the related word. The differential pattern of findings between the parafoveal effect and the foveal effect suggests that readers had accessed the word's meaning prior to fixating it, but the nature of that process was different than the semantic processing they had done during direct fixation; for example, an initial process based on semantic spreading activation and then a second process based on pure predictability (see Kretzschmar et al., 2009). Alternatively, these data may reflect a singular process of word recognition in which readers hone in on a particular word (i.e., narrow a set of lexical candidates), and do so using a range of information (e.g., prior linguistic context, parafoveal preview, etc.).

It is exciting that a growing number of studies are co-registering eye movements and EEG, and these studies have the potential to help shed light on questions about the extent, nature, and timing of parafoveal lexical processing in reading. At the moment, these studies only provide preliminary evidence that parafoveal lexical processing occurs, even to the point of semantic processing of the parafoveal word, but much more work needs to be done to determine (1) whether this processing occurs after lexical processing of the fixated word, or in parallel with it, and (2) how such processing interacts with saccade planning (e.g., word skipping, forced fixations, trans-saccadic integration failure that may lead to regressions, etc.). As more of these co-registration studies are planned, it is important to connect their design with what we know about the timing of lexical processing and saccadic control, and the constraints they mutually impose on each other (i.e., the assumptions of computational models of oculomotor control and cognitive processing in reading). To this end, the final section of this paper covers current issues in modeling parafoveal preview effects in reading.

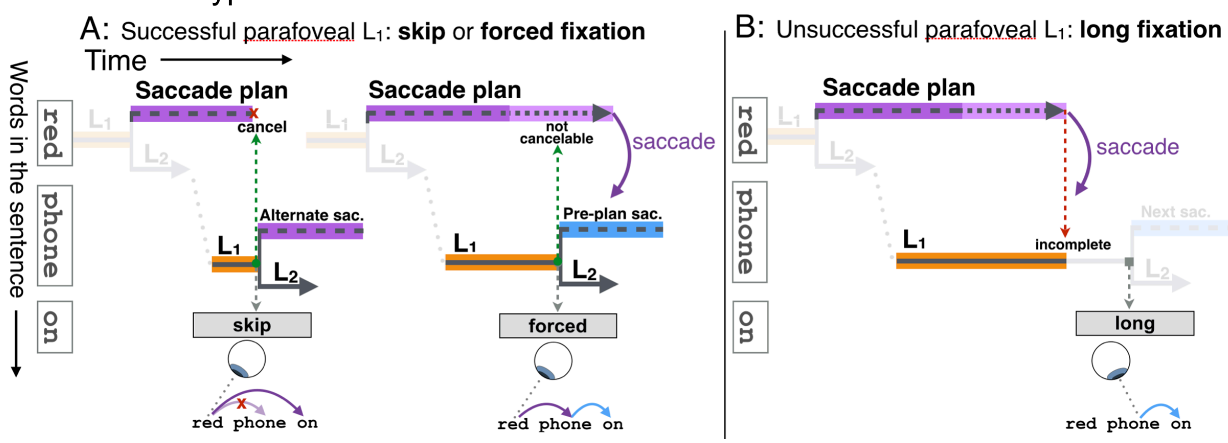
Modeling parafoveal preview effects

Because the effects of parafoveal preview have important implications for models of saccadic control in reading, it is important to understand how such models would be able to explain the types of effects summarized here. Few simulations have actually addressed parafoveal processing directly, so many of the explanations that follow are merely conjecture – the actual modeling work still needs to be done. Furthermore, these modeling efforts have not yet incorporated any data from the RSVP with flankers paradigm or the FRP paradigm.

Modeling forced fixations. As mentioned above, current models of oculomotor control in reading posit that the decision to start planning a saccade forward from a word is made before complete recognition of it. For example, the E-Z Reader model (Reichle et al., 1998) posits two stages of word recognition; the first stage is a *familiarity check* (L_1), which initiates both saccade programming and a second stage of *lexical access* (L_2), in which word recognition is completed. Given this architecture, forced fixations can already be explained within the E-Z Reader model (Reichle et al., 1998) and potentially any model that has two-stage lexical processing and two-stage saccade program assumptions (e.g., Engbert et al., 2005). In fact, the forced fixations account that Schotter and Leinenger (2016) proposed was based on the modeling approach of Schotter, Reichle, and Rayner (2014), who used the E-Z Reader model to simulate data from Schotter (2013) and to estimate how far into lexical processing the model has progressed based on the preview. They found that there were times in which the model reached the second stage of word recognition (i.e., L_2, which is initiated by the completion of the completion of L_1, which also initiates saccade programming).

Within the architecture of the E-Z Reader model, fixation behavior on the upcoming word depends on the timing of word recognition of the upcoming word relative to the timing of saccade planning toward that word (Figure 7). In addition to the two stages of word recognition mentioned above (represented with solid horizontal lines), E-Z Reader posits two stages of saccade planning (represented with dashed horizontal lines); during the first stage (M_1: dark purple bar), the current saccade plan can be canceled but during the second stage (M_2: light purple bar) the current saccade cannot be cancelled. If L_1 (orange bar) for the upcoming word completes during the M_1 stage of the saccade program toward it, that saccade would be cancelled and replaced with a skip (Figure 7a, left side: lower dark purple bar). However, if L_1 for the upcoming word completes during the M_2 stage, the saccade toward that word could not be cancelled, and the system would instead pre-initiate the subsequent saccade program forward from the upcoming word (Figure 7a, right side: lower blue bar) because saccades can be programmed in parallel (Becker & Jürgens, 1979; Morrison, 1984; Rayner et al., 1983). The pre-initiation of saccade programs, due to an inability to execute a skip, leads to the intervening fixation on that word being relatively short – these are forced fixations (Figure 7a, right side). When skips or forced fixations do not happen, the word will be fixated for a relatively longer amount of time, and foveal information is needed in order to initiate the progressive saccade (Figure 7b). If the display had changed in these cases, the system must deal with the fact that the new information obtained in the fovea differs from the information that has been previously obtained from the parafovea and may be subject to trans-saccadic integration failure.

Figure 7. Schematic of how the architecture of the E-Z Reader model can lead to three different types of fixation/saccade behaviors.



Modeling trans-saccadic integration. The issue of modeling trans-saccadic integration is more complicated than the relatively straightforward and currently implemented forced fixations scenario. To adequately model how preview and target information are adjudicated when both are represented, one needs a detailed account of the process of word recognition in the context of saccadic control in reading that incorporates parafoveal preview. Extant modeling work has not yet done this, and instead has focused on explaining standard preview effects with two approaches that make different assumptions. One approach assumes that lexical processing does not start until fixation on the target (e.g., Pollatsek, Reichle, & Rayner, 2006; Sheridan & Reichle, 2016), analogous to the idea that there is only an influence of the target word. The other approach assumes that lexical processing resets after a display change (e.g., Risse, Hohenstein, Kliegl, & Engbert, 2014), analogous to the idea of trans-saccadic integration failure.

It may be the case that delaying lexical processing is what happens when the parafoveal preview is completely unrecognizable (i.e., an orthographically illegal nonword or an x mask), but such a process could not explain why nonword previews that are orthographically or phonologically related to the target provide a benefit relative to unrelated previews (i.e., trans-saccadic integration). Likewise, completely resetting lexical processing after a display change would not be able to account for these effects, either. Therefore, any model simulations that set out to explain standard preview benefit effects (i.e., those that align with the idea of trans-saccadic integration) must, to some degree, take into account how the words are represented *as they are being processed*. That is, presumably these standard preview benefit effects are due to the “resetting” of processing being less severe or costly when the preview and target are similar compared to when they are dissimilar. This may mean that sublexical components are activated in the process of word recognition and are used for trans-saccadic integration. Alternatively, these sub-lexical units may be used to narrow down a set of lexical candidates – to the extent that the nonword preview leads the reader toward word forms like the target word, that word will be processed more easily if it is subsequently encountered. Teasing apart these alternatives is an exciting area for future research because adequately simulating these effects might give us a better idea of the ongoing process of word representation during reading.

Summary

In this paper, I reviewed eye tracking and electrophysiological evidence suggesting that readers start to read a word before looking at it (i.e., obtain parafoveal preview), and discussed different theories about how that preview affects the reading process. I suggested that the key to understanding reading efficiency is understanding that, although the durations of fixations are determined by language processing, readers plan to move their eyes forward from a word before they have completely identified it (i.e., hedge their bets on the success of word recognition). When the word is processed in parafoveal vision and is (or rather, seems) easy to identify, the reader may make saccade decisions (i.e., skip over it or make a forced fixation on it) and potentially not even register what the word was when they did fixate it. When this doesn’t happen, the parafoveal information may be compared or integrated with subsequently obtained foveal information (i.e., via trans-saccadic integration). I suggest that, together, these two processes contribute to a hybrid mechanism of saccadic control.

Many open questions remain about the role of parafoveal processing in reading, and we should not forget to return to the theories and explanations that have been proposed over a century ago, as many of them are still supported by work that is being conducted using methodologies those researchers likely had never imagined were possible. As Dodge notes,

> The adequacy of a fixation is a relative matter, depending … on central conditions, and in part on a number of peripheral circumstances ... A complete analysis of the relative influence of these various factors would be a most desirable piece of experimental work for which considerable material is already at hand.
> (Dodge, 1907, p. 27)

To answer all of the questions about parafoveal processing in reading would be an amazing scientific feat; there has already been a great amount of work aimed at addressing these questions by various researchers, across many fields. But, as should be clear from the fact that we have been investigating these questions for over a century, in order to gain more traction on these issues the somewhat insular fields eye movements in reading and electrophysiology of language comprehension should engage in more collaboration and cross-pollination of ideas. For example, what kind of information is used in the decision to trigger saccades, if it is not complete word recognition? Does this architecture suggest that pre-saccade plan and post-saccade plan word recognition are two distinct processes that are influenced by different linguistic properties or cognitive processes, or that there is it a “threshold” in a singular process that creates the distinction? If so, is this threshold something that is fixed for a reader, develops with experience, or is flexible from moment to moment? Currently, models of saccadic control contain parameters that account for three benchmark effects on fixation durations (e.g., word length, frequency, and predictability) but we currently do not have a detailed account of the *process* of word identification during reading.

Electrophysiology studies may help shed light on the word identification in reading, but there are few extant studies using either the RSVP with flankers paradigm or the FRP paradigm, and many used tasks that only *approximate* reading. Furthermore, when taking advantage of the strengths of one methodology, we often lose the rich information (i.e., the signal) afforded by the other. Therefore, more work needs to be done to detail how ERP components index different aspects of parafoveal processing (e.g., which component relates to parafoveal processing of frequency, sensibility, etc., and which component relates to trans-saccadic integration). The framework I have laid out here may help with this endeavor, by allowing researchers to group trials by saccade behavior (e.g., skip, forced fixation, long fixation, etc.) and investigate the neurocognitive components that should, in theory, reflect similar processing (e.g., word recognition based on the preview, or trans-saccadic integration). With respect to the idea of trans-saccadic integration, it is not clear whether it is one process (e.g., a holistic comparison between the preview and target representations), a constellation of processes (e.g., orthographic comparisons, phonological comparisons, semantic comparisons, etc.), or not an integration process at all (i.e., the consequence of the narrowing of lexical candidates based on sublexical and contextual information).

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