WHAT IS THE MOST PLAUSIBLE ACCOUNT OF THE ROLE OF PARAFOVEAL PROCESSING IN READING?

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Online reading requires exquisitely precise co-ordination of the oculomotor processes involved in extracting and integrating information from both the word currently fixated in foveal vision and upcoming words in the parafovea. Parafoveal preview effects, assessed using the gaze-contingent boundary paradigm, provide a rich source of evidence about the extent and depth of processing conducted on upcoming parafoveal words and how it contributes to reading. This review focuses on recent demonstrations of plausibility preview effects which provide strong evidence that readers extract semantic information from parafoveal words, and that newly identified words are rapidly and incrementally integrated with the developing representation of the sentence to generate graded predictions about potential plausible continuations. Individual differences in the quality of skilled readers' lexical representations, indexed by the combination of reading and spelling ability, determine how semantic and contextual information extracted from parafoveal words influences oculomotor control. This evidence has important implications for theories of eye movement control in online reading.

Keywords

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Running head: Parafoveal processing in reading

Successful reading comprehension requires exquisitely refined co-ordination of a complex array of operations: automatic perceptual, oculomotor, and cognitive processes extract information from written text which provides input to the more attentionally demanding processes required to retrieve word meanings and integrate them with information from long-term memory in order to construct sentence and discourse representations. Although models have been proposed to explain each of these components in isolation (see Reichle, 2015), research on reading has been fragmented. Isolated word recognition and reading comprehension have been investigated and modelled relatively independently, within different research traditions. But the central questions about reading lie between these two traditions, at the interface between lexical retrieval and comprehension: co-ordinating the simultaneous demands of word identification and comprehension processes lies at the heart of reading skill.

Efficient word identification is central to skilled reading because words provide the bridge between spoken and written language processing (Andrews, 2006). As elaborated below, the precision and coherence of readers' lexical representations that define Perfetti's (2007) influential construct of *lexical quality* remain significant predictors of individual differences among skilled readers (Andrews, 2008, 2012, 2015). But to justify a claim that lexical quality is critical for skilled *reading* it is necessary to consider how lexical retrieval fits into the broader architecture of the reading system and specify the role it plays during online text reading (Andrews & Reichle, 2019).

Eye-tracking is an ideal methodology for investigating the role of lexical retrieval in online reading because it provides fine-grained, real-time measures of reading behaviour that yield rich insights into how readers translate the perceptual information in text into a conceptual understanding of its meaning in ecologically valid conditions that approximate naturalistic reading (Rayner, 2009). This review focuses on *parafoveal preview effects* during sentence reading: a robust

eye movement phenomenon that provides a window on the timecourse and co-ordination of lexical processing and oculomotor control during reading.

1. The role of oculomotor control in skilled reading

Efficient oculomotor control is a critical, reading-specific skill. During reading, the eyes move across the lines of a text through a series of rapid movements, or *saccades,* that average 7-9 letters in length, which are interspersed by brief *fixations*, averaging 200-250 ms duration, when the eyes are static. Visual acuity is greatest at the *fovea* – the central 2° of the visual field – so saccades are necessary to project new information into this high-acuity region to extract the high spatial frequency information required to identify words. Comprehending a sentence or text therefore requires readers to somehow integrate information obtained from the temporally and spatially distributed 'snapshots' obtained on successive fixations.

To interrogate how this is achieved, reading researchers use a systematic set of eye movement measures, summarized in Table 1, to draw inferences about the processes underlying word identification and comprehension. *First-pass fixation duration* measures and *skipping* probability are typically interpreted as indexing early word-identification processes, while the later *second-pass fixations* and regressive eye movements that contribute to *go-past* and *total fixation* duration measures are attributed to re-analysis processes associated with the integrative and inferential processes required for comprehension. In combination, these measures provide highly refined information about the time-course of online reading.

TABLE 1 ABOUT HERE

Although visual acuity is very limited in the *parafovea* (~6-15 characters from fixation), the speed of reading is severely reduced if the information available to the reader is artificially limited to foveal vision (Rayner, 1975), indicating that parafoveal information is essential to fluent reading. Evidence from the *gaze-contingent moving window paradigm* (McConkie & Rayner, 1975, 1976), in

which readers are presented with a limited window of text that moves with each fixation, shows that skilled readers require a text window of around 18 characters to read fluently (see Rayner, 2014, for review). The constraints on this *perceptual span* appear to reflect cognitive and linguistic factors rather than visual acuity because the window is highly asymmetric (Rayner, Well, & Pollatsek, 1980) and depends on characteristics of the writing system such as reading direction. For example, English readers use 3-4 characters to the left and 14-15 to the right of fixation, but the asymmetry reverses in right-to-left scripts like Hebrew (Pollatsek, Bolozky, Well, & Rayner, 1981) and Arabic (Jordan et al, 2014). Direct evidence that the limits of the perceptual span are not due to visual acuity alone is provided by Miellet, O'Donnell, and Sereno's (2009) ingenious use of parafoveal magnification to show that the 14-15 character rightward span did not increase when the size of the letters increased with distance from fixation.

Accumulated evidence from the moving window paradigm clearly demonstrates that foveal and parafoveal regions of the perceptual span both contribute to efficient, effective reading, but play at least partially distinct roles. Oculomotor control in reading requires decisions about *when* to move the eyes from one word to another, and *where* to move the eyes to. These two decisions appear to be controlled by separate neural pathways (e.g., Findlay & Walker, 1999). The temporal characteristics of eye movements (the *when* decision, reflected in measures of *fixation duration)* are best predicted by the ongoing demands of lexical processing, indexed by linguistic factors such as the frequency and predictability of the word fixated in the high-acuity foveal region. In contrast, the spatial characteristics of eye movements (the *where* decision, assessed by measures of *fixation location)* depend principally on coarse low spatial-frequency information about word spacing and letter shape extracted from parafoveal vision (Rayner & Pollatsek, 1981).

In principle, these different roles of foveal and parafoveal information appear to support models of oculomotor control in reading in which lexical processing is the 'engine' that drives eye

movements (Morrison, 1984). Such a view appears to be consistent with modular views of the architecture of the reading system which assume that word recognition and comprehension processes rely on independent cognitive structures (Andrews & Reichle, 2019). However, critical analysis of neurophysiological and cognitive constraints on the timing of perceptual, attentional, and motor operations involved in on-line reading reveals that this is too simple an account of the eye-mind link (Reichle & Reingold, 2013). Most critically, there is a 125-200 ms lag between the initiation of a saccadic program and its execution (Becker & Jurgens, 1979; Reingold et al., 2012), which severely constrains the time available for visual encoding and lexical retrieval. Reichle and Reingold (2013) proposed that a solution to this paradox of how a relatively slow process like lexical retrieval can govern decisions about when to move the eyes is to "assume that a significant portion of the lexical processing of a word that must be completed to 'trigger' saccadic programming … [uses] visual information that was acquired from the parafovea" (p. 5). That is, the accumulation of linguistic information from at least the upcoming word contributes to saccadic programming by influencing decisions about when to initiate planning of a new saccade (Schotter, 2019). Thus, while the neural mechanisms implementing 'when' and 'where' decisions might be independent, they depend on overlapping sources of information and neurophysiological constraints that yield complex interactions with task demands and individual differences. Understanding how readers co-ordinate the use of foveal and parafoveal information is critical for a full account of the reading process.

The *E-Z Reader* model (Reichle, Pollatsek, Fisher, & Rayner, 1998) provides the most fully specified current approach to understanding these complex interactions. E-Z Reader's core assumption is that the attention necessary for lexical processing is allocated in a strictly serial manner—the currently fixated word (word *n)* must be fully identified before lexical processing of the next word (word *n*+1) can begin. This seriality assumption distinguishes E-Z Reader from models

assuming parallel lexical processing, such as *SWIFT* (Engbert, Nuthmann, Richter, & Kliegl, 2005), in which words *n* and *n*+1 can be processed simultaneously. To sustain the assumption that word identification operates serially while allowing for efficient oculomotor control E-Z Reader implements two critical mechanisms: (i) that readers initiate saccadic programming on the basis of the outcomes of early lexical processing (referred to as L_1) before completing full retrieval (L_2) of the currently attended word; and (ii) that saccadic programming and attention are decoupled, so that, when L_2 for word *n* completes before the programmed saccade has been executed, covert attention shifts to support (parafoveal) processing of word *n*+1.

The most direct evidence that linguistic information extracted from parafoveal words influences saccadic planning is provided by skipping behaviour. Skilled readers skip about 30% of words, but skipping is much more likely for short than long words. Evidence that skipping is also predicted by lexical factors such as word frequency and predictability (Brysbaert, Drieghe, & Vitu, 2005; Drieghe, Rayner, & Pollatsek, 2005) implies that some words are fully identified in the parafovea. More refined evidence about the extent and depth of parafoveal processing is provided by parafoveal preview effects, which are the major focus of this review.

2. Parafoveal preview effects

Parafoveal preview effects are typically assessed by manipulating the availability of parafoveal information during online reading using the *gaze contingent boundary paradigm* (Rayner, 1975; see Figure 1). The *parafoveal preview effect* is the widely replicated finding that target processing is facilitated in *valid preview* conditions, in which a target word is presented normally within a sentence and therefore potentially available for parafoveal processing, relative to *invalid preview* conditions in which the target is replaced with an alternative stimulus until the reader's eyes cross an invisible boundary positioned immediately before it. During the saccade that crosses the boundary, the invalid preview is replaced with the target word so that readers fixate an

identical target word in both conditions (see Figure 1). A difference in fixation duration between targets preceded by valid versus invalid previews therefore demonstrates that the parafoveal stimulus has been processed. Readers are usually unaware of the change from the preview to the target stimulus and participants who notice many changes are typically removed, so the differences are unlikely to be due to strategic responses to the preview.

FIGURE 1 ABOUT HERE

The parafoveal preview effect has been the focus of substantial research across a range of writing systems and populations and played an important role in evaluating models of eye movements during reading. Schotter, Angele, and Rayner's (2012) review of parafoveal processing in reading included a comprehensive summary of evidence on preview effects to that point and Vasilev and Angele (2017) recently reported a meta-analysis of 93 studies using the boundary paradigm. The conclusions of these reviews are briefly summarized below to provide the springboard for our specific goals of elaborating two sources of recent evidence that have received little attention in previous reviews: individual differences in parafoveal preview effects; and plausibility preview effects. These two accumulating bodies of research provide valuable insights into outstanding questions about the mechanisms underlying parafoveal processing and, more broadly, the relationship between lexical retrieval and comprehension.

Although the preview effect is "one of the most robust and least controversial findings in the [eye tracking] literature" (Vasilev & Angele, 2017, p. 666), there remain at least three inter-related, unresolved questions that are critical to evaluating its significance for the reading process. The first concerns the relative contribution of preview benefit and preview cost to the overall preview effect. Differences in target processing following valid and invalid previews could simply reflect costs associated with the change from the parafoveal stimulus to the target that is ultimately fixated, without implicating any substantive processing of the parafoveal stimulus. There

also appear to be specific costs of visual and orthographic illegality of the invalid previews: Vasilev and Angele's meta-analysis also revealed stronger preview costs for a string of Xs than for random-letter or orthographically legal pseudoword strings which, in turn, yielded more interference than unrelated words. Orthographically illegal previews are also more likely to disrupt processing of word *n*, before the reader crosses the boundary—a phenomenon referred to as a *parafoveal-on-foveal effect*. Such effects are not observed when the invalid preview is a word (Brothers, Hoversten, & Traxler, 2017) implying that illegal information in the parafovea is a specific source of preview costs.

While the costs of invalid previews clearly contribute to the preview effect, there is also evidence of preview benefit: *related* parafoveal previews that share features with the target yield reduced fixation duration on the target relative to invalid previews (Vasilev & Angele, 2017). Disentangling the relative contributions of preview benefit and cost is critical to interpreting the implications of the preview effect for normal reading (Kliegl, Hohenstein, Yan, & MacDonald, 2013). If they were *solely* due to preview cost, preview effects would be an interesting existence proof of linguistic parafoveal processing but may have little relevance to normal reading in which parafoveal information is virtually always valid.

This leads to the second unresolved issue: how deeply are parafoveal words processed? Like the masked priming paradigm that has been used to investigate the early stages of lexical retrieval for isolated words (e.g., Forster & Davis, 1984), the boundary paradigm has been used to diagnose the information that readers extract from a parafoveal word that they are not consciously aware of processing. The evidence available at the time of Schotter et al.'s (2012) review confirmed that previews that are orthographically, phonologically, or morphologically similar to the target all yield a preview benefit, although morphological effects may be language-specific. However, the evidence for lexical and semantic processing of parafoveal words was far less clear. The higher skipping rates

observed for short, high-frequency, predictable words (Brysbaert et al., 2005) seem to clearly demonstrate that lexical retrieval is completed for at least some parafoveal words. But Schotter et al. argued that it was difficult to unequivocally distinguish truly lexical effects from the orthographic and phonological influences that necessarily precede them.

The third unresolved question concerns the sufficiency of the best accepted account of the preview effect, which attributes it to the integration of information across successive fixations. This *trans-saccadic integration* can explain both costs due to discrepancies between information extracted from the parafovea and the target word that is ultimately fixated, and benefits from previews that share some of the target word's features. Although the trans-saccadic integration account was originally attributed to the extent of *visual* overlap with the target (McConkie & Rayner, 1976), early evidence that preview effects are unaffected by letter-case changes between the preview and target (McConkie & Zola, 1979) demonstrated that integration across fixations occurs at a more abstract level. Cutter, Drieghe, and Liversedge's (2015) comprehensive review of research using preview effects to index how information is integrated across fixations concluded that integration occurs at the level of abstract codes for the various components of a word's lexical representation - orthography, phonology, and semantics. However, recent evidence from studies investigating higher-level linguistic effects on parafoveal processing strongly challenges any account of the preview effect that relies solely on the relationship between the preview and the target word.

Before reviewing this research on semantic and contextual influences on parafoveal processing, it is important to consider whether and how the preview costs and benefits described so far are modulated by reading ability to evaluate the implications of such individual differences for accounts of the mechanisms underlying preview effects.

3. Individual differences in parafoveal processing

Most research on preview effects has relied on averaged data for samples of young adult readers. This reflects an implicit *uniformity assumption* (Andrews, 2012): that the cognitive architecture underlying reading is common across all skilled readers. This assumption is challenged by recent evidence of systematic individual differences among skilled readers in the processes contributing to both lexical retrieval (e.g., Andrews & Hersch, 2010; Andrews & Lo, 2012, 2013; Yap, Balota, Sibley, & Ratcliff, 2012) and parafoveal processing during sentence reading (Choi, Lowder, Ferreira, & Henderson, 2015; Slattery & Yates, 2018; Veldre & Andrews, 2014, 2015a, 2015b, 2016a, 2016b). Variability among competent adult readers may arise from differential reading experience and/or from differences in the trajectory of reading development that shape the cognitive architecture of the mature reading system.

3.1 Developmental changes in parafoveal processing

Unsurprisingly, beginning readers' eye movements are less efficient than adults. Developing readers make more fixations for longer durations, shorter saccades, and more regressions (e.g., Blythe & Joseph, 2011; Rayner, 1986) until the age of 11-12, when children's average eye movements are equivalent to those of adults. Moving-window studies suggest that children begin to use parafoveal information by the 3rd grade (e.g., Rayner, 1986; Vorstius, Radach & Lonigan, 2014) and show an adult-like perceptual span by Grade 5-6. Children show qualitatively similar, but somewhat exaggerated, patterns of sensitivity to word length on skipping, landing position, and refixations compared to adults (Blythe, Liversedge, Joseph, White & Rayner, 2011), suggesting they use similar coarse parafoveal information to guide saccadic planning. The gradual increase in perceptual span with reading development is predicted by linguistic rather than oculomotor skill (e.g., Rayner, 1986).

Research using the boundary paradigm to track the development of parafoveal processing is, so far, very limited. Phonological preview effects were found in 8-year old German-speaking

children, but fine-grained orthographic sensitivity to letter transposition was only observed in 11-12-year-olds (Tiffin-Richards & Schroeder, 2015). English-speaking children of this age are also sensitive to letter identity and letter order in parafoveal words (Pagan, Blythe, & Liversedge, 2016). A recent study of 6-12–year-old English-speaking children found that an overall preview effect on fixation duration for valid relative to invalid previews was evident in the youngest age/grade groups and increased with reading development (Johnson, Oehrlein, & Roche, 2018). However, the orthographic benefit of a preview that shared initial letters with the target only emerged in the oldest age/grade groups, and preview benefits only extended to skipping in older children with higher decoding ability. Better decoders also showed a greater preview benefit for predictable words, providing further evidence that lexical proficiency is associated with more effective use of parafoveal information.

Thus, the limited evidence about the development of parafoveal processing demonstrates that successful reading acquisition is associated with increasingly effective use of coarse parafoveal information to guide saccadic programming, and that the cost of being deprived of a valid preview of the upcoming word is evident from early in reading development. However, deeper parafoveal processing of the orthographic features required for lexical retrieval does not emerge until around 11-12, and only in better readers. Rather than being due to direct effects of reading practice on oculomotor control, efficient parafoveal processing appears to reflect the opposite causal pathway: increased linguistic proficiency supports more effective eye-movement co-ordination.

This interpretation is consistent with systematic simulations of the E-Z Reader model which showed that eye-movement differences between children and adults could not be simulated by changing parameters directly related to eye-movement control. However, virtually all of the developmental differences in both English (Reichle et al., 2013) and French readers (Mancheva, Reichle, Lemaire, Valdois, Ecalle & Guerin-Dugue, 2015) were accurately simulated by modifying a

single parameter determining the rate of lexical processing. Individual differences in orthographic knowledge were also better predictors of eye-movement data than measures of sentence processing or general intelligence (Mancheva et al., 2015), consistent with the view that lexical quality plays a critical role in online reading.

3.2 Individual differences in parafoveal processing among skilled readers

The relationship between parafoveal processing and reading ability observed across reading development persists into adulthood. One possible source of individual differences in the efficiency of reading and parafoveal processing is readers' *visual span* – the range over which letters can be identified without moving the eyes, which is typically measured by assessing the identification of letters in consonant trigrams presented at various eccentricities from the reader's fixation. Visual span has been argued to impose a sensory 'bottleneck' on the extent of parafoveal processing due to constraints on visual acuity (Legge, Cheung, Cheng, Lee, & Owens, 2007), and the detrimental impact of crowding from flanking letters (Pelli, Tillman, Freeman, Su, Berger, & Majaj, 2007). Consistent with this view, larger visual span has been shown to predict faster reading of rapidly presented single words (Legge et al., 2007; Pelli et al., 2007). Risse (2014) demonstrated that this relationship extended to the speed of reading sentences. However, that there was no relationship between visual span and parafoveal preview effects, even though there was considerable individual variability in the magnitude of parafoveal preview effects, and preview effects were significantly related to reading speed. Unexpectedly, the form of this relationship was a reduced preview effect in faster readers, due principally to a larger cost for invalid previews in slower readers. These data appear to conflict with evidence that faster adult readers utilise larger perceptual spans than slower readers (Ashby, Yang, Evans, & Rayner, 2012; Rayner, Slattery, & Belanger, 2010). Further research is necessary to determine the complex relationship between visual span, parafoveal processing, and reading speed, but Risse's (2014) data suggest that visual span is not responsible

for individual differences in parafoveal preview effects. An accumulating body of evidence suggests that the source of these effects lies in individual differences in the proficiency of linguistic, rather than visual, processes.

Veldre and Andrews (2014) found that higher levels of reading comprehension and spelling ability in university-student samples were both independently associated with a larger perceptual span to the right (but not the left) of fixation, and greater disruption from being deprived of close parafoveal information. The combination of high reading and spelling ability was associated with the greatest benefit from larger rightward windows, principally because of longer forward saccades. This evidence of greater parafoveal reliance was attributed to the benefits of the orthographically precise, high-quality lexical knowledge indexed by superior reading and spelling ability (Andrews, 2012) for efficient parafoveal processing and effective saccadic targeting. Using a larger test battery including measures of oculomotor control, Choi et al. (2015) confirmed the association between reading proficiency and perceptual span, and showed that it was predicted by linguistic proficiency but not oculomotor control.

Converging evidence that lexical quality modulates orthographic processing in the parafovea has been obtained using the boundary paradigm (Veldre & Andrews, 2015a). The combination of superior reading and spelling ability predicted stronger benefits for valid previews, and greater sensitivity to the length of parafoveal words. The enhanced benefit from identical previews was evident on both early and late fixation measures, and most marked for more difficult pre-target words – i.e., when *foveal load* was high (Henderson & Ferreira, 1990). This suggests that good readers/spellers' more efficient processing of the currently fixated word allows them to rapidly shift attention to begin processing the next word. In contrast, individual differences in sensitivity to parafoveal length information were restricted to early fixation measures, and insensitive to foveal load. Inaccurate length previews were also insensitive to orthographic similarity implying that they

relied on coarse cues such as word spacing. These differential effects of preview identity and preview length suggest that lexical quality facilitates the use of both the coarse parafoveal information assumed to contribute to specifying *where* to target the next saccade, and the more fine-grained information required to determine *when* sufficient information has been extracted to move the eyes to a new location. These findings support the view that efficient linguistic processing mediates effective oculomotor co-ordination.

Evidence that individual differences in reading skill modulate the *depth* of parafoveal processing of word n+*1* was provided by Chace, Rayner, and Well's (2005) finding that the benefit of a phonologically related preview was restricted to readers with above-average reading comprehension scores. Direct evidence that higher lexical quality supports deeper parafoveal processing derives from individual differences in sensitivity to manipulations of the lexical status of orthographically similar previews (Veldre & Andrews, 2015b). Previous investigations of the average preview effect for skilled readers have found either no difference between orthographically related word and nonword previews (e.g., Johnson & Dunne, 2012), or stronger preview benefits from similar words than nonwords (e.g., Williams, Perea, Pollatsek & Rayner, 2006). This evidence implies that preview effects depend on sublexical overlap between the preview and the target with no indication of the lexical competition from orthographically similar word neighbors that has been observed in single word masked priming tasks (e.g., Davis & Lupker, 2006). The absence of effects of lexical competition on preview effects has bolstered the view that the time available for parafoveal processing is insufficient to achieve lexical retrieval (Williams et al., 2006). Veldre and Andrews' (2015b) average data replicated the null effects of preview lexicality observed in previous research, but found that the combination of high reading and spelling ability was associated with an *inhibitory* effect of an orthographically similar word neighbor on early

fixation measures – the signature of lexical competition. In contrast, lower proficiency readers showed the *facilitatory* effect of word neighbors reported by Williams et al. (2006).

The modulating role of individual differences in lexical proficiency on orthographic, phonological, and lexical preview effects aligns with the E-Z Reader simulations of developmental data by showing that lexical processing efficiency predicts variability in measures of oculomotor control by modulating the time available for parafoveal processing. The data also contribute to specifying the source of lexical proficiency by showing that measures of spelling ability account for variance in parafoveal processing that is not predicted by the tests of reading comprehension or reading speed, which are more commonly used to assess reading ability in adult samples. Reading comprehension was typically the best predictor of the overall speed and efficiency of sentence reading (Veldre & Andrews, 2015a), but it only yielded significant interactions with preview effects when combined with measures of spelling ability (Veldre & Andrews, 2015b). Spelling ability has also been shown to uniquely predict skipping rates (Slattery & Yates, 2017; Veldre & Andrews, 2016, Veldre, Drieghe, & Andrews, 2017), further supporting its association with parafoveal processing. These findings are consistent with Mancheva et al.'s (2015) developmental evidence for the unique contribution of orthographic ability, and with the view that orthographic precision is a defining feature of high-quality lexical representations (Perfetti, 2007; Andrews, 2012, 2015).

The implications of orthographic precision for preview effects depend on the relative contribution of preview benefit and preview cost. Higher lexical quality supports faster foveal word identification which, in turn, increases the time available for parafoveal processing and the efficiency of saccadic targeting. These correlated consequences of high lexical quality contribute to a greater benefit for valid previews. However, the impact of enhanced parafoveal processing for invalid previews depends on the particular preview conditions used, and the mechanisms responsible for preview effects. More efficient processing of illegal, uninformative previews (e.g.,

xxxxx, cfpnkw) would be expected to increase preview costs due to trans-saccadic integration at the level of either visual features or abstract letter codes, but to increase preview benefits from orthographically similar previews that share sublexical units with the target. However, the deeper lexical processing afforded by higher quality representations may introduce another source of preview costs due to lexical competition between similar words (Veldre & Andrews, 2015b). Further insight into how higher-level linguistic representations affect parafoveal processing is provided by evidence of semantic and plausibility preview effects.

4. Plausibility preview effects

As noted in Section 2, evidence that readers extract semantic information from the parafovea has been elusive. None of the studies of English reviewed by Schotter et al. (2012) showed semantic preview benefits, but such effects were evident in Chinese (e.g., Tsai, Kliegl, & Yan, 2012; Yan, Richter, Shu, & Kliegl, 2009) and German (e.g., Hohenstein & Kliegl, 2014). The absence of semantic preview benefit in English was taken as confirmation that the time available for parafoveal processing is insufficient to retrieve semantic information (Rayner, Balota, & Pollatsek, 1986; Rayner, Schotter, & Drieghe, 2014). Semantic preview effects in Chinese and German were attributed to script-specific attributes such as the density of Chinese characters, and the capitalization of German nouns (e.g., Laubrock & Hohenstein, 2012; Rayner & Schotter, 2014).

Schotter (2013) argued that, rather than reflecting an absolute temporal limit on semantic activation, semantic preview effects in English may require a high degree of semantic overlap between the preview and target to overcome interference from the orthographic differences between semantically related words. This hypothesis was tested by comparing three non-identical previews of a critical target (*curlers* in example 1 below): a synonym of the target (*rollers*), a semantically related but not synonymous word (*styling*), and a semantically unrelated word (*suffice*).

(1) *She tried using (**rollers/styling/suffice) curlers** on her stubborn straight hair before prom.*

Schotter found a preview benefit from a synonym preview, but not from a semantically related preview, relative to the unrelated baseline. These data suggested that the critical constraint may not be on whether semantic information is activated for parafoveal words, but rather on the extent to which that activation overlaps with the semantic features of the target: Semantic preview effects only occurred when the preview and target were very similar in meaning.

Schotter's (2013) findings were initially interpreted as suggesting that trans-saccadic integration can operate at the level of semantic features, but more recent data challenge this conclusion. Veldre and Andrews (2016b) highlighted a confound in the materials used to investigate semantic preview effects. The synonym previews for which Schotter (2013) found a preview benefit were not only highly related to the target but they also formed locally coherent sentence fragments. In contrast, the unrelated previews used as the baseline to assess preview effects were not only semantically unrelated to the target but also usually contextually anomalous in the sentence. For example, in (1), *She tried using rollers* is an acceptable sentence fragment, whereas *She tried using suffice* is ungrammatical. It is therefore impossible to determine whether the semantic preview effect arose from enhanced target processing due to the semantic relatedness between the preview and target, or reflected a direct benefit/cost from the contextual plausibility/implausibility of the preview in the sentence. Studies using foveally presented targets have observed rapid sensitivity to anomalous and implausible words, evident from the first fixation duration (e.g., Abbott & Staub, 2015; Rayner, Warren, Juhasz, & Liversedge, 2004), and even as early as skipping (e.g., Matsuki et al., 2011), suggesting that such violations can be detected parafoveally.

To determine whether the semantic preview effect was due to this plausibility confound, Veldre and Andrews (2016b) factorially manipulated preview-target relatedness and within-

sentence preview plausibility. The non-identical previews of the target word (*psycho* in 2) were therefore semantically related to the target and contextually plausible in the sentence (*insane*), related but implausible (*murder*), unrelated but plausible (*modest*), or both unrelated and implausible (*circus*).

(2) *Melanie thought that the man was really (**insane/murder/modest/circus) psycho** after learning of his horrific crimes.*

The results of this study revealed a significant *plausibility preview effect* on first-pass measures of reading: a benefit from previewing a plausible continuation of the sentence (*insane* or *modest*) relative to an implausible preview (*murder* or *circus*) was evident on the earliest fixation duration measures. However, there was no benefit from semantic relatedness, and the two factors did not interact, i.e., the benefit to reading the target *psycho* from the synonym preview *insane* was equivalent to that for the plausible but semantically unrelated preview *modest*. This finding was consistent with plausibility preview effects observed in Chinese (Yang et al., 2012, 2014) that had previously been assumed to be specific to its logographic writing system. Converging evidence for the plausibility preview effect in English was provided by Schotter and Jia (2016) who found that synonym, antonym, and plausible unrelated previews all yielded benefits on first-pass reading relative to implausible previews.

These findings imply that higher-order influences on parafoveal processing are due to the contextual fit of the preview in the evolving sentence representation rather than the semantic relationship between the preview and target. Because the contextually plausible preview words shared few orthographic or semantic features with the target, plausibility preview effects cannot be explained by trans-saccadic integration. To establish the relationship between preview plausibility effects and the orthographic preview benefits that provide the classic evidence for trans-saccadic integration, Veldre and Andrews (2017) factorially manipulated preview plausibility and preview-

target orthographic overlap in sentences like (3). The preview of the target *rats* was either a one-letter-different neighbor word (*rags, rate*) or an orthographically unrelated word (*junk, sigh*), and either a plausible *(rags, junk*) or implausible (*rate, sigh*) continuation of the sentence.

(3) *The cupboard was full of filthy (**rags/rate/junk/sigh**) **rats** because nobody had bothered to clean it.*

The results replicated the plausibility preview effect on first-pass reading of the target, but also showed an orthographic preview benefit on all reading measures. Importantly, plausibility and orthographic relatedness did not interact, suggesting that they reflect distinct mechanisms. The effect of orthographic relatedness also contrasts with the absence of any effect of semantic relatedness when plausibility was controlled (Veldre & Andrews, 2016b). These data therefore indicate that plausibility preview effects depend on a separate mechanism that is independent of the trans-saccadic integration processes responsible for orthographic preview effects, and suggest that direct integration across saccades may operate only at the level of abstract orthographic codes. This conclusion begs the question of what mechanism *is* responsible for plausibility preview effects.

4.1 The role of contextual predictability

One possibility is that plausibility preview effects arise from mechanisms related to those responsible for effects of *predictability*. The predictability of a word in the sentence context has a robust facilitatory effect on early eye-movement measures (see Staub, 2015, for a review) and is also associated with an enhanced preview effect (e.g., Balota, Pollatsek, & Rayner, 1985; Li, Wang, Mo, & Kliegl, 2018; Schotter, Lee, Reiderman, & Rayner, 2015). A word's predictability is typically indexed by its *cloze probability*— i.e., the proportion of participants that generate the word given

the prior context – but cloze probability provides a description rather than an explanation of the mechanisms responsible for predictability effects (Staub, Grant, Astheimer, & Cohen, 2015).

The studies demonstrating the plausibility preview effect described above all used previews and targets that were extremely *low* in cloze probability in order to distinguish the effect of plausibility from predictability. However, plausibility and predictability are necessarily correlated to some extent in natural language. Therefore, Veldre and Andrews (2018a) sought to establish whether the plausibility preview effect could be observed in constraining sentences that strongly predicted a specific word by comparing conditions in which the target word was the most predictable continuation with identical sentences in which the target was a plausible, but low-predictability alternative (*guilty* vs *insane* in example 4). For both targets, counterbalanced conditions compared valid previews with three non-identical conditions: plausible previews of the alternative target (i.e., *insane* for *guilty* or *guilty* for *insane);* implausible previews that were semantically related to the sentence context (*courts*); and unrelated implausible words (*mirror*).

(4) *a. The lawyer feared his client was probably (**insane/courts/mirror**) **guilty** when he was preparing the case.*

*b. The lawyer feared his client was probably (**guilty/courts/mirror**) **insane** when he was preparing the case.*

Predictability exerted a robust effect on parafoveal processing—previewing the expected, predictable word (*guilty*) yielded as much benefit on first-pass reading times as an *identical* preview of the plausible, unpredictable target (*insane*). However, the critical finding was that the highly predictable target (*guilty*) showed a significant benefit on fixation duration from a preview of the unpredictable but plausible word (*insane*), relative to an implausible preview (*mirror*). That is, despite strong contextual support for the target word, readers still showed a benefit from previewing a plausible but unpredictable alternative. This evidence that plausibility preview effects

can be observed even in contexts that are constrained towards a single highly predictable continuation has important theoretical implications that are discussed in section 5.

4.2 The contribution of contextual integration to plausibility preview effects

Another possible explanation for the plausibility preview effect is that it reflects the early automatic analysis of syntactic structure predicted by the garden-path model of sentence processing (Frazier, 1987). There is substantial evidence that eye movements are disrupted as soon as readers encounter a syntactic ambiguity or violation (see Clifton, Staub, & Rayner, 2007, for a review) implying that words are rapidly and incrementally integrated into sentence-level representations. The implausible unrelated previews used as the baseline to assess the plausibility preview effect typically violate local phrase structure rules, as illustrated in examples (2), (3), and (4)– e.g., *circus* is implausible in (2) because the sentence cannot continue with a noun in the target location. Plausibility preview effects may therefore be principally due to costs arising from syntactic illegality.

To evaluate this possibility, Veldre and Andrews (2018b) compared plausible and implausible previews matched to the word class of the target using sentences like (5).

(5) *She eventually found a spare (**glass/uncle/begin**) **stool** behind the crowded bar.*

A preview benefit from the plausible noun *glass* relative to the semantically implausible, but syntactically acceptable noun, *uncle,* was observed on both skipping and early fixation duration measures. An additional cost for syntactically invalid previews (*begin*) over semantically implausible but syntactically acceptable previews (*uncle*) emerged relatively late, on gaze duration on the target word, due to a higher rate of refixations.

To assess the relative contribution of syntactic and semantic violations, a second experiment used sentences like (6) to compare syntactically invalid but semantically plausible previews (*books*) with syntactically valid but semantically implausible previews (*brain*).

(6) I bought a brand new ***(dress/books/brain) phone*** *with the money I got from my grandparents.*

Both types of contextual violation disrupted skipping and early fixation duration measures relative to plausible previews (*dress*). Differences between semantic and syntactic violations emerged in later eye-movement behaviours. Semantic violations (*brain)* resulted in significantly higher rates of refixations on the target word, perhaps related to evaluation of alternative possible meanings of senses of the word. In contrast, syntactically invalid forms of otherwise contextually appropriate words (*books*) were more likely to trigger regressions back to previously read text, consistent with rapid re-analysis to resolve the syntactic violation. These data show that readers use information extracted from the parafovea to plan both progressive *and* regressive saccades. Importantly, the preview conditions were matched on letter overlap with the target and were semantically unrelated to the target word, so the effect could not be explained by trans-saccadic integration of orthographic or semantic information.

4.3 The time course of plausibility preview effects

The studies reviewed above all demonstrated plausibility preview effects from the earliest measures of first-pass reading: first fixation duration, single fixation duration, and gaze duration. Moreover, several studies have found that readers are more likely to skip a plausible word (or preview) than an implausible or anomalous word (Brothers & Traxler, 2016; Matsuki et al., 2011; Snell, Meeter, & Grainger, 2017; Staub, 2011; Veldre & Andrews, 2017, 2018a, 2018b, 2018c). Skipping effects imply that plausibility impacts the earliest stages of lexical processing. However, these findings appear to contradict previous evidence showing that high frequency words are

skipped more than low frequency words, even when they are contextually unacceptable in the context (Abbott & Staub, 2015; Abbott, Angele, Ahn, & Rayner, 2015; Angele & Rayner, 2013; Angele, Laishley, Rayner, & Liversedge, 2014). Further research is therefore required to determine whether, and under what conditions, parafoveal plausibility can affect skipping.

When beneficial effects of preview plausibility occur in early processing, they are typically short-lived: total fixation duration on the target is often equivalent following plausible and implausible previews (e.g., Schotter & Jia, 2016; Veldre & Andrews, 2017, 2018a, 2018c; Yang et al., 2014) because readers are *more* likely to regress back to the target word when the preview was plausible rather than implausible. This implicates a processing trade-off: relative to implausible parafoveal words, plausible previews yield increased skipping and reduced first-pass fixation duration on the target, but they also trigger higher rates of regressions back to the target leading to late costs associated with difficulties in subsequent integration processes.

Skipping of plausible previews can also lead to comprehension illusions because readers occasionally incorporate the preview word into their sentence representation in place of the target. Such preview encoding is most common when the reader skips the target in first-pass reading and never refixates it (Schotter & Jia, 2016; Schotter, Leinenger, & von der Malsburg, 2018; Veldre & Andrews, 2017).

4.3 Individual differences in semantic and plausibility preview effects

Further insight into the time-course of plausibility preview effects derives from evidence about how individual differences modulate semantic and contextual influences on parafoveal processing. Veldre and Andrews (2016a) confirmed Schotter's (2013) evidence of significant semantic preview effects in the average data for skilled readers of English when the preview and target stimuli shared many semantic features (e.g., *grill-roast*). However, unlike the orthographic preview manipulations described earlier (Veldre & Andrews, 2015a, 2015b), semantic preview

effects showed *opposite* effects of reading comprehension and spelling ability: higher reading ability was associated with strong semantic preview effects that were equivalent to the effects of preview validity, whereas high spelling ability was associated with a reduced semantic preview benefit[1]. Importantly, the lack of semantic preview benefit in good spellers did not reflect a general insensitivity to semantic information in the parafovea: their higher average skipping rates and patterns of regressions revealed rapid lexical identification of parafoveal words. Rather, the absence of semantic preview benefit in good spellers appeared to reflect greater sensitivity to the *orthographic* mismatch between the semantically related preview and target. Although the enhanced semantic preview benefit shown by better readers was evident from the earliest fixation measures, the association of superior spelling with reduced semantic preview benefit was restricted to the late measures of gaze and total fixation duration. The late emergence of the orthographic mismatch effect is consistent with the known lag of 50-60 ms from fixation onset until visual information from the target word reaches visual areas of the brain to trigger conflict with the features of the preview (Reichle & Reingold, 2013).

Thus, the presence or absence of semantic preview effects depends on when orthographic information from the target becomes available. If little information has been extracted from the parafoveal preview before it is fixated, no semantic preview benefit will be observed because the preview features will be replaced by orthographic features of the target– the pattern shown by poor readers. The more efficient foveal processing of superior readers and spellers allows more time for deep parafoveal processing of the preview to the lexical or semantic level, yielding a semantic preview benefit in superior readers. However, individuals with the precise orthographic

[1] Reading and spelling ability are, of course, correlated (r= 0.5 in this sample), but the differential effects of these two dimensions of lexical quality was confirmed by showing that, when overall proficiency indexed by the average of reading and spelling ability was partialled out, the difference between reading and spelling ability significantly predicted the semantic preview benefit: higher reading than spelling ability was associated with a preview effect that was absent in individuals with higher spelling than reading ability.

representations indexed by better spelling ability are more sensitive to the orthographic conflict between the preview and target, either because they retrieve a more fully specified orthographic representation of the preview and/or because they are faster at extracting and integrating information from the target word once it is fixated (Veldre & Andrews, 2016b). The mismatch between the orthographic features of the preview and the information extracted from the target eliminates the semantic preview benefit.

As reviewed above, Veldre and Andrews' (2016b) factorial manipulation of semantic relatedness and contextual plausibility showed that the 'semantic preview benefit' is due to the contextual fit of the preview in the sentence rather than the semantic relationship between the preview and target. Consistent with this interpretation, their independent manipulation of preview plausibility effects showed similar modulating effects of individual differences to those Veldre and Andrews (2016a) observed for semantically related previews. High overall proficiency, indexed by the combination of reading and spelling ability, was associated with a *reduced* plausibility preview effect. Specifically, individuals with higher levels of overall lexical quality showed a preview validity benefit, but no benefit for contextually plausible over implausible previews. In contrast, lower proficiency individuals showed as much benefit for contextually plausible previews as for valid previews of the target word. Collinearity between reading and spelling in this sample precluded clear separation of their effects in models including both covariates, but analyses including each covariate separately found that only spelling ability interacted significantly with the plausibility preview effect. Thus, higher order parafoveal influences of contextual plausibility appear to be eliminated by orthographic mismatch between the preview and target in individuals with precise, high-quality lexical knowledge.

5. Mechanisms underlying parafoveal preview effects

The trans-saccadic integration traditionally invoked to explain preview effects undoubtedly contributes to orthographic preview benefits and costs (e.g., Cutter et al., 2015), but it cannot explain plausibility preview effects for plausible and implausible previews that are equally (dis)similar to the target. Trans-saccadic integration is also incompatible with recent evidence of *preview difficulty effects* which have stimulated proposals of alternative mechanisms based on characteristics of the preview alone, rather than its relationship to the target.

5.1 Accounts of preview difficulty effects

Risse and Kliegl (2014) compared sentences containing a high- or low-frequency target word preceded by either an identical or invalid preview. Critically, when the target was a high-frequency word, the invalid preview was a low-frequency word, and vice versa. A typical preview validity effect was observed: longer fixation durations on the target following an invalid than an identical preview. However, there was also an independent effect of preview difficulty because fixations on the target were longer when the preview was a low-frequency word than when it was a high-frequency word. More striking evidence of the contribution of preview difficulty to oculomotor planning was provided by Schotter and Leinenger's (2016) report of a *reversed preview benefit* for low-frequency target words: shorter fixation durations following an *invalid*, high-frequency preview than a valid identical preview. Risse and Seelig (2018) confirmed that these effects were not due to comparing conditions with and without a display change by showing a significant preview difficulty effect when the target was an unrelated medium-frequency word. These findings demonstrate a direct influence of preview processing, regardless of preview-target similarity, that affects oculomotor planning before the target is presented: easy to process previews are more likely to yield a skip, or a benefit to early fixation duration on the target.

Schotter and Leinenger (2016) proposed a *forced fixation* account of preview difficulty effects based on simulations of the E-Z Reader model (Schotter, Reichle, & Rayner, 2014). They

noted that processing of word *n*+1 occasionally reached an advanced stage (completion of L_1) before it was fixated. Within the E-Z Reader framework, the completion of L_1 signals to the reading system that word recognition is imminent, which triggers cancellation of the planned saccade to word *n*+1, and initiates planning of a new eye movement to skip the word. This sequence of events is the mechanism underlying frequency and predictability effects on word skipping. However, if completion of L_1 for word *n*+1 occurs too late in the saccade planning window to cancel the previously planned saccade, a new saccade from word *n*+1 to word *n*+2 is planned in parallel with execution of the saccade to word *n*+1, resulting in a short 'forced' fixation on word *n*+1 that is terminated by the programmed saccade to word *n*+2. Importantly, these parallel saccade programs rely entirely on information extracted from the preview word and occur before new visual information from the target becomes available. Preview difficulty effects arise because forced fixations are more common for high-frequency previews than for difficult, low-frequency previews, which are less likely to be sufficiently processed in the parafovea to complete L_1 and trigger programming of a new saccade.

Risse and Kliegl (2012, 2014) proposed an alternative *delayed parafoveal-on-foveal* account of preview difficulty effects based on the parallel lexical processing instantiated in SWIFT (Engbert et al., 2005), which allows for crosstalk between processing of word *n* and word *n*+1. In contrast to E-Z Reader's assumption that saccadic programming is contingent on lexical processing of the attended word, SWIFT assumes that saccades are triggered by an autonomous timer that is principally controlled by relatively low-level visual information. However, saccadic programming can be inhibited when lexical processing of the currently fixated word is difficult. Such inhibition would typically have an immediate effect reflected in extended fixations on word *n* – that is, it would yield the parafoveal-on-foveal effects that have been argued to provide a major, albeit contested, source of evidence for the crosstalk predicted by the parallel processing assumptions of

SWIFT (see Drieghe, 2011, for a review). However, if saccade planning is already at an advanced stage, the slow processing of difficult previews in the low acuity parafoveal region can potentially spill over to fixations on word n+*1* to produce an effect of preview difficulty on target processing that Risse and Kliegl (2014) conceptualized as a delayed parafoveal-on-foveal effect.

This account of the effects of preview frequency attributes it to unusually long target fixations following low-frequency previews, while the forced fixation mechanism attributes the effect to unusually short fixations following high-frequency previews. Despite this conceptual distinction between the two views, it is difficult to distinguish them. Analyses of the time-course of the preview difficulty effect on target processing have yielded contradictory evidence. Schotter and Leinenger (2016) found that preview frequency only affected short fixations on the target, consistent with the forced fixation account. However, Risse and Seelig's (2018) timecourse analysis found that the preview frequency effect extended across the entire distribution of fixation durations on word n+*1*. A recent Bayesian meta-analysis also found strong evidence *against* the existence of effects of word *n*+1 frequency or plausibility on word *n* (Brothers et al., 2017), challenging the delayed parafoveal-on-foveal account of effects of preview difficulty due to lexical or contextual manipulations. Simulation data may be necessary to evaluate the relative validity of the forced fixation and delayed parafoveal-on-foveal accounts of preview difficulty effects.

5.2 Plausibility preview effects as a sub-type of preview difficulty

Whatever the precise source of the early effects of preview difficulty on oculomotor planning, it could potentially be extended to the plausibility preview effect if plausible and implausible previews differed in processing difficulty. There are, however, problems with this generalization. The preview difficulty effects reviewed above relied on manipulations of the frequency of the preview – an attribute that is inherent to the preview word and independent of its relationship to either the target word or the sentence context. What is not explained by either

account of preview difficulty effects, or by models of eye movements more generally, is how contextual plausibility can influence parafoveal processing.

Within the serial processing assumptions of the E-Z Reader model that are fundamental to the forced fixation account, there is no reason why parafoveal processing difficulty would differ between words that are matched on length, frequency, and cloze probability and differ *only* in contextual acceptability (Veldre & Andrews, 2016b, 2017, 2018a, 2018b). Contextual fit *can* influence a postlexical integration stage in E-Z Reader 10 which responds to difficulty in semantic or syntactic integration by cancelling all planned forward saccades and programming refixations and regressions back to the source of the integration difficulty (Reichle, Warren, & McConnell, 2009). This mechanism could potentially explain the greater difficulty of implausible previews if postlexical integration failure for implausible previews occurred early enough, and on enough trials, to yield significant integration cost. Evidence of the impact of plausibility on skipping appears to be even more difficult to reconcile with a postlexical account. Within E-Z Reader, full lexical access (L_2) for word *n*+1 must complete before postlexical integration begins. For the plausibility of word *n*+1 to influence skipping, integration must fail for an implausible word during the early, labile stage of saccade planning in order to cancel the skipping saccade and program a new saccade to fixate on word *n*+1. Simulations of E-Z Reader reported by Abbott and Staub (2015) showed that this sequence of events occurs rarely and is restricted to targets less than 5 letters in length. However, more recent simulations of stimuli selected to factorially manipulate target length, frequency, and plausibility revealed that E-Z Reader 10 successfully simulated empirical effects of plausibility on skipping. This suggests that postlexical integration may be at least partially responsible for the preview plausibility effect (Veldre, Reichle, Wong, & Andrews, submitted).

Extending the delayed parafoveal-on-foveal account to plausibility preview effects is more complicated. To date, parallel lexical processing models, including SWIFT, have not implemented

higher-level language processing within their architectures, so they do not provide an explicit account of effects of the contextual plausibility of stimuli matched on frequency and cloze probability. The additional issue that needs to be addressed by parallel models is how the word order information that is critical to computing the contextual plausibility of an upcoming word is maintained when there is no requirement that words are identified in sequential order. The critical role of word order in comprehension of English is one of the motivations for the serial processing assumptions of E-Z Reader (Reichle et al., 1998).

5.3 Plausibility versus predictability

Plausibility preview effects on skipping and early fixation durations may reflect anticipatory prediction of upcoming words, consistent with recent arguments for the role of 'strong' prediction in language processing (e.g., Kutas, De Long, & Smith, 2011). Most demonstrations of plausibility preview effects compared previews that were extremely low in cloze probability (~ 1-2%). However, the relationship between cloze probability and processing time may not be linear. Smith and Levy's (2013) analysis of the relationship between a statistical index of predictability and gaze duration supported a logarithmic function, suggesting that very small differences among low cloze-probability continuations may be sufficient to produce effects of 'predictability'.

Staub's (2015) critical evaluation of empirical evidence about the impact of contextual predictability on eye-movements found no evidence of the early disruption from anomalous parafoveal words expected from a logarithmic predictability function (e.g., Rayner et al., 2004). His analyses also showed that predictability affects the entire distribution of target fixations, rather than selectively influencing long fixations as expected from post-lexical integration accounts. However, there was also no evidence of qualitative differences between highly predictable words and those of lower cloze probability, or of the costs for plausible words in sentences that strongly predicted another word which should accompany anticipatory prediction (Frisson, Harvey, Drieghe,

& Staub, 2015). Staub (2015) therefore concluded that predictability effects reflect graded, rather than discrete all-or-none predictions. He also argued that the consistent evidence for an additive relationship between effects of predictability and frequency, combined with the fact that predictability preview effects on early measures, including skipping, are restricted to valid preview conditions, suggests that predictability "may not operate during lexical access itself" (Staub, 2015, p. 321). Rather, it may arise during very early lexical, or even pre-lexical processing: graded activation of potential continuations may facilitate extraction of visual or orthographic information from the parafovea – the early L_1 stage of E-Z Reader that controls saccadic planning – rather than later lexical identification.

6. Conclusions and implications for the cognitive architecture of skilled reading

This review has focused on plausibility preview effects because they contribute novel evidence about the benefits and costs of parafoveal processing that highlight the interplay between multiple mechanisms. The consistent, robust effects of preview plausibility on the earliest eye-movements observed across multiple studies using different materials (Schotter & Jia, 2016; Veldre & Andrews, 2016b, 2017, 2018a, 2018b; Yang et al., 2012; 2014) highlight four major issues that shed light on the role of parafoveal processing in online reading.

First, deep parafoveal processing, to the lexical or semantic level, occurs much more frequently than has typically been assumed (e.g., Schotter et al., 2012; Cutter et al., 2015). A number of methodological factors have contributed to previous failures to observe reliable semantic preview effects, including the strength of the semantic similarity manipulation (Schotter, 2013; Veldre & Andrews, 2016a), the counteracting effects of orthographic mismatch, and reliance on averaged data which conflate different dimensions of variability between individuals (Veldre & Andrews, 2016a, 2016b).

The second, more critical implication is that preview effects are sensitive not only to lexico-semantic attributes of parafoveal words or to their syntactic acceptability, but to their *fit* in the sentence context across both these dimensions. Early effects of contextual plausibility shed light on the dynamic interactions between lexical retrieval and the processes involved in constructing sentence/discourse representations (Kintsch, 1988). The early disruptions to eye movements, including skipping, caused by plausibility violations in the parafovea, and the distinct patterns of reanalysis observed in response to semantic and syntactic violations (Andrews & Veldre, 2018b) implicate rapid, incremental, word-by-word integration of new input with the developing representation of the sentence (Altmann & Mirkovic, 2009). When an implausible preview is a short, easy to process word, rapid postlexical integration failure may directly trigger re-analysis processes that influence first-pass reading, but the timecourse and information requirements of post-lexical integration make it unlikely that that this mechanism is the sole source of the plausibility preview effect (Veldre et al., submitted).

The third critical finding is the consistent evidence of plausibility effects on skipping of previews that were semantically *and* syntactically compatible relative to both semantic and syntactic violations. These skipping effects appear to demonstrate a genuine *benefit* for previews that fit the sentence context (Veldre & Andrews, 2017, 2018a, 2018b, 2018c). The sensitivity to both semantic and syntactic fit, combined with evidence of a plausibility preview effect even for sentences constrained to a highly predictable target (Veldre & Andrews, 2018a), supports Staub's (2015) conclusion that a diffuse set of possible sentence continuations are activated. Such activation yields differences in processing difficulty between plausible and implausible previews that contribute to plausibility preview effects. Graded predictions about upcoming words may combine with orthographic information extracted from the parafovea to yield early plausibility benefits on skipping, or forced fixations on the target word. These early influences of plausibility

can result in comprehension errors when plausible previews are incorporated into sentence representations in place of the target (Schotter & Jia, 2016; Veldre & Andrews, 2017), or late regressions back to resolve lingering uncertainty about the correct identity of the target word (Schotter, et al., 2018) triggered by failures in sentence integration processes.

The fourth source of novel evidence highlighted in this review concerns how preview effects are modulated by individual differences. The most critical findings are that higher lexical proficiency was associated with early lexical competition from orthographically similar word neighbors (Veldre & Andrews, 2015b), consistent with deeper parafoveal processing, but *reduced* influences of higher-order semantic and contextual information on preview effects (Veldre & Andrews, 2016a, 2016b). The resolution to this apparent paradox lies in the interplay between the efficiency of preview processing and trans-saccadic integration. The deeper foveal and parafoveal processing afforded by higher lexical proficiency increases the likelihood that sufficient processing of the preview will occur to trigger planning of a saccade out of the target word before it has been fixated, leading to a skip or a forced fixation. However, if completion of lexical processing of the preview results in retrieval of its orthographic representation, or enhances rapid extraction of information from the target once it is fixated, trans-saccadic integration mechanisms will yield orthographic conflict between the preview and target. This conflict terminates the saccade planned on the basis of the parafoveal preview information and eliminates the preview benefit arising from a plausible word (Veldre & Andrews, 2016a). According to this view, the benefits of semantic and contextual plausibility associated with superior reading ability are primarily due to mechanisms like those proposed to account for effects of preview difficulty. The opposite relationship of semantic and plausibility preview effects with spelling ability reflects costs due to sensitivity to discrepancies between the orthography of the preview and target that disrupt trans-saccadic integration. The net

preview effect shown by an individual, and its timecourse across early and late eye movement measures, depends on the relative contribution of these two mechanisms.

More broadly, the incremental, word-by-word processing demonstrated by readers' sensitivity to the contextual plausibility of parafoveal words is consistent with a modular cognitive architecture in which the outcomes of independent word identification processes determine the extent and time-course of parafoveal processing (Andrews & Reichle, 2019), but individual differences in lexical quality determine exactly how parafoveal information affects oculomotor control. The detailed accounts of online reading provided by computational models of eye movements, like E-Z Reader and SWIFT, go a long way towards explaining how interactions between foveal and parafoveal processing contribute to the complex patterns of eye-movement behavior observed in online sentence reading. However, to provide a complete account of reading, these models need to be extended to specify how the information extracted from text is integrated and combined with long-term knowledge and inferential processes to construct meaning, and how these processes are modulated by individual differences in reading skill. Plausibility preview effects provide an important source of evidence that will contribute to such future developments.

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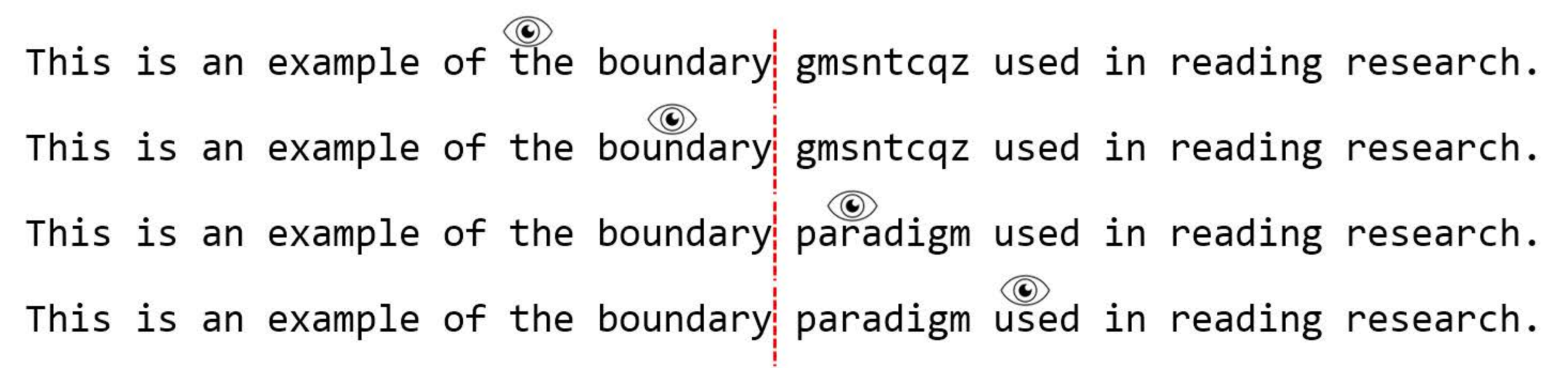
Figure legend

Figure 1. Illustration of the gaze-contingent boundary paradigm used to assess parafoveal preview effects across four successive fixations. The location of the reader's fixation is indicated by the eye. The dashed line indicates the location of the invisible boundary. During the saccade that crosses the boundary the invalid preview *gmsntcqz* is replaced by the valid target word *paradigm.*


This is an example of the boundary gmsntcqz used in reading research.
This is an example of the boundary gmsntcqz used in reading research.
This is an example of the boundary paradigm used in reading research.
This is an example of the boundary paradigm used in reading research.