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Parafoveal processing in reading

A dissertation submitted in partial satisfaction of the
requirements for the degree
Doctor of Philosophy

in

Psychology

by

Bernhard M. Angele

Committee in charge:

Professor Keith Rayner, Chair
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2013

The dissertation of Bernhard M. Angele is approved, and it is acceptable in quality and form for publication on microfilm and electronically:

Chair

University of California, San Diego

2013

DEDICATION

To my parents.

EPIGRAPH

To completely analyze what we do when we read would almost be the acme of a psychologist's achievements, for it would be to describe very many of the most intricate workings of the human mind, as well as to unravel the tangled story of the most remarkable specific performance that civilization has learned in all its history.

—Edmund Burke Huey

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Chapter 2, in full, is a reprint of the material as it appears in Parafoveal processing of word *n+2* during reading: Do the preceding words matter? (Angele & Rayner, 2011). The dissertation author was the primary investigator and author of this paper.

Chapter 3, in full, is a reprint of the material as it appears in Eye movements and parafoveal preview of compound words: Does morpheme order matter? (Angele & Rayner, 2013a). The dissertation author was the primary investigator and author of this paper.

Chapter 4, in full, is a reprint of the material as it appears in Processing *the* in the parafovea: Are articles skipped automatically? (Angele & Rayner, 2013b). The dissertation author was the primary investigator and author of this paper.

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ABSTRACT OF THE DISSERTATION

Parafoveal processing in reading

by

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Doctor of Philosophy in Psychology

University of California, San Diego, 2013

Professor Keith Rayner, Chair

In this dissertation, I describe a series of experiments designed to answer a number of questions about parafoveal pre-processing: (1) How many words can readers pre-process parafoveally at the same time? (2) How do readers parafoveally pre-process unspaced compound words? (3) What role does parafoveal pre-processing play in word skipping? In the first set of studies, Experiments 2.1 and 2.2 (Angele & Rayner, 2011), the availability of both the first word (*n+1*) and the second word (*n+2*) to the right of the pre-boundary target word (word *n*) were manipulated orthogonally. Additionally, in Experiment 2.2, the word frequency of word *n* was manipulated. The results show that availability of *n+2* preview had no effect on fixation times on either word n, *n+1*, or *n+2*. In the second set of studies, Experiments 3.1 and 3.2 (Angele & Rayner, 2013a), both the order of morphemes in the preview for a compound target word (cowboy vs. boycow) and, in Experiment 3.2, the identity of the letters comprising the constituent morphemes were manipulated (e.g. *cowboy* vs. *boyenz*). The results show that (1) subjects obtained less preview benefit from a reversed order preview (e.g. *boycow*) than from an identical preview (e.g. *cowboy*) and that (2) a correct preview for one of the morphemes led to a slight preview benefit even when the morpheme order was reversed. This suggests that, at least during early processing, compound words are processed as a whole. In the third study, Experiment 4 (Angele & Rayner, 2013b), the preview that readers received for a three-letter target verb (e.g. eat) was manipulated, so that the upcoming word appeared to be (1) the definite article the (although in an infelicitous position), (2) a random letter string (*cxf*), or (3) identical to the target verb. The results show that readers are likely to skip *the* even when it does not fit into the sentence context. In summary, the results of the experiments performed as part of this dissertation show that parafoveal pre-processing is, in general, rather shallow, involves only one parafoveal word, and is restricted to the orthographic level.

Chapter 1

Introduction

The ability to obtain relatively detailed information not only from the small fovea but also from the much larger parafovea can be extremely useful in a wide variety of tasks, such as extracting the gist from a visual scene and searching for objects within a scene. However, the wealth of information available from the visual field also leads to a problem: at almost any given point, a viewer receives more detailed information than he or she can process. As a consequence of this, a viewer constantly has to select which area of the visual field he or she wants to process preferentially, that is, where to allocate his or her (covert) visual attention. How to allocate visual attention is a fundamental problem every viewer faces. It is closely related to the problem of where to move the eyes—in fact, there is evidence suggesting that, in most cases, an attention shift to a new location necessarily precedes an eye movement to the same location (Deubel & Schneider, 1996; Shepherd, Findlay, & Hockey, 1986). Because of this, one can assume that, in most cases, a viewer's attentional focus coincides with the fovea and he or she constantly has to decide whether to maintain attention there or to shift attention to the parafovea. In consequence, parafoveal processing is critically dependent on attention.

The task of reading a word, a sentence, or a passage of text is quite different from viewing a natural scene. In written language, linguistic information is compressed into a line of text and follows a strict serial order. This tremendously facilitates the task of finding areas of interest compared with scene viewing—in English, the relevant information will always be to the right of the current fixation (except if one has reached a line break or makes a regression). On the other hand, this means that, since a reader's fovea will invariably contain a word that is different from the parafoveal word, parafoveal information (i.e. information about the upcoming word that has not yet been fixated) may not only be irrelevant to the current task of identifying the foveated word, but it might actually hinder that effort by activating a competitor of that word. This situation differs quite drastically from scene viewing, where one can reasonably assume that any part of the scene is somewhat related to the overall gist of the scene and contains cues as to where objects of interest might be located. Still, in reading, the parafovea contains valuable information about upcoming words that can greatly increase the efficiency of the reading process. Because of this, readers have to allocate their attention carefully in order to obtain parafoveal information to a degree that is useful, but not harmful. In this chapter, I will provide a short summary of what we know about parafoveal processing during reading and also highlight some open questions.

1.1 Evidence for the use of parafoveal information

Parafoveal processing in general has been studied for a long time, starting with Helmholtz's experiments on covert attention and continuing with the partial report paradigm by Sperling (1960) —for a review, see Wright and Ward (2008). It is also easy to show that subjects can identify letter strings in the parafovea (Bouma, 1970, 1973). Despite this, it was not clear whether parafoveal information is actually used in reading until McConkie and Rayner (1975) provided an estimate of the perceptual span, that is, the area from which readers can obtain useful information. McConkie and Rayner (1975) used eye-tracking to control the amount of parafoveal information subjects received while reading sentences on a computer screen.

On each fixation the subjects made, only a limited region of the sentence around the fixation point was made available to them, while the rest of the sentence was masked, e.g. by replacing all the characters with Xs (moving window paradigm). By comparing reading speeds and fixation duration measures in the moving window conditions with those measured when the entire sentence was available on the screen, they were able to measure the extent of the perceptual span, i.e. the area from which a reader can obtain useful information. They found that readers of English use information from up to 14 – 15 characters to the right of fixation, a region which is clearly part of the parafovea. Further research showed that to the left of fixation, the area from which readers obtain useful information is limited to 3-4 characters (McConkie & Rayner, 1976), and that this asymmetry is reversed for readers of Hebrew, which is written right-to-left (Pollatsek, Bolozky, Well, & Rayner, 1981). Furthermore, Inhoff and Liu (1998) found that Chinese readers have a very small perceptual span of one character to the left and three characters to the right of fixation, consistent with the high information density of Chinese characters.

A final piece of evidence about the importance of parafoveal information comes from Rayner, Liversedge, and White (2006), who found that readers' performance at reading sentences declined markedly when, on each fixations readers made, the word to the right of fixation disappeared 60 ms after fixation onset. This is in marked contrast to the findings of Rayner and colleagues and Liversedge and colleagues (Liversedge et al., 2004; Rayner, White, Kambe, Miller, & Liversedge, 2003), who showed that readers were able to read sentences fairly normally even if every word they fixated disappeared 60 ms after fixation onset. This suggests that readers fixate words much longer than would be necessary in order to obtain sufficient information to identify them. However, the extra time is not wasted, since the upcoming word can be processed parafoveally. While the studies above demonstrate that parafoveal information plays an important role during reading, this does not mean that reading is possible using only parafoveal information. A critical demonstration that much less parafoveal information can be used in reading than in isolated letter or word naming comes from Rayner and Bertera (1979), who used a variation of the moving window paradigm to study the effects of reading without a fovea. In effect, their manipulation was the opposite of the moving window paradigm: during each fixation readers made, those characters closest to the center of fixation were masked. Rayner and Bertera used different mask sizes. When the mask was small enough to allow some information to reach the fovea (i.e. if it was only 3 – 4 characters wide), subjects read more or less normally, although at a reduced rate. When the mask was extremely wide (13 – 18 characters), many subjects were unable to report any information about the sentence. Even when only the fovea was masked (mask width 7 characters), reading was markedly slower than the control and readers made a large number of errors when trying to repeat the sentences after they had finished reading them.

1.2 Parafoveal pre-processing

If parafoveal information cannot replace foveal information entirely, what is it used for? The classic gaze-contingent boundary experiment conducted by Rayner (1975) demonstrates that the availability of parafoveal information about the upcoming word (that is, the availability of parafoveal preview) can reduce the time necessary to process that same word once it is fixated compared to a situation in which no parafoveal preview is available. This is known as the parafoveal preview benefit effect. Rayner (1975) was able to measure the size of the preview benefit by monitoring readers' eye movements while they were reading a sentence and placing an invisible boundary on the screen just to the left of the target word whose parafoveal preview was to be manipulated. While readers were fixating to the left of the target word, the target word was replaced on the screen by a preview word whose properties depended on the experimental condition: In the identical control condition, the preview word was exactly the same as the target word (e.g. song — song). In the experimental condition, the preview word consisted of a string of Xs with the same length as the target word (e.g. song — XXXX). Once a reader's gaze crossed the invisible boundary, the preview word was always replaced by the target word. Since this replacement occurred during a saccade, the display change was masked by saccadic suppression (Matin, 1974), preventing subjects from conscious noticing it. Rayner's gaze-contingent boundary experiment has since been replicated and extended numerous times, providing us with a good idea of what kind of information can and cannot be processed parafoveally (for a more detailed review, see Schotter, Angele, & Rayner, 2012).

1.2.1 Types of parafoveal pre-processing

Evidence for orthographic parafoveal pre-processing

Obviously, preview benefit effects require some type of parafoveal information to persist during the saccade to the target word and to be available during the subsequent fixation. What type of information can we assume to persist in this manner? In theory, information at any processing level could be imagined to persist across saccades. In a series of parafoveal naming and semantic decision experiments based on the gaze-contingent display change paradigm, Rayner, McConkie, and Zola (1980) tested three hypotheses about how parafoveal information can be maintained across a saccade. They assumed that subjects might either hold the parafoveal information in a visual storage, a phonological buffer, or they might encode and store abstract letter codes (as suggested by McConkie & Zola, 1979). Rayner et al. found that when there was phonemic, but no orthographic overlap between a target word and its preview (e.g. WRITE—ROUGH), there was no preview benefit, which they saw as evidence against the phonological buffer hypothesis. Furthermore, the same amount of preview benefit was found when a preview did not match the case of the target word (write—WRITE) as when it did, suggesting that the visual storage hypothesis was not correct either. Finally, they also found no preview benefit effect due to semantic relatedness of preview and target. However, strong facilitation was observed when the preview shared two or three of the initial letters of the target word, which is in agreement with the abstract letter code hypothesis.

Even though, as I will show in the following sections, there are more recent experiments showing that phonological and semantic information might, in fact, be obtained from the parafovea, and although it is not clear whether there is a lexical component to the effects observed, Rayner et al.'s experiments make a clear case for the importance of the initial letters of a parafoveal word (see also Beauvillain & Doré, 1998). These findings were confirmed by Briihl and Inhoff (1995), who showed that a preview containing the initial letters of a word provided more benefit than a preview containing the interior letters of that word (i.e. its orthographic body). A similar effect was reported in parafoveal naming and lexical decision tasks by Inhoff and Tousman (1990). Furthermore, the availability of the word-final letter in the preview did not provide any benefit. However, the picture was complicated by the finding that preview for the entire word provided more facilitation than the word-initial letters (see also Inhoff, 1989b, 1990; Lima & Inhoff, 1985). It appears that word-initial letters can provide a preview benefit even when available in isolation while the other letters in a word cannot. Those letters only provide a preview benefit when available in the context of the word-initial letters.

Evidence for phonological parafoveal pre-processing

In contrast to the results obtained by Rayner, McConkie, and Zola (1980), some more recent studies have found some indication that readers can obtain phonological information from words in the parafovea. Pollatsek, Lesch, Morris, and Rayner (1992) found that homophone previews (e.g. *reins* as a preview for *rains*) resulted in a larger preview benefit effect than previews that had the same amount of orthographical overlap, but were not homophones (e.g. *ruins* as a preview for *rains*). The same effect was shown by Chace, Rayner, and Well (2005), although it was not present in less skilled readers. Henderson, Dixon, Petersen, Twilley, and Ferreira (1995) found that lexical decisions on target words containing phonologically regular initial trigrams such as *button* benefited more from an identical preview (compared to a dissimilar preview) than those containing irregular initial trigrams such as *butane*. Words with regular initial trigrams were also easier to identify from the preview alone and subjects were more likely to detect a display change from regular to irregular trigrams than in the other direction.

Lesch and Pollatsek (1998) found that a preview word can affect a semantic decision even when it is a false homophone of a semantically related word. For example, subjects were less likely to reject a word as a semantic associate for *pillow* when its preview had been *bead* (a letter string which could, in principle, be pronounced like *bed*, analogous to *head*) than *bend*. This implies that readers do not only activate the correct pronunciation of a parafoveal word, but also other alternative pronunciations. The results presented so far show that readers can obtain phonological information from a word preview. Miellet and Sparrow (2004) were able to replicate the findings of Pollatsek et al. using pseudohomophone previews in French (e.g. *kaurs* as a preview for *corps*). Ashby, Treiman, Kessler, and Rayner (2006) showed that readers can obtain phonological information from nonwords even if the vowel phoneme is represented by different letters (e.g. *dauk* as a preview for *dawn*). Additionally, they found that readers are sensitive to the effect of the subsequent phoneme on ambiguous vowel letters, such as *oo*. For example, *bloon* provided more preview benefit for *bloom* than *blook*. This shows that readers can process relatively complex phonological relationships in parafoveal words and nonwords.

A related question concerns the use of prosody information in the parafovea: Can readers obtain information on the syllabic structure of a parafoveal word? Ashby and Rayner (2004) performed a boundary experiment in which readers could either get a valid syllable preview (e.g. *de_zxz* for *demand*) or an invalid syllable preview (*dem_zx* for *demand*). They found that the correct syllable preview resulted in a significantly larger preview benefit effect compared to the incorrect preview. Ashby (2006) replicated this effect for low frequency target words, but did not find it for high frequency target words. Additionally, Ashby and Martin (2008) replicated the effect in a lexical decision task. Based on these results, Ashby (2006) proposes that readers store information about the words in a sentence in phonological form (phonological hub theory).

Evidence for morphological parafoveal pre-processing

There is some evidence that readers of English do not have access to the morpheme structure of parafoveal words. Lima (1987) found that pseudoprefixed words were fixated longer than prefixed words, but there was no difference between a prefixed and a pseudoprefixed parafoveal preview. This finding was replicated by Kambe (2004). Inhoff (1989a) manipulated the preview that readers received for three- or four-letter compound (e.g. *cowboy*) and pseudocompound words (e.g. *carpet*). He found that there was no difference in preview benefit between cases where the letters available in the preview corresponded to the morpheme structure of the compound words (e.g. *cowxxx* for *cowboy*) or not (e.g. *cowbxx* for *cowboy*), nor was there a difference between the effect of such previews on the pre-processing of compound and pseudocompound words.

In contrast, Deutsch et al. (Deutsch, Frost, Pelleg, Pollatsek, & Rayner, 2003; Deutsch, Frost, Pollatsek, & Rayner, 2000) found that readers of Hebrew were able to obtain morpheme-level information from a preview, as they showed a greater preview benefit if the preview word was derived from the same root as the target word than when the preview word was an orthographic control. This suggests that the absence of effects of parafoveal morpheme information may be specific to the English language.

A related issue is the processing of compound words, i.e. words that are composed of several morphemes which can also stand on their own as content words (for example, both *cow* and *boy* in *cowboy* are content words in their own right). Hyönä, Bertram, and Pollatsek (2004) performed a variation of the gaze-contingent boundary paradigm in which they placed the invisible boundary in between two morphemes constituting a Finnish compound word. By doing this, they manipulated the preview readers received for the second morpheme of a compound word while they were fixating its first morpheme. They found large preview benefit effects on fixation times on the second morpheme, yet the availability of preview for the second morpheme did not appear to affect fixation times on the first morpheme. This suggests that readers do not process the morphemes that constitute a compound word in parallel.

Interestingly, the preview benefit observed by Hyönä et al. (2004) was, at 80 ms, much larger than the usual effect size observed in boundary experiments. Juhasz, Pollatsek, Hyönä, Drieghe, and Rayner (2009) and White, Bertram, and Hyönä (2008) were able to replicate this effect. Juhasz et al. found a similar effect for spaced compound words such as *tennis ball*, which was slightly larger than the usual preview benefit effect.

Drieghe, Pollatsek, Juhasz, and Rayner (2010) tested the hypothesis that the constituents of compound words are processed serially directly by manipulating the preview for the second morpheme of compound words as well as for the second part of length-matched monomorphemic words (with the boundary located between the first and the second morpheme or the equivalent location within a monomorphemic word). They found that readers fixated longer on the first part of a monomorphemic word when preview for its second part was denied. This suggests that the presence of a morpheme boundary causes readers to process the constituents of compound words serially. However, when readers first encounter a word, they do not know whether it is a monomorphemic word or a compound word. As a consequence, there likely is a very early stage of parafoveal processing during which all letters in a word are processed. Once readers detect the morpheme boundary, they focus their attention on one morpheme at a time. I will return to this issue later in this chapter, as Experiment 2 was designed to investigate this early stage of parafoveal processing.

Evidence for semantic parafoveal processing

There is a long and, at least up until very recently, largely unsucessful history of attempts to find evidence of high-level parafoveal processing. As described at the beginning of this section, Rayner, McConkie, and Zola (1980) found that there was no difference in parafoveal naming performance between related and unrelated parafoveal preview conditions. Similarly, Rayner, Balota, and Pollatsek (1986) did not find a difference in preview benefit effects between word previews that were related and those that were unrelated to the parafoveal target word, suggesting that readers were unable to make use of the semantic relatedness in order to identify the parafoveal word. In contrast, in a recent study, Hohenstein, Laubrock, and Kliegl (2010) used a parafoveal fast-priming paradigm to limit the time during which the preview word was present in the parafovea. They found evidence for semantic pre-processing for fairly short parafoveal prime durations (125 ms). As a consequence, there is now some evidence that readers can obtain semantic information from the parafovea, but the conditions under which these effects appear still need to be clarified.

1.2.2 Open questions about parafoveal pre-processing

In the past section, I have presented an overview of what we know about parafoveal pre-processing so far. In the following, I will describe three particular questions about parafoveal pre-processing which, up to now, have not been resolved. These questions will form the theoretical background to the experiments described in the following chapters.

How many words can we pre-process at the same time?

The experiments on parafoveal pre-processing described so far focused on pre-processing of the first word to the right of fixation (*n+1*). This makes sense since the decrease in visual acuity usually makes any further words quite hard to process. However, there is a possibility that, when *n+1* is short, the following word (*n+2*) may also be processed. Whether such *n+2* pre-processing occurs is theoretically important, as current models of eye-movement control during reading differ in their predictions regarding the possibility of *n+2* effects. Serial-attention-shift (SAS) models such as E-Z Reader (Reichle, Pollatsek, Fisher, & Rayner, 1998; Reichle, Pollatsek, & Rayner, 2006; Reichle, Warren, & McConnell, 2009) predict that readers process only one word at a time and therefore should not be able to parafoveally process word *n+2* (unless they have already finished processing *n+1* and are planning on skipping it). In contrast, guidance-by-attentional-gradient (GAG) models such as SWIFT (Engbert, Longtin, & Kliegl, 2002; Engbert, Nuthmann, Richter, & Kliegl, 2005) predict that readers process all words in the perceptual span at the same time and therefore should be able to make use of available parafoveal information about *n+2*.

The first study to investigate this question was a gaze-contingent boundary experiment conducted by Rayner, Juhasz, and Brown (2007), who did not find any evidence of *n+2* preview benefit effects. In contrast, a study by Kliegl, Risse, and Laubrock (2007) found effects of *n+2* preview on fixation times on word *n+1*. There is a possibility that this effect is caused by a failed attempt to skip *n+1* so that fixation times on *n+1* actually reflect processing on *n+2*. This explanation would be compatible both with SAS and GAG accounts of word identification during reading. In order to test this, Angele, Slattery, Yang, Kliegl, and Rayner (2008) performed an experiment in which both the availability of preview for *n+1* and the availability of preview for *n+2* were manipulated separately. If *n+1* is masked, no attempted skips of it should be attempted and therefore any *n+2* preview effects could be clearly attributed to parafoveal pre-processing of two words simultaneously. However, Angele et al. (2008) did not find any effects of *n+2* preview either on fixation times on *n+1* or on fixation times on *n+2* itself. One potential issue with this result is that the *n+1*-words used by Angele et al. (2008) were relatively long, potentially pushing word *n+2* out of the parafovea while readers are fixating the pre-boundary word *n*. Furthermore, the pre-boundary words *n* used by Angele et al. (2008) were mostly low-frequency, which can reduce the amount of preview benefit a reader can obtain (Henderson & Ferreira, 1990).

Chapter 2 of this dissertation describes two experiments designed to follow up on Angele et al. (2008) and address these objections. The first concern is addressed by

Experiment 2.1 which uses *n+1*-words that are no more than three letters long. This experiment also investigates whether there is a difference in parafoveal pre-processing between sentences in which word *n+1* is the article *the* or another high-frequency three-letter word. In Experiment 2.2, word *n+1* is always *the* and the frequency of the pre-boundary word *n* is manipulated. Thus, Experiment 2.2 creates the most favorable conditions possible with respect to word *n+2* pre-processing—if *n+2* processing is at all possible, it should be observed under these conditions.

How many morphemes can we pre-process at the same time?

Just as it is not fully clear how many words can be pre-processed at the same time, the same question applies to processing morphemes within a word. While it seems quite plausible that bound morphemes such as the plural suffix "-s" or the past suffix "-ed/-d" are processed together with the root morpheme, compound words such as *cowboy*, which are made up from two free constituent morphemes, might as well be two separate words (and often were originally spelled as such). The question, then, is whether both constituents in such compound words can be processed at the same time. Furthermore, if compound words are processed like two separate words, the order in which the morphemes are presented should also matter. For example, the two sentences "The dog bit the cat" and "The cat bit the dog" have very different meanings. On the other hand, there is evidence that reversing the order of some letters within a word does not cause a great deal of disruption (e.g. *clam* vs. *calm*, see Johnson & Dunne, 2012; Johnson, Perea, & Rayner, 2007; Johnson et al., 2007). In the experiments described in Chapter 3, I test whether readers are able to obtain any preview benefit from a reverse morpheme preview such as *boycow* as a preview for *cowboy*.

To what extent does a word have to be pre-processed in order to make the decision to skip it?

The results reported so far seem to suggest that parafoveal pre-processing takes place mostly at the orthographic and phonological level. However, it is a fact that readers skip words quite often. Some of this skipping of words is due to oculomotor error (Nuthmann, Engbert, & Kliegl, 2005), but there is evidence that words which are easy to process (such as high-frequency or function words) are skipped more often than words that are more difficult to process. The first piece of evidence of this kind was provided by O'Regan (1979) and Carpenter and Just (1983), who showed that readers were more likely to skip three-letter function words than three-letter content words.

Gautier, O'Regan, and Le Gargasson (2000) replicated O'Regan's finding that articles are skipped much more often than other short words even when they are not predictable from the preceding sentence structure, as did Drieghe, Pollatsek, Staub, and Rayner (2008). Drieghe et al. interpreted the higher skipping rates for articles as an effect of syntactic category and went as far as calling it the "the largest reported effect of a linguistic nature" on word skipping. While this is certainly possible, an alternative explanation for this phenomenon might be far simpler: readers might start planning a skipping eye movement if they encounter a highly familiar letter string in the parafovea without actually identifying the letter string first or attempting to integrate the parafoveal word into the sentence context. In Chapter 4, I will report an experiment testing whether the skipping of articles in English is sensitive to context information or whether it is truly automatic in the sense that any occurrence of the letter string *the* will likely trigger a skipping.

1.3 Summary

In summary, attention and the presence of foveal information have a tremendous effect on parafoveal processing. In reading, the interaction between foveal and parafoveal information is critically important, and readers must deploy their attention carefully in order to make optimal use of parafoveal information. In the following sections, I report three lines of investigation containing a total of five experiments which examine different aspects of how parafoveal processing can influence—and be influenced by—the processing of foveal information. The first line of research is concerned with the extent of parafoveal processing between words: Can readers process more than one parafoveal word at a time? The second line deals with parafoveal processing within words: Can readers process both morphemes of a parafoveal compound word simultaneously? Finally, the third line investigates which factors can influence a skipping decision.

Presumably, this decision is triggered by parafoveal identification of a word. However, not all information about a parafoveal word and its context may be available at the time of the skipping decision.

Chapter 2

Parafoveal processing of word *n*+2 during reading: Do the preceding words matter?

A major debate in the study of eye movements in reading concerns the question of how attention is allocated during word identification and, consequently, how many words can be identified at the same time. This debate is reflected in the recent development of several competing computational models of eye movements in reading. A serial account of word identification (e.g. Reichle, Liversedge, Pollatsek, & Rayner, 2009) assumes that readers obtain and process information about printed words in essentially the same way they process spoken words: they focus their attention (a "spotlight" as proposed by Posner, 1980) on one word at a time, process it, and then shift their attention to the subsequent word. This view is implemented in serial attention-shift (SAS) models such as E-Z Reader (Reichle et al., 1998, 2006). While there are parallel components of E-Z Reader, lexical processing of words occurs in a serial fashion.

Conversely, proponents of parallel accounts of word identification (e.g. Kennedy & Pynte, 2008) posit that readers are able to distribute their visual attention (an "attentional gradient") over more than one word, and, consequently, process multiple words at the same time. Guidance by attentional gradient (GAG) models such as SWIFT (Engbert et al., 2002, 2005) have been developed to implement parallel processing. In SWIFT, the current processing status of all words in the visual field is represented by a field of activation which is constantly updated over the course of processing. As in E-Z Reader, processing of each word takes place in two stages: During pre-processing, activation on a word increases until it reaches a threshold determined by its processing difficulty. This is followed by lexical completion, during which the activation on the word decreases until it reaches zero.

The amount of activation on a word directly determines the probability that it will be the target of the upcoming saccade, which is triggered by a random timer (although the processing difficulty of the currently foveated word can cause a delay in triggering the next saccade). Processing speeds for each word are determined by eccentricity as well as processing difficulty. Since the activation of every word in the visual field is updated simultaneously, lexical processing of words in parafoveal vision in SWIFT is generally assumed to be the norm instead of the exception (which it is in E-Z Reader). How the meanings of multiple words can be processed and integrated simultaneously in GAG models is not fully clear. An alternative interpretation of parallel processing is that some processing which is independent of lexical processing (rather than lexical identification itself) occurs in parallel. This is perhaps a critical distinction that has not been fully addressed by proponents of GAG models. Our sense is that the latter is the case.

Both E-Z Reader and SWIFT do a good job of accounting for a variety of established phenomena in reading such as word frequency and predictability effects or costs of word skipping. Because of this, attempts to provide evidence for one or the other model have mostly focused on a small number of effects for which E-Z Reader and SWIFT make divergent predictions. One such class of effects, parafoveal-on-foveal effects, involves the properties of a word in the parafovea influencing the processing of the currently fixated word (as evidenced by the fixation times measured on that word). There is a considerable body of evidence for orthographic parafoveal-on-foveal effects, i.e. the effect of an unusual letter string in the parafovea on fixation times on the current word (e.g. Drieghe, Brysbaert, & Desmet, 2005; Pynte, Kennedy, & Ducrot, 2004).

Since such effects are at a sublexical level, however, they cannot be considered a valid test for models of lexical processing such as E-Z Reader and SWIFT. The reliability of lexical parafoveal-on-foveal effects (i.e. an effect of the word frequency of a parafoveal word on fixation measures on the current word), on the other hand, which would be a valid test for the models, is still being debated (see Rayner, 2009).

With respect to lexical parafoveal-on-foveal effects, the predictions of the two models are not clear-cut. In general, lexical parafoveal-on-foveal effects are not predicted by E-Z Reader. In contrast, SWIFT might be able to predict parafoveal-on-foveal effects, but only for certain fixation time measures such as gaze duration. In the following, we will discuss these predictions in detail. In SWIFT, only properties of the currently fixated word can influence fixation times directly through foveal inhibition. Therefore, SWIFT does not have a mechanism that would directly predict parafoveal-on-foveal effects. Since parafoveal processing of an upcoming word affects the relative activation level of the current word, SWIFT might, however, predict effects of lexical variables on refixation probability (and, consequently, gaze duration; see Risse, Engbert, & Kliegl, 2008). Also, it is worth noting that in its current version, SWIFT does not incorporate effects of orthographic regularity, although they would be easy to add to the model.

In contrast, E-Z Reader currently has no specific implemented mechanism (apart from mislocated fixations, see below) to account for parafoveal-on-foveal effects of any kind, be they orthographic or lexical. Despite this, the SAS account of lexical processing does not preclude the possibility that certain visual or even orthographic properties of the upcoming words might be processed early on in a parallel fashion. As a consequence, it would certainly be possible to include such early visual processing in the E-Z Reader model without violating its general premises. Indeed, E-Z Reader includes a low-level attentional scan stage which could be influenced by unusual patterns in the parafovea. Lexical parafoveal-on-foveal effects, however, cannot, in principle, be accounted for in an SAS model—again, with the exception of mislocated fixation cases. Evaluating the presence or absence of such lexical effects is therefore critical in order to distinguish between serial and parallel accounts of word identification.

Given the inconclusiveness of parafoveal-on-foveal effects, a second test ground to distinguish between the models has revolved around preview effects. The parafoveal preview of a word during a prior fixation influences fixation times on that word itself once it is fixated. This influence, which yields a reduction in fixation times on the pre-processed word, is known as the parafoveal preview benefit effect. It is usually measured via the boundary paradigm (Rayner, 1975) in which a reader is presented with either a valid or an invalid preview of the target word while fixating to the left of the target word. Once the reader's eyes cross an invisible boundary between the pretarget and the target word, the preview is replaced by the target word. Since these gaze-contingent display changes occur during the saccade from the pretarget to the target, readers usually do not notice the changes due to saccadic suppression.

Parafoveal preview benefit effects for the word to the right of fixation (word *n+1*) have been found in a large number of studies (see Rayner, 1998, 2009 for overviews). There is, however, also the possibility that readers can obtain a preview benefit from word *n+2*. While *n+1* preview benefit effects are predicted both by E-Z Reader and SWIFT, preview benefit effects on the second word to the right of fixation (*n+2*) are only predicted by SWIFT (except for one scenario in E-Z Reader described next). In E-Z Reader, parafoveal pre-processing of word *n+1* occurs whenever the lexical completion stage for the currently fixated word *n* finishes before the saccade programming stages initiate a saccade to *n+1*. In this situation, the attentional spotlight shifts to *n+1* while the eyes remain on *n*. Preprocessing of word *n+2* is much rarer in E-Z Reader. It is only possible when lexical processing for both word *n* and word *n+1* can be completed before the saccade programming terminates. In this case word *n+1* does not need to be fixated at all and a new eye movement to *n+2* is programmed, skipping *n+1*. In SWIFT, parafoveal pre-processing takes place constantly for all words in the perceptual span including word *n+1* and word *n+2*, although SWIFT predicts a smaller preview benefit on word *n+2* due to its eccentricity.

Recently, a number of studies have attempted to examine the effects described above. Rayner, Juhasz and Brown (2007) used the boundary paradigm to manipulate the preview of a target word. They found a standard *n+1* preview benefit effect but were unable to find either a word *n* preview benefit effect or parafoveal-on foveal effects. While Kliegl, Risse and Laubrock Kliegl et al. (2007) also did not find an *n+2* preview benefit, they reported finding both a significant parafoveal-on-foveal effect of *n+1* lexical status (content or function word) on first fixation and gaze durations on word *n* and an effect of *n+2* preview availability on gaze durations on word *n+1*. Kliegl et al.'s findings might, however, be explained by mislocated fixations (Nuthmann et al., 2005). Due to the saccadic range error long saccades often tend to fall short of their targets—they undershoot (McConkie, Kerr, Reddix, & Zola, 1988). It is therefore possible that the effects observed on word *n+1* by Kliegl et al. were due to readers intending to skip word *n+1* (and fixate *n+2*), but undershooting their target and landing on *n+1* instead. In this case, fixation times on *n+1* actually reflect processing of word *n+2*. Such an explanation is compatible with E-Z Reader. A similar explanation could be applied to the apparent parafoveal-on-foveal effects found on word *n+1*, which might be caused by readers trying to fixate on word *n+1* but undershooting and refixating word *n+2* instead (Drieghe, Rayner, & Pollatsek, 2008).

In order to further examine *n+2* preview effects and to eliminate the possibility of mislocated fixations leading to parafoveal-on-foveal effects, Angele et al. (2008) used a variation of the boundary paradigm in which, prior to crossing the boundary to the right of word *n*, readers received either (1) correct previews for *n+1* and *n+2* (both correct), (2) an incorrect preview of *n+1* and a correct preview of *n+2* (*n+1* incorrect), (3) a correct preview of *n+1* and an incorrect preview of *n+2* (*n+2* incorrect) or (4) incorrect previews for both *n+1* and *n+2* (both incorrect). The comparison between the *n+1* incorrect and the both incorrect conditions provided a critical test for *n+2* parafoveal preview, since E-Z Reader does not allow for skipping of an illegal letter string (lexical processing will not be able to terminate normally for a random letter string), making pre-processing of word *n+2* in the *n+1* incorrect condition impossible. Parallel models, on the other hand, do allow for the possibility of *n+2* pre-processing even if *n+1* processing has not terminated yet. Angele et al. (2008) found a standard *n+1* preview benefit effect but were unable to find parafoveal-on-foveal or *n+2* preview benefit effects.

Radach, Inhoff, Glover, and Vorstius (2013) employed a similar paradigm and reported finding both *n+2* preview benefit and lexical parafoveal-on-foveal effects. Furthermore, Risse and Kliegl (2011) found *n+2* preview benefit effects and an effect of *n+2* preview on word *n+1* both in college-age and older readers. Why did Kliegl et al. (2007), Radach et al. (2013), and Risse and Kliegl (2011) find effects when Angele et al. (2008) did not? One possible explanation might be the length of the *n+1* words used in the studies. While Kliegl et al. (2007) and Radach et al. (2013) exclusively used three-letter words,Angele et al. (2008) used *n+1* words that were on average six characters long. Because of this, *n+2* might have been too far in the parafovea for any meaningful pre-processing to take place.

While the Angele et al. (2008) study therefore establishes upper limits for the spatial extent of parafoveal pre-processing, it is still unclear how acuity constraints impact pre-processing at lower eccentricities. We tested this hypothesis in Experiment 2.1 by manipulating word type and frequency of word *n+1* while using the same preview manipulation for word *n+1* and *n+2* as Angele et al. (2008).

A second explanation for the diverging results described above concerns the properties of the pre-target word *n+2*. Specifically, the extent of parafoveal processing might not only be influenced by the properties of word *n+1* but also by the properties of word *n*. The effect of foveal load caused by word *n* on pre-processing of word *n+1* has been documented by Henderson and Ferreira (1990) as well as White, Rayner, and Liversedge (2005), who manipulated word frequency (and, correspondingly, ease of processing) of word *n*. Both studies found reduced preview benefit on word *n+1* when word *n* was a low frequency word (spillover effect). Foveal load might also limit the amount of preview that can be obtained from word *n+2*.

Alternatively, a parallel processing model such as SWIFT might predict that by prompting longer fixations immediately to the left of the boundary, low frequency pre-target words could actually result in a higher amount of pre-processing than high frequency pre-target words. If either of these hypotheses is true, the choice of pre-target words in a given study might determine whether effects of *n+2* pre-processing can be observed or not. In Experiment 2.2, we tested whether pre-target frequency can account for the divergence in results by directly manipulating the frequency of word *n* in addition to the preview manipulation utilized in Experiment 2.1.

2.1 Experiment 2.1

In Experiment 2.1, we used the same experimental procedure as in the Angele et al. (2008) study to manipulate preview information for very short (three-letter) *n+1* words as well as word *n+2*. If parafoveal pre-processing of *n+2* is indeed influenced by *n+1* word length, we would expect to find a much stronger degree of pre-processing in this case. Importantly, while parallel models predict an influence of eccentricity on *n+2* preview benefit and parafoveal-on-foveal effects, serial models predict no such effects even for extremely short *n+1* words. Radach's (1996) word grouping hypothesis represents a different approach to parafoveal processing. He proposed that an article and the subsequent noun might be processed as a perceptual unit. Because of this, parafoveal pre-processing of word *n+2* might be restricted to cases where *n+1* was an article. Drieghe, Pollatsek, et al. (2008) attempted to replicate Radach's (1996) findings in an experimental design. However, their findings suggested that readers targeted the articles and the subsequent nouns separately. In this case, we would not expect increased parafoveal processing of words following articles. In the present experiment, we tested both of these possibilities.

2.1.1 Method

Subjects

Thirty-two undergraduate students at the University of California, San Diego participated in the experiment for course credit. All were native speakers of English, had either normal or corrected to normal vision, and were naïve concerning the purpose of the experiment. Data were collected from 14 additional subjects, but subsequently excluded from the analysis due to reasons described below.

Apparatus

An SR Research Eyelink 2000 eyetracker was used to record subjects' eye movements with a sampling rate of 2000 Hz (i.e. the eye position was sampled twice every millisecond). The experimental sentences were displayed on an Iiyama Vision Master Pro 454 video monitor with a refresh rate of 150 Hz. Subjects read binocularly, but only their right eyes were recorded. Viewing distance was approximately 60 cm, with 3.8 letters equaling one degree of visual angle. Custom designed software ensured that the display change occurred within 9 ms of a reader's gaze crossing the boundary.

Table 2.1: Length and Frequency Information for the three target words in Experiment 2.1 (standard deviations in parentheses). The frequency information was obtained from CELEX via N-Watch (Davis, 2005).

Target word	Length range	Mean length	Mean word frequency/million
n	3-10	7 (1.4)	56 (119)
n+1	3	3 (0)	*the*: 62,281 (0) 3–letter word: 2793 (1556)
n+2	3 – 11	7 (1.8)	57 (97)

Materials

120 sentence frames featuring a succession of a verb (word *n*), the article *the* or a three letter word (word *n+1*), and a noun (word *n+2*) were used to create the experimental conditions. Sixty of the sentence frames were taken from Drieghe, Pollatsek, et al. (2008) and sixty more were newly created. In the three-letter word condition, word *n+1* was a high frequency three-letter word (either two, one, old, his, her, new or all) instead of the article the. Fifty University of California, San Diego undergraduates who participated for course credit provided norming data in order to ensure that articles and non-article three-letter words fit the sentence frames equally well. Table 2.1 shows length and frequency (determined from the CELEX count using the N-Watch software, Davis 2005) of the critical words *n*, *n+1* and *n+2*.

Using the gaze contingent boundary paradigm (Rayner, 1975) readers were presented with either identical or nonword previews of word *n+1* and *n+2* prior to fixating the target word. Once readers crossed the invisible boundary located immediately to the right of word *n*, the previews were replaced by the target words. The nonword previews were generated using the same algorithm employed in Angele et al. (2008) and Kliegl et al. (2007), replacing *n+1* and *n+2* with randomly chosen letters while keeping the word shape intact. In total, there were three preview conditions (see Figure 2.1): (1) Preview was either available for both *n+1* and *n+2*, (2) preview was denied for word *n+1*, but available for word *n+2*, or (3) preview was denied both for word *n+1* and *n+2*.

Procedure

After receiving the experimental instructions participants read 10 practice sentences without display changes. They were then presented with the 120 experimental sentences embedded in 48 filler sentences in random order. Approximately 33% of the sentences were followed by a two-alternative forced choice comprehension question which participants answered by pressing the button corresponding to the correct answer on a button box. After the experiment, participants were asked whether they had noticed anything unusual during the experiment. If participants confirmed this and reported seeing a display change, they were asked to give an estimate of the number of changes they had seen. The 14 excluded subjects reported seeing more than three changes. Because of this, their data were discarded from the subsequent analysis (leaving 32 subjects as noted above). This high exclusion rate is likely due to the size of the display change region (two words). The Angele et al. (2008) study, which featured even larger display change regions, reported similar exclusion rates.

2.1.2 Results and Discussion

As in Kliegl et al. (2007), inferential statistics are reported based on a linear mixed model (LMM) with subjects and items as crossed random effects. This is necessary as high skipping rates in the the condition lead to unequal group sizes, reducing the statistical power of traditional ANOVA methods (Baayen, Davidson, & Bates, 2008).

Preview	*n+1* type	Sentence prior to display change		
		Word *n*	*n+1*	*n+2*
Both available	*the*	The impertinent youth insulted	the	ladies on the street.
Both denied	*the*	The impertinent youth insulted	ldc	toktaz on the street.
n+1 denied	*the*	The impertinent youth insulted	ldc	ladies on the street.
Both available	3-letter Word	The impertinent youth insulted	two	ladies on the street.
Both denied	3-letter Word	The impertinent youth insulted	lmc	toktaz on the street
n+1 denied	3-letter Word	The impertinent youth insulted	lmc	ladies on the street.

Figure 2.1: Examples of the three preview conditions prior to the display change in Experiment 2.1. After a participant's gaze position crossed the boundary located to the right of word *n* (vertical line), all incorrect previews changed to the correct words (i.e. the sentence appeared as it did in the "both available" condition).

In order to fit the LMMs, the `lmer` function from the `lme4` package (Bates, Maechler, & Dai, 2009) was used within the R Environment for Statistical Computing (R Development Core Team, 2013); as in Kliegl et al. (2007), regression coefficients (*b*), standard errors and *p* -values based on confidence intervals generated from the posterior distribution of parameter estimates using Markov Chain Monte Carlo methods (obtained from the `mcmcsamp` function contained in the `lme4` package with default parameters) will be reported. For each measure, the initial models fitted included both the main effects of word *n* frequency and preview and their interaction. If the interaction term was not significant in a model, we fitted a restricted model without the interaction. In this case, the coefficients and *p* -values reported are from the restricted model rather than the full one.

For each of the critical words, we examined first pass fixation times as well as first-pass fixation probability and initial landing position. Trials with track losses or display changes that were not effectively implemented during the saccade were eliminated (6.6% of the data), as well as fixations shorter than 80 ms or longer than 800 ms (0.7% of the data). Subjects answered 94.5% of the comprehension questions correctly. The fixation time measures (see Rayner, 1998, 2009) computed included first fixation duration (the mean duration of the first fixation on a word, FFD); gaze duration (the mean sum of first fixations and subsequent refixations on a word, GD); single fixation duration (mean fixation time for all cases in which a word was fixated exactly once, SFD); and go-past time (also known as regression path duration: the mean time from the point when a word was first fixated to when a reader first moves his or her eyes past it). Since there were three preview conditions, two orthogonal contrasts were used in the analysis.

The first contrast compared the both correct condition to the mean of the *n+1* denied and the both denied conditions and therefore represents the effect of word *n+1* preview availability, while the second contrast compared the *n+1* denied to the both denied condition and represents the effect of denying preview for word *n+2* when word *n+1* preview was denied as well. In order to make sure that the effects found in the models are not due to violations of normality, we fitted the models both for raw and log-transformed data. Since the pattern of effects was virtually identical for raw and

Table 2.2: Mean fixation times for the three target words *n*, *n+1*, and *n+2* in Experiment 2.1. Standard deviations are in parentheses. FFD = First fixation duration, SFD = Single fixation duration, GD = Gaze duration, Go-past = Go-past time.

Measure	***n+1* type**	**Preview**	**Word *n***	**Word *n+1***	**Word *n+2***
FFD	Article (*the*)	Both available	244 (96)	214 (75)	232 (73)
	Article (*the*)	Both denied	249 (101)	214 (66)	212 (72)
	Article (*the*)	n+1 denied	245 (92)	215 (60)	209 (70)
	3-letter Word	Both available	239 (89)	224 (83)	215 (70)
	3-letter Word	Both denied	244 (91)	236 (72)	217 (75)
	3-letter Word	n+1 denied	247 (95)	238 (75)	213 (74)
SFD	Article	Both available	252 (97)	214 (77)	233 (69)
	Article	Both denied	256 (105)	216 (67)	212 (73)
	Article	n+1 denied	252 (96)	216 (58)	205 (68)
	3-letter Word	Both available	247 (92)	226 (85)	214 (71)
	3-letter Word	Both denied	250 (92)	242 (71)	214 (75)
	3-letter Word	n+1 denied	256 (96)	242 (70)	211 (70)
GD	Article (*the*)	Both available	280 (121)	228 (90)	264 (99)
	Article (*the*)	Both denied	292 (131)	225 (76)	241 (105)
	Article (*the*)	n+1 denied	288 (121)	227 (78)	237 (106)
	3-letter Word	Both available	282 (117)	233 (91)	248 (112)
	3-letter Word	Both denied	284 (118)	252 (85)	247 (112)
	3-letter Word	n+1 denied	297 (131)	254 (84)	241 (106)
Go-past	Article (*the*)	Both available	320 (183)	250 (127)	323 (184)
	Article (*the*)	Both denied	339 (197)	260 (143)	304 (207)
	Article (*the*)	n+1 denied	332 (181)	267 (137)	304 (201)
	3-letter Word	Both available	311 (163)	276 (164)	281 (152)
	3-letter Word	Both denied	332 (196)	306 (162)	301 (186)
	3-letter Word	n+1 denied	337 (188)	303 (161)	298 (181)

log-transformed values (with one exception detailed below) we will report coefficients based on the raw data which are directly interpretable as differences between group means (adjusted for the other effects included in the model). The mean fixation times for the target words *n*, *n+1*, and *n+2* are shown in Table 2.2, while the fixation probabilities, and initial landing positions for those words are shown in Table 2.3.

Word *n*

There was a significant difference between the both identical and the masked preview conditions, i.e. an effect of *n+1* preview availability, for gaze durations (*b*

Table 2.3: Mean fixation probability and mean landing position for the three target words *n*, *n+1*, and *n+2* in Experiment 2.1. Standard deviations are in parentheses.

Measure	*n+1* type	Preview	Word *n*	Word *n+1*	Word *n+2*
Fixation probability	Article (*the*)	Both available	0.96 (0.19)	0.31 (0.46)	0.91 (0.29)
	Article (*the*)	Both denied	0.95 (0.21)	0.71 (0.45)	0.91 (0.29)
	Article (*the*)	n+1 denied	0.94 (0.23)	0.66 (0.47)	0.92 (0.28)
	3-letter Word	Both available	0.96 (0.21)	0.61 (0.49)	0.87 (0.34)
	3-letter Word	Both denied	0.95 (0.22)	0.75 (0.44)	0.86 (0.35)
	3-letter Word	n+1 denied	0.94 (0.24)	0.70 (0.46)	0.88 (0.32)
Landing position	Article (*the*)	Both available	2.59 (1.70)	1.70 (1.21)	2.40 (1.78)
	Article (*the*)	Both denied	2.46 (1.70)	1.45 (1.08)	2.25 (1.77)
	Article (*the*)	n+1 denied	2.59 (1.68)	1.65 (1.09)	2.49 (1.71)
	3-letter Word	Both available	2.32 (1.74)	1.62 (1.20)	2.14 (1.61)
	3-letter Word	Both denied	2.43 (1.65)	1.70 (1.16)	2.07 (1.67)
	3-letter Word	n+1 denied	2.38 (1.62)	1.63 (1.10)	2.16 (1.62)

= 6.196, SE = 2.701, $p = 0.024$) as well as go-past times ($b = 12.575$, SE = 4.055, $p < .01$) with durations being longer in the masked conditions. A similar effect was observed on landing position, with fixations landing slightly further to the right when preview for word *n+1* was denied ($b = 0.116$, SE = 0.057, $p = 0.046$). Since the preview manipulation introduced orthographically illegal letter strings into the parafovea, this effect is clearly driven by orthography and thus can be interpreted as an orthographic parafoveal-on-foveal effect. None of the other effects or interactions on fixation time measures reached significance, nor were there any significant main effects or interactions in a logistic gLMM analysis of fixation probability for word *n* (all *p*s > .05). In particular, there was no evidence of a parafoveal-on-foveal effect of *n+1* word type on fixations on word *n*.

Word *n+1*

There was a highly significant effect of *n+1* word type on all fixation time measures, with three-letter words being fixated longer than the definite article *the* (FFD: b = 20.53, SE = 2.79, $p < .01$; SFD: b = 22.98, SE = 2.88, $p < .01$; GD: b = 20.07, SE = 3.35, $p < .01$; Go-past: b = 36.84, SE = 6.075, $p < .01$). Mostly, this reflects the difference in word frequency and predictability between the definite article and other three-letter words, but it might also in part be a direct effect of word type. There also was a significant effect of *n+1* preview availability (FFD: $b = 7.558$, SE = 2.148, $p < .01$; SFD: $b = 9.145$, SE = 2.209, $p < .01$ GD: $b = 8.451$, SE = 2.591, $p < .01$; Go-past: $b = 18.308$, SE = 4.695, $p < .01$), which can be considered a replication of the standard preview benefit effect (Rayner, 1975). In gaze duration, there was also a significant interaction between *n+1* preview availability and *n+1* word type ($b = 13.492$, SE = 5.179, $p = .01$), to the point where the *n+1* preview benefit effect was not present at all when *n+1* was the and the main effect described above was driven exclusively by the strong preview effect on three-letter words.

The same numerical pattern was present in first-fixation duration and single fixation duration on *n+1*, even though the corresponding interaction terms did not reach significance. The absence of any preview effect in the article condition might be a result of the high skipping rate in that condition. Alternatively, the processing of articles might be so easy that the availability of preview does not make a significant difference in fixation times on an article.

On fixation probability, the logistic LMM analysis showed that three-letter words were fixated significantly more often than the article the ($b = .63$, SE = .079, $p < .01$). Additionally, word *n+1* had a higher fixation probability when preview for it had been denied ($b = .85$, SE = .056, $p < .01$). In addition to this, the interaction between *n+1* preview and word type was significant ($b = .86$, SE = .11, $p < .01$). This interaction is driven by the extremely low fixation probability for the definite articles (31%) when their preview had been available. Receiving a correct preview of the seems to almost automatically trigger skipping, while receiving a preview of another three-letter word or a mask is much more likely to prompt readers to fixate on that word. Whether the skipping of the definite article is truly automatic (as suggested by Gautier et al., 2000) or just the result of extremely fast lexical access remains to be determined[1].

In contrast, when preview for *n+2* had been unavailable (in addition to the *n+1* mask), *n+1* was less likely to be fixated than when preview for *n+2* had been available and only *n+1* had been masked ($b = -.28$, SE = .097, $p < .01$). It might be plausible to assume that the highly irregular *n+2* letter string in the parafovea attracted fixations away from *n+1*. This could be seen as evidence of orthographic parafoveal pre-processing.

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[1] Chapter 4 describes an experiment designed to address this question.

Interestingly, a similar effect reached significance on landing position, with fixations landing slightly further to the right when *n+2* preview had been denied along with *n+1* preview ($b = .025$, SE = .012, $p = .044$). This effect might reflect readers' attention being attracted by the irregular orthographic information in the parafovea. However, it did not reach significance when log-transformed landing position was used as a dependent variable, thus it might be a spurious effect due to violations of normality assumptions.

Word *n+2*

There was a significant effect of *n+1* preview on all fixation time measures, with fixation times being shorter when *n+1* preview was denied (FFD: $b = -7.74$, SE = 1.684, $p < .01$; SFD: $b = -9.94$, SE = 1.85, $p < .01$, GD: $b = -10.212$, SE = 2.441, $p < .01$). A similar effect was observed on landing position, with fixations landing further to the right on *n+2* when *n+1* preview had been denied ($b = 0.161$, SE = 0.064, $p = 0.012$). Like the effect observed on word *n+1*, this effect may reflect a difference in saccade targeting when the parafovea contained an irregular letter string. For go-past time, the *n+1* preview effect was only significant in the log-transformed analysis ($b = -0.024$, SE = 0.011, $p = 0.037$). This appears to be an issue of outliers in the raw data affecting the statistical power of the analysis.

The fact that this effect is reduced or even reversed for three-letter words *n+1* as evidenced by a significant interaction between *n+1* preview and word type (FFD: $b = 13.59$, SE = 3.38, $p < .01$; SFD: $b = 14.28$, SE = 3.72, $p < .01$; GD: $b = 15.54$, SE = 4.91, $p < .01$, Go-past: $b = 29.28$, SE = 8.71, $p < .01$) points to it being caused by the high skipping probability in the both correct condition when *n+1* was the article the. This would also explain the landing position effect: saccades from word *n+1* are shorter than saccades from word *n* and thus should have a higher probability of ending up further inside word *n+2*.

Finally, there was a significant effect of *n+1* word type on *n+2* fixation probability ($b = -.46$, SE = 0.12, $p < .01$), which is most likely due to the enhanced skipping probability when *n+1* was the article the. Since readers very rarely skip two words in a row, the probability of skipping word *n+2* is clearly much higher in trials where *n+1* was fixated compared to trials where *n+1* was skipped.

In summary, while we found the expected effects of word type and *n+1* preview, we found no effects that would point to parafoveal lexical processing of more than one word to the right of the currently fixated word. The only measure that was affected at all by the availability of *n+2* preview was the probability of making a fixation on word *n+1*, suggesting that an unusual letter string in the parafovea might attract fixations. This is, however, not a lexical effect.

2.2 Experiment 2.2

In Experiment 2.2, we tested whether properties of the pre-target word *n* influenced the extent of pre-processing of word *n+2* (i.e. whether spillover from processing of word *n* extended to pre-processing of *n+2*). In order to do this we manipulated the frequency (and with it, processing difficulty) of word *n*. We used the same preview conditions as in Experiment 2.1, with the addition of a condition in which preview for word *n+1* was available, but preview of word *n+2* was denied. This condition corresponds to the designs used in Kliegl et al. (2007) and Radach et al. (2013). Including this condition also allowed us to test directly whether the effects related to pre-processing of word *n+2*, found in those studies when preview for word *n+1* was available, can be explained by failed skipping of word *n+1* (i.e., mislocated fixations).

2.2.1 Method

Subjects

Thirty-two undergraduate students at the University of California, San Diego participated in the experiment for course credit or pay. All were native speakers of English, had either normal or corrected to normal vision, and were naïve concerning the purpose of the experiment. None of the subjects had participated in Experiment 2.1. Data were collected from 14 additional subjects, but subsequently excluded from the analysis due to reasons described below.

Word *n*	Preview	Sentence prior to display change		
frequency	condition	Word *n*	*n+1*	*n+2*
high	Both available	The generous aunt gives	the	present to her niece.
high	Both denied	The generous aunt gives	dlc	gmocxak to her niece.
high	*n+1* denied	The generous aunt gives	dlc	present to her niece.
high	*n+2* denied	The generous aunt gives	the	gmocxak to her niece.
low	Both available	The generous aunt sends	the	present to her niece.
low	Both denied	The generous aunt sends	dlc	gmocxak to her niece.
low	*n+1* denied	The generous aunt sends	dlc	present to her niece.
low	*n+2* denied	The generous aunt sends	the	gmocxak to her niece.

Figure 2.2: Examples of the four preview conditions prior to the display change in Experiment 2.2. After a participant's gaze position crossed the boundary located to the right of word *n* (vertical line), all incorrect previews changed to the correct words (i.e. the sentence appeared as it did in the "both available" condition).

Apparatus

The apparatus was the same as in Experiment 2.1.

Materials

The materials consisted of 120 new sentence frames not used in Experiment 2.1, which featured a succession of a verb (word *n*), the article the (word *n+1*) and a noun (word *n+2*). In each sentence frame, word *n* could either be a low or a high frequency word.

We used the same preview manipulation as in Experiment 2.1, adding a preview condition in which the preview was correct for word *n+1*, but incorrect for word *n+2* for a total of four preview conditions and two word *n* frequency conditions (see Figure 2.2 for examples).

One hundred and twenty-nine University of California, San Diego undergraduates who participated for course credit provided norming data in order to ensure that high and low frequency words *n* fit the sentence frames equally well. Twenty-seven additional undergraduates recruited from the same population performed a cloze task for the sentence frames up to *n*. From the results, we calculated predictability norms for the high and low frequency versions of word *n*. Table 2.4 shows length and frequency (determined from the CELEX count using the *N-Watch* software by Davis, 2005) of the critical words *n*, *n+1* and *n+2* as well as the predictability measure obtained from the cloze task.

Procedure

The procedure was identical to Experiment 2.1. Thirty-nine of the sentences were followed by a comprehension question. As in Experiment 2.1, subjects were asked whether they were aware of the display changes after the experiment. Thirteen of the 14 excluded subjects reported seeing more than three changes and their data were discarded from the subsequent analysis. In addition, the data for an additional subject who showed an exceptionally high proportion of late display changes (43%) were removed from the analysis, resulting in a total of 32 subjects included in the analysis as reported above.

2.2.2 Results and Discussion

As in Experiment 2.1, we examined first pass fixation times as well as first-pass fixation probability and landing positions for words *n*, *n+1* and *n+2*. Trials with track losses or display changes that were not effectively implemented during the saccade were eliminated (14.1% of trials), as well as individual first-pass and go-past times shorter than 80 ms or longer than 800 ms (less than 0.5 % of the data). On average, subjects answered 93.2% (minimum: 84.6 %) of the comprehension questions correctly.

The data were analyzed in a fashion similar to Experiment 2.1: For each dependent variable (FFD, SFD, GD, go-past time, fixation probability and initial landing position), a linear mixed model (LMM) with subjects and items as crossed random effects and word *n* frequency (high vs. low) and *n+1*/*n+2* preview conditions as fixed

Table 2.4: CELEX Mean word frequency (occurrences per million, obtained from Davis, 2005) for the critical words as well as predictability estimates from a cloze task for Word *n+1*.

Critical word	Length range	Mean length	Word frequency	Predictability
n (high frequency)	3 – 9	5.25 (1.15)	129 (122)	.023 (.091)
n (low frequency)	3 – 9	5.25 (1.15)	5.69 (7.79)	.0019 (.039)
n+1	3	3 (0)	64,368 (0)	—
n+2	3 – 14	5.75 (1.99)	50.76 (101)	—

effects was fitted using the `lmer` function from the `lme4` package in the R statistical software. In order to determine how the dependent variables were influenced by the four preview conditions, we specified three contrasts. The first contrast compared the two preview conditions in which preview for *n+1* was available with the two preview conditions in which it was unavailable. This contrast therefore reflects the standard *n+1* preview benefit effect. The second contrast compared the two preview conditions in which preview for *n+1* was available, i.e. it reflects the effect of *n+2* preview availability when *n+1* preview was unavailable. This contrast is theoretically important since it indicates whether processing on *n+2* took place before *n+1* processing had finished (processing of the random letter *n+1* mask should not be able to complete normally).

Finally, the third contrast compared the two preview conditions in which preview for *n+1* was available, i.e. it reflects the effect of *n+2* preview availability when *n+1* preview was available as well. The inclusion of this comparison, which was absent from Experiment 2.1, enabled us to examine whether the presence of an *n+1* mask in the parafovea had an effect on the processing of *n+2*. However, the comparison specified by the third contrast might be influenced by mislocated fixations stemming from attempted but failed skipping of the easily identifiable word *n+1* which was always the definite article *the*. As in Experiment 2.1, the initial models fitted included both the main effects of word *n* frequency and preview and their interaction, followed by a restricted model without the interaction if the interaction term was not significant in the full model.

In this case, the coefficients and *p* -values reported are from the restricted model. Again, in order to make sure that the effects found in the models are not due to violations of normality, we fitted the models both for raw and log-transformed data. The pattern of effects was identical for raw and log-transformed values; therefore, we will report coefficients based on the raw data which are more easily interpretable. Tables 2.5 and 2.6 shows the raw fixation time measures, fixation probabilities and landing positions for the three target words.

Word *n*

As expected, all fixation time measures showed a strong frequency effect (FFD: $b = 16.629$, SE = 2.943, $p < .01$; GD: $b = 27.541$, SE = 3.869, $p < .01$; SFD: $b = 19.683$,

Table 2.5: Mean first fixation duration, single fixation duration, and gaze duration for the three target words *n*, *n+1*, and *n+2* in Experiment 2.2. Standard deviations are in parentheses. FFD = First fixation duration, SFD = Single fixation duration, GD = Gaze duration

	Word *n* frequency	Preview condition	Word *n*	Word *n+1*	Word *n+2*
FFD	high	Both available	234 (81)	204 (59)	233 (77)
	high	Both denied	233 (77)	223 (66)	220 (74)
	high	*n+1* denied	232 (81)	223 (68)	220 (78)
	high	*n+2* denied	231 (86)	208 (51)	238 (82)
	low	Both available	245 (90)	211 (65)	250 (94)
	low	Both denied	255 (96)	226 (62)	223 (85)
	low	*n+1* denied	250 (96)	229 (68)	225 (80)
	low	*n+2* denied	246 (91)	216 (82)	251 (85)
SFD	high	Both available	236 (75)	204 (58)	238 (80)
	high	Both denied	236 (74)	226 (63)	221 (73)
	high	*n+1* denied	236 (81)	227 (64)	221 (80)
	high	*n+2* denied	234 (85)	209 (50)	240 (83)
	low	Both available	247 (91)	211 (66)	252 (99)
	low	Both denied	262 (92)	228 (60)	222 (83)
	low	*n+1* denied	259 (97)	233 (64)	224 (78)
	low	*n+2* denied	253 (87)	217 (84)	255 (84)
GD	high	Both available	256 (105)	207 (65)	261 (102)
	high	Both denied	263 (106)	234 (70)	241 (98)
	high	*n+1* denied	263 (114)	234 (72)	242 (104)
	high	*n+2* denied	258 (111)	216 (68)	275 (116)
	low	Both available	266 (108)	218 (73)	277 (114)
	low	Both denied	298 (126)	235 (69)	256 (121)
	low	*n+1* denied	297 (126)	240 (75)	248 (109)
	low	*n+2* denied	289 (120)	224 (88)	288 (114)

Table 2.6: Mean go-past time, mean fixation probability and mean landing position for the three target words *n*, *n+1*, and *n+2* in Experiment 2.2. Standard deviations are in parentheses.

	Word *n* frequency	Preview condition	Word *n*	Word *n+1*	Word *n+2*
Go-past time	high	Both available	311 (211)	238 (126)	312 (171)
	high	Both denied	322 (219)	282 (147)	313 (186)
	high	*n+1* denied	316 (213)	276 (138)	309 (205)
	high	*n+2* denied	294 (176)	275 (159)	331 (183)
	low	Both available	323 (198)	254 (138)	360 (226)
	low	Both denied	359 (202)	297 (175)	336 (219)
	low	*n+1* denied	351 (211)	292 (154)	331 (204)
	low	*n+2* denied	345 (209)	279 (168)	361 (225)
Fixation probability	high	Both available	0.88 (0.33)	0.35 (0.48)	0.87 (0.34)
	high	Both denied	0.88 (0.33)	0.63 (0.48)	0.87 (0.34)
	high	*n+1* denied	0.90 (0.30)	0.68 (0.47)	0.84 (0.36)
	high	*n+2* denied	0.88 (0.33)	0.34 (0.47)	0.88 (0.32)
	low	Both available	0.91 (0.28)	0.31 (0.46)	0.89 (0.32)
	low	Both denied	0.91 (0.29)	0.65 (0.48)	0.88 (0.32)
	low	*n+1* denied	0.91 (0.29)	0.66 (0.47)	0.89 (0.32)
	low	*n+2* denied	0.91 (0.28)	0.34 (0.47)	0.88 (0.32)
Landing position	high	Both available	2.59 (1.70)	1.70 (1.21)	2.40 (1.78)
	high	Both denied	2.46 (1.70)	1.45 (1.08)	2.25 (1.77)
	high	*n+1* denied	2.59 (1.68)	1.65 (1.09)	2.49 (1.71)
	high	*n+2* denied	2.32 (1.74)	1.62 (1.20)	2.14 (1.61)
	low	Both available	2.43 (1.65)	1.70 (1.16)	2.07 (1.67)
	low	Both denied	2.38 (1.62)	1.63 (1.10)	2.16 (1.62)
	low	*n+1* denied	2.41 (1.73)	1.52 (1.07)	2.28 (1.51)
	low	*n+2* denied	2.40 (1.61)	1.71 (1.21)	2.18 (1.64)

SE = 3.134, *p* < .01; Go-past: *b* = 33.281, SE = 6.883, *p* < .01). Additionally, there was an orthographic parafoveal-on-foveal effect of *n+1* preview availability on gaze durations (*b* = 28.409, SE = 7.766, *p* < .01), single fixation durations (*b* = 15.123, SE = 6.275, *p* = 0.018), and go-past times (*b* = 37.087, SE = 13.816, *p* < .01). This indicates that the presence of an orthographically unusual mask in place of the upcoming word caused readers to stay longer on the current word, and, consequently, that word *n+1* was pre-processed at least at a sublexical level while readers were fixating word *n*. Finally, in a logistic generalized LMM, there was a significant effect of word *n* frequency on fixation probability on word *n* (*b* = .35, SE = .12, *p* < .01). None of the other contrasts or interactions reached significance.

Word *n+1*

As expected, all fixation time measures showed the standard preview benefit effect, i.e. fixation times on word *n+1* were longer when preview for *n+1* had not been available (FFD: *b* = 28.989, SE = 6.717, *p* < .01, *p* < .01; SFD: *b* = 34.885, SE = 6.728, *p* < .01; GD: *b* = 39.605, SE = 7.435, *p* < .01; Go-past: *b* = 48.419, SE = 15.837, *p* < .01). Additionally, there was a significant spillover effect of word *n* on go-past times on word *n+1* (*b* = 14.781, SE = 7.303, *p* = 0.043). Finally, go-past times on *n+1* showed a significant effect of *n+2* preview in those conditions where *n+1* preview was available (*b* = 29.65, SE = 12.904, *p* = 0.02). This replicates Kliegl et al.'s (2007) findings of a delayed parafoveal-on-foveal effect on word *n+1*, albeit in a later fixation time measure. However, in the conditions where *n+1* preview was unavailable, there was no effect of *n+2* preview (*p* > .05), replicating the findings of Angele et al. (2008). This suggests that whether readers can pre-process word *n+2* depends on whether they have the opportunity of pre-processing word *n+1* as well.

As mentioned above, one possible explanation for this phenomenon may be that, if *n+1* preview is available, readers frequently finish processing it while they are still fixating word *n*. As a consequence, they plan an eye movement directly to word *n+2*, skipping word *n+1*. Furthermore, these skipping saccades undershoot occasionally, resulting in a mislocated fixation on word *n+1* which nevertheless is influenced by the properties of word *n+2*. In the case of the present study, it is entirely possible that making a saccade to the wrong word triggers a breakdown in processing, which then leads to readers making a regressive saccade, thus increasing go-past time on word *n+1*. Indeed, a logistic lme analysis showed that fixation probability on word *n+1* was significantly affected by availability of preview for *n+1* ($b = 2.92$, SE = .16, $p < .01$), with a higher probability of fixations on *n+1* when it had been masked. The higher probability of skipping *n+1* when preview for it had been available should also lead to a higher probability of failed skipping attempts, which fits in well with the hypothesis described above.

Finally, on landing positions, there was a significant interaction between *n+2* preview availability when *n+1* preview was denied and word *n* frequency ($b = 0.313$, SE = 0.13, $p = 0.018$). Specifically, separate analyses showed that when word *n* was a high-frequency word, fixations landed further to the left of a previously masked word *n+1* when word *n+2* had been masked as well in the preview ($b = -.191$, SE = .092, $p = .045$). When *n* was a low-frequency word, this effect did not reach significance, and there was a nonsignificant trend in the opposite direction ($p > .05$). This effect is potentially interesting since it is the only effect of availability when *n+1* preview was denied in Experiment 2.2 and the only effect on which word *n* frequency modulated a preview effect. This parafoveal-on-foveal effect seems to suggest that parafoveal orthographic information can influence the decision of where to fixate on a word to some degree; however, its small effect size makes it difficult to interpret.

Word *n+2*

As on word *n+1*, there was a significant spillover effect of word *n* frequency in all measures (FFD: $b = 9.72$, SE = 2.826, $p < .01$; SFD: $b = 8.73$, SE = 3.173, $p < .01$; GD: $b = 13.335$, SE = 3.784, $p < .01$; Go-past: $b = 30.937$, SE = 7.169, $p < .01$), indicating that the frequency of word *n* has an impact on processing even two words down the line. This effect was also present in landing position, with a low frequency word *n* resulting in fixations landing further to the left ($b = -.159$, SE = .058, $p < .01$). Furthermore, there was a significant effect of *n+1* preview availability on word *n+2* in all the measures (FFD: $b = -40.873$, SE = 5.67, $p < .01$; SFD : $b = -33.966$, SE = 8.954, $p < .01$; *b* GD: $b = -56.314$, SE = 7.581, $p < .01$; Go-past $b = -39.175$, SE = 14.388, *p*

< .01). Notably, this effect is in the opposite direction compared to the effect of *n+1* preview on fixation times on word *n+1* itself: while fixation times on word *n+1* were longer when its preview had been unavailable, the subsequent fixations on word *n+2* were shorter.

One explanation for this effect might be that the longer fixation times on word *n+1* enabled readers to perform more pre-processing of word *n+2* (the preview of which was always available at this point). Again, there was a corresponding effect on landing position, with fixations landing further to the right when preview for word *n+1* had been denied. Importantly, we found a significant effect of *n+2* preview when *n+1* preview had been available on GD (b = 12.338, SE = 5.442, p = 0.026). This difference was not significant when *n+1* preview had been denied (p > .05). This can be considered an *n+2* preview benefit effect. However, fitting separate models for cases in which *n+1* was skipped and for cases in which it was not shows that the *n+2* preview benefit effect on GD was only significant if the fixation on *n+2* had been preceded by skipping (*n+1* skipped: b = 15.42, SE = 6.438, p = 0.015; *n+1* fixated: p > .05). This is consistent with the predictions of the E-Z Reader model.

Furthermore, there was a significant interaction between *n+1* preview availability and word *n* frequency in SFD (b = -29.74, SE = 12.665, p = 0.019): If word *n* had been a low frequency word, single fixations on word *n+2* were even shorter in those conditions where *n+1* preview had not been available compared to those where it had been available. This effect is surprising and unexpected and it is not clear whether it is interpretable, since there was no interaction between word *n* frequency and *n+1* preview availability on word *n+1* itself. As with *n+1*, landing positions on *n+2* showed an effect of word *n+2* preview when *n+1* had been masked, with first fixations landing further to the right when *n+2* preview had been denied (b = 0.177, SE = 0.081, p = 0.031). This might be a consequence of the corresponding effect on word *n+1*. In any case, it can be considered a type of preview benefit effect, albeit on an orthographic level. Finally, there were no significant effects on *n+2* fixation probability (all ps > .05).

Post-hoc analysis: Effects of word *n* frequency

In addition to the analyses described above, we also attempted to test whether the frequency of word *n* had an influence on the degree to which it was parafoveally processed. In order to do this, we fitted an additional model for each measure described above containing the preview contrasts, log *n* frequency as a continuous predictor, and the interactions between those factors. None of the interaction terms reached significance (all ps > .05), indicating that the frequency of word *n* had no impact at all on the size of parafoveal preview benefit and parafoveal-on-foveal effects on the target words. An exception was the landing position analysis, which showed an interaction between log *n* frequency and preview availability of *n+2* when preview for *n+1* had been available as well ($b = -.112$, SE = .053, $p = .029$). This potential lexical parafoveal-on foveal effect of *n+2* may be caused by subsequent skipping of word *n+1*. Indeed, when cases in which *n+1* was skipped were removed from the analysis, the effect no longer reached significance.

2.3 General Discussion

In the present study, we were able to test two factors that might explain why some studies found evidence of parafoveal pre-processing of the second word to the right of fixation (i.e., *n+2*), while other studies found no such evidence. In Experiment 2.1, we investigated whether the properties, specifically word length and word type (the definite article the vs. high-frequency three-letter word), of the first word to the right of fixation (word *n+1*) influenced whether word *n+2* could be processed parafoveally or not. Even when word *n+1* was the article *the*—arguably the word that can be identified with the least processing effort—we found no evidence of parafoveal lexical pre-processing of *n+2*, neither when *n+1* was the definite article nor when it was a non-article 3-letter word.

In Experiment 2.2, we tested whether the amount of pre-processing of word *n+2* was influenced by the frequency of word *n*. Again, we did not find any solid evidence of parafoveal *n+2* processing, except in those conditions where parafoveal information about *n+1* was available, so that it could be easily identified and subsequently skipped or attempted to be skipped. The only variable that showed some effects of *n+2* preview even when *n+1* preview was denied was landing position, although these effects might reflect low-level properties of the masks used rather than effects of lexical processing.

It is, of course, possible, that the extent of parafoveal processing of word *n+2* is determined by a variable not systematically manipulated in this or any previous study. This study, therefore, does not demonstrate that readers never use parafoveal information from beyond an unidentified word *n+1*, or that they never process word *n+1* and word *n+2* at the same time. It does however show that readers, at least when reading English, do not seem to make use of parafoveally available information about word *n+2* on a regular basis. This implies that parallel lexical processing is a fairly rare phenomenon in reading, with serial lexical processing being the default.

An alternative explanation might be that fixation times simply are not very reliable indicators of parafoveal pre-processing in reading beyond word *n+1*. In the face of a wealth of studies that demonstrate a clear link between word identification and fixation times (Rayner, 1998, 2009), that would be quite surprising. Experiment 2.2 did show some effects of word *n+2* preview on landing positions on *n+1* and *n+2*. It is not clear however what type of process would only affect landing positions while having no effect at all on fixation durations. One possibility is that saccade target selection is determined more by low-level characteristics such as orthographic regularity, while the decision when to move the eyes is influenced more by lexical processing. Nevertheless, it might be profitable for future studies attempting to distinguish between parallel and serial processing models to focus on different measures such as landing position. Additionally, the effects of different masks on fixation location should be studied.

In conclusion, despite providing near-optimal conditions for pre-processing, the present study did not find clear evidence for parallel modes of processing. On the contrary, the results of this study suggest that if parallel processing does exist, it is limited to very specific effects in very specific circumstances, with all other processing occurring serially by default.

Chapter 2, in full, is a reprint of the material as it appears in Parafoveal processing of word *n+2* during reading: Do the preceding words matter? Angele and Rayner (2011). The dissertation author was the primary investigator and author of this paper.

Chapter 3

Eye movements and parafoveal preview of compound words: Does morpheme order matter?

One of the most robust findings in research on the reading process is that readers obtain preview benefit from the word to the right of the currently fixated word in writing systems that are printed from left-to-right (see Rayner, 1998, 2009, for reviews). Preview benefit is typically assessed via the use of the boundary paradigm (Rayner, 1975) which utilizes the gaze-contingent display change technique wherein words are changed as a function of eye location (McConkie & Rayner, 1975). In a typical experiment with the boundary paradigm, a preview word is initially displayed and changes to a target word during the saccade when the readers' eyes cross an invisible boundary just to the left of the beginning of the target word (see Figure 3.1 for an example). Because the display change takes place during a saccade, when vision is suppressed, readers are typically not aware of it. The amount of preview benefit is typically determined by subtracting the amount of time readers look at the target word when they had a valid preview of the target word (i.e., when the preview and target are identical) from the amount of time they fixate on the target word when there was not a valid preview.

Readers' fixations on target words are consistently shorter when the preview and target word are identical, but various other properties of the preview word can influence how long readers look at the target word. For example, when the beginning letters (first

2–3 letters) of the target are preserved in the preview, fixations are shorter than when they are not preserved (Rayner, 1975; Rayner, Well, & Pollatsek, 1980). Likewise, when the letters at the end of the target word are preserved in the preview, fixation time is shorter than when they are not (Briihl & Inhoff, 1995; Johnson, 2007; Johnson et al., 2007). More interestingly, it has also been demonstrated that when letters are transposed in the preview, fixations are shorter on the target word than when letters are replaced by visually similar letters (Johnson, 2007; Johnson et al., 2007). Thus, *jugde* is a better preview for *judge* than *jubpe*.

In the present experiments, we examined the influence of a transposition in which the order of morphemes (as well as orthographic and phonological units) is changed. Specifically, six letter compound words with two 3-letter morphemes were used as targets and (1) the preview word and the target word were identical (*cowboy*-*cowboy*) or (2) the order of the morphemes was transposed (*boycow* as a preview for *cowboy*). The interesting thing about this type of preview is that all of the letters from the target word are preserved, but in a different order, as is the case with transposed letters (Johnson, 2007; Johnson et al., 2007). Additionally, this preview manipulation also preserves the phonemes present in the target word, which is not true for transposed letters.

Recent research by Crepaldi, Rastle, and Davis (2010), using the lexical decision task, indicated that nonwords that appear to be morphologically complex (i.e. appear to be prefixed or suffixed, e.g. *gasful*) were rejected more slowly than nonwords that do not have this apparent morphological structure (e.g. *gasfil*). However, this effect disappeared when the apparent morphemes were reversed (*fulgas* vs. *filgas*). This seems to suggest that some morphemes might be processed in a position-specific manner. Even more interestingly, when the morphemes of words were reversed (e.g. *nesskind*), the resulting nonwords were as easily rejected in a lexical decision task as orthographic controls (*nusskind*). Thus, reversing the order of some types of morphemes, namely suffixes and prefixes, appears to have a strong impact on lexical processing. In contrast, (Crepaldi, Rastle, Davis, & Lupker, 2013) showed in a further experiment that reverse morpheme order primes facilitated lexical decisions about target compound words (e.g. *fireback* facilitated the lexical decision for *backfire* compared to a random letter prime). This was not true for monomorphemic target words (e.g. processing of *maverick* was not facilitated by *rickmave*). Additionally, subjects were slower to reject reversed compounds like *moonhoney* than matched control words like *moonbasin*. Taken together, these results suggest that, at least in lexical decision tasks, subjects are able process compound morphemes (but not prefixes or suffixes) regardless of the order in which they are presented. The monomorphemic control condition shows that this effect goes beyond the orthographic level.

However, lexical decision tasks measure influences that occur late in processing. Earlier, online measures such as fixation times might reveal a different picture. Thus, we deemed it theoretically interesting to determine how transpositions of morphemes in compound words influence the amount of preview benefit readers obtain from the next word. It is also of interest to examine morpheme order in the context of recent debates (see Kennedy & Pynte, 2008; Rayner, Pollatsek, Liversedge, & Reichle, 2009) concerning whether multiple words can be identified at the same time or whether they are identified one at a time. One important implication of processing words in parallel is that, at least in some of the cases, words will be identified out of order—for example, an article may be identified before the preceding verb. In a language like English, identifying words out of order may have major consequences on the interpretation of a sentence—"Dogs bite cats" has a very different meaning compared to "Cats bite dogs" (Rayner et al., 2009).

It is well-known that, during reading, words are not fixated in the canonical order (as some words are skipped), but Rayner et al. (2009; see also Reichle, Liversedge, et al., 2009) have argued that implicit speech processes do maintain the correct order. In general, compound words are much more constrained than sentences. As a consequence, processing morphemes within compound words in the correct order may be more flexible than processing words within sentences, and it may be possible to process multiple morphemes at the same time. This hypothesis has been tested in recent studies by Juhasz et al. (2009), as well as White et al. (2008), who manipulated the preview that readers received for the second morpheme of a compound word while they were fixating its first morpheme.

Juhasz et al. and White et al. found that the morpheme boundary had a clear effect: They found large preview benefit effects on fixation times on the second morpheme, yet the availability of preview for the second morpheme did not appear to affect fixation times on the first morpheme. The absence of intra-word parafoveal-on-foveal (PoF) effects when reading compound words thus suggests that readers do not process all the morphemes that constitute a compound word at the same time. Instead, readers might attempt to decompose the compound word into its constituents and process them serially. Drieghe et al. (2010) tested this hypothesis directly by manipulating the preview for the second morpheme of compound words as well as for the second part of length-matched monomorphemic words. They found that readers fixated longer on the first part of a monomorphemic word when preview for its second part was denied, but obtained no such effect for the fixations on the first morpheme of a compound word when preview of the second morpheme was denied. However, such an effect was recently found in Finnish by Häikiö, Bertram, and Hyönä (2010). In their study, readers had longer gaze durations on the first morpheme of a compound word when the preview for the second morpheme was a nonword than when the preview showed the correct second morpheme. This suggests that readers take the morphological structure of compound words into account and, perhaps depending on the language, at least sometimes process the constituents of compound words in parallel. The same might be true for the parafoveal pre-processing of compound words.

Alternatively, readers might only start to pre-process the second morpheme once they have identified the first morpheme. In this case, we would expect large effects of first constituent preview availability, while the availability of preview for the second constituent should result in little or no facilitation. In this context, it is important to note that it is impossible to manipulate the preview of a morpheme without also manipulating the preview of the letters and syllables that it contains. While we discuss our experiments in terms of morphological processing, it is the case that the results could also be related to orthographic and phonological processing (which we will address in the General Discussion).

3.1 Experiment 3.1

Experiment 3.1 was designed simply to determine how different fixation times on a target word were when the preview was valid (*cowboy*) compared to when the morphemes were transposed (*boycow*). That is, all prior research (Rayner, 1998, 2009) suggests that fixation time should be longer in the latter case than the former case, but our goal in Experiment 3.1 was to obtain an estimate of what the effect size might be. In Experiment 3.2, we then more systematically examined the effect by including more conditions in the experiment.

3.1.1 Method

Subjects

Thirty-two undergraduate students at the University of California San Diego participated for course credit. All were native speakers of English, had either normal or corrected to normal vision, and were naïve concerning the purpose of the experiment. Apparatus. An SR Research *Eyelink 1000* eyetracker was used to record subjects' eye movements with a sampling rate of 2000 Hz (i.e. the eye position was sampled twice every millisecond). Subjects read sentences displayed on an Iiyama *Vision Master Pro 454* video monitor with a refresh rate of 150 Hz binocularly, but only their right eye was recorded. Viewing distance was approximately 60 cm, with 3.8 letters equaling one degree of visual angle.

Materials and Procedure

Participants read 48 experimental sentences containing compound words. Each compound word consisted of two 3-letter morphemes (e.g. *cowboy*). Frequency estimates for each word were obtained using an unlemmatized frequency list generated from the British National Corpus (Kilgarriff, 2006). Acceptability ratings for each of the sentences in Experiment 3.1 and Experiment 3.2 were obtained from 46 University of California San Diego undergraduates who participated for course credit and were native speakers of English. Predictability ratings for each whole compound word were calculated from cloze task data provided by 22 UCSD undergraduates. None of the subjects who had participated in the norming studies participated in the eye-tracking experiment. Table 3.1 provides the means of each of these measures.

Table 3.1: Properties of pretarget, target and posttarget words for Experiment 3.1 and 2. Word frequency in occurrences per million, length in letters. Word predictability was obtained in a cloze task. Acceptability ratings were collected on a scale from 1 (unacceptable) to 7 (perfectly acceptable). The frequency information was obtained from CELEX via N-Watch (Davis, 2005).

	Experiment 3.1		Experiment 3.2	
Measure	Mean	SD	Mean	SD
Pretarget frequency	23546.94	26711.16	18508.6	25357.6
Pretarget length	3.58	2.2	4.81	3.01
Target frequency	5.2	22.73	5.21	16.6
Target length	6	0	7.26	0.97
Posttarget frequency	10206.31	16631.24	10157	14835.3
Posttarget length	3.88	1.85	3.93	1.85
Morpheme 1 frequency	204.03	379.17	270.8	378.55
Morpheme 2 frequency	372.36	591.62	281.39	454.43
Target predictability	0.01	0.05	0.01	0.04
Acceptability rating	5.36	1.52	5.23	1.58

The sentences containing the target words were presented in conjunction with 120 filler sentences unrelated to the present study. Using the gaze contingent boundary paradigm (Rayner, 1975), we presented the subjects with either a normal morpheme order (*cowboy*) or a transposed morpheme preview (*boycow*) of the target words. In order to do this, an invisible boundary was placed to the left of the space between the target word and the preceding word. Once the readers moved their eyes across the boundary, the preview was replaced by the target word (e.g. *cowboy*). Software was custom designed to maximize the chance that the display changes were completed before the end of the saccades that triggered them. Approximately 33% of the sentences were followed by a two-alternative forced choice comprehension question which subjects answered by pressing the button corresponding to the correct answer on a button box. After the experiment, subjects were asked whether they had noticed anything unusual during the experiment. If subjects confirmed this and reported seeing a display change, they were asked to give an estimate of the number of changes they had seen. The data from 14 additional subjects who reported noticing more than five display changes were excluded from the experiment, as detecting a display change can have an effect on fixation times (Slattery, Angele, & Rayner, 2011).

3.1.2 Results and Discussion

For each of the critical words, we examined fixation time on the target word. Trials with track losses or display changes that completed after fixation onset were eliminated (13.93% of the data)[1], as well as trials in which a blink occurred immediately before or during a fixation on the target word (2.3% of the data) and fixations shorter than 80 ms or longer than 800 ms (less than 1% of the data). All subjects answered at least 85% of the comprehension questions correctly. Finally, we only report means and analyses of those trials during which the pretarget word had received at least one first-pass fixation (53.1 % of the total remaining trials)[2].

From the eye movement records obtained, we computed mean first fixation duration (the mean duration of the first fixation on a word) and mean gaze duration (the mean sum of first fixations and subsequent refixations on a word prior to moving to another word) for each of the critical words. In order to quantify the effect of the manipulation on late processing, we also computed mean go-past time (also called regression path duration which is the mean sum of all fixations, including those on previous words, from the time the target word was first fixated until the time the subsequent word was first fixated) and total viewing time (the sum of all fixations, including regressions, on the target word). Table 3.2 shows the condition means and standard deviations computed for each of the fixation time measures.

Inferential statistics are reported based on linear mixed models (LMM) with subjects and items as crossed random effects (Baayen et al., 2008). In order to fit

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[1] Including those trials in which the pretarget word was skipped during first-pass reading did not lead to a change in the pattern of results.

[2] This high rate of data loss was partly because there is considerable jitter at the end of a saccade, and the eyes typically have not settled into place by this time. For both experiments, we also perfomed a more lenient analysis which included data when the display change was completed up to 9 ms after the saccade ended. This resulted in the elimination of only 3.4% of the data in Experiment 3.1. Importantly, this analysis revealed exactly the same pattern of results as the stricter method, and all of the effects that were significant in the strict analysis were significant in the more lenient method. The only exception was a significant spillover effect of preview morpheme order on log-transformed go-past durations on the posttarget word in the more lenient analysis ($b = 0.06$, SE = 0.032, $t = 1.99$).

Table 3.2: Condition means and standard deviations (in parentheses) for first fixation duration, gaze duration and go-past time (in ms) in Experiment 3.1

Measure	Word	Morpheme order preview	
		Identical	Transposed
		cowboy	*boycow*
First fixation duration	pretarget	221 (80)	218 (74)
	target	247 (88)	262 (92)
	posttarget	236 (81)	246 (98)
Gaze duration	pretarget	241 (103)	230 (89)
	target	295 (131)	316 (124)
	posttarget	259 (104)	271 (117)
Go-past time	pretarget	278 (155)	289 (164)
	target	339 (182)	376 (196)
	posttarget	306 (190)	327 (192)
Total viewing time	pretarget	273 (152)	267 (142)
	target	345 (184)	376 (180)
	posttarget	288 (150)	299 (162)

the LMMs, the `lmer` function from the `lme4` package (Bates et al., 2009) was used within the R Environment for Statistical Computing (R Development Core Team, 2013); regression coefficients (b), standard errors, and t-values will be reported. We do not report p-values, since it is not clear how to determine the degrees of freedom for LMMs, which makes it difficult to estimate p-values. However, since our analyses contain a large number of subjects and items and only a few fixed and random effects are estimated, we can assume that the distribution of the t-valuesestimated by the LMMs approximates the normal distribution. We will therefore use the two-tailed criterion $|t| \geq 1.96$ which corresponds to a significance test at the 5% α-level.

Pretarget word

There was no effect of target word morpheme order on any of the fixation time measures on the pretarget word (see Table 3.3 for coefficients, standard errors, and t-values). As expected, we observed an effect of pretarget word frequency. There also was an effect of target word predictability on first fixation and gaze durations as well as well as an effect of target frequency on go-past time, which might be considered parafoveal-on-foveal effects. None of the other predictors reached significance.

Target word

All first pass fixation time measures on the target word showed strong effects of morpheme order: First fixation duration, gaze duration, and go-past time were inflated when readers received a transposed morpheme preview of the target word prior to fixating it (see Table 3.4 for coefficients, standard errors, and *t*-values). Readers clearly incurred a cost for receiving an incorrect morpheme order preview. In other words, there was a clear benefit to receiving a correct morpheme order preview. For total viewing time, this effect only reached significance in the analysis using log-transformed values ($b = 0.09$, SE = 0.03, $t = 2.79$). Additionally, there was a significant effect of target word frequency and predictability on all fixation time measures, as well as a spillover effect of pretarget word frequency on first fixation durations.

Posttarget word

We found a significant spillover effect of morpheme order preview on all first-pass fixation time measures, but not on total viewing time on the posttarget word (see Table 3.5 for coefficients, standard errors, and *t*-values). The effect on first fixation duration did not reach significance in the analysis using log-transformed values ($b = 0.05$, SE =0.03, $t = 1.61$).Of the continuous predictors, only posttarget word frequency reached significance in all fixation time measures.

In summary, we found a clear indication that transposed morpheme previews of compound words result in processing disruptions and that, as expected, information about the morpheme order in a compound word is critical for its identification. The fact that the preview benefit effect observed in this study (around 20 ms in gaze durations) was smaller in magnitude than the preview benefit effect of 30-50 ms typically observed (Rayner, 1998, 2009) suggests that even though processing the transposed morpheme preview is clearly more difficult than processing an identical preview, readers still be able to obtain some information from it.

In particular, readers might be able to extract some letter information from the preview, since it contains the same letters as the actual target word. In order to test this hypothesis directly, we additionally manipulated the availability of preview for each of the two target word morphemes in Experiment 3.2, such that the target word preview could be identical or dissimilar to the target word with regard to morpheme order, first morpheme letter identity, second morpheme letter identity, or any combination of the above. By manipulating the availability of letter identity preview for the two morphemes separately, we were also able to test whether only the first morpheme is pre-processed parafoveally or whether readers can obtain preview benefit from both morphemes.

3.2 Experiment 3.2

3.2.1 Methods

Subjects

Forty undergraduate students at the University of California San Diego participated for course credit. All were native speakers of English, had either normal or corrected to normal vision, were naïve concerning the purpose of the experiment and had not participated in Experiment 3.1.

Apparatus

The apparatus was the same as in Experiment 3.1.

Materials and Procedure

In addition to the 48 compound words used in Experiment 3.1, 11 new bimorphemic compound words with three-letter morphemes and 101 bimorphemic compound words with 4-letter morphemes (e.g. *railroad*) were embedded in sentences for a total of 160 experimental sentences, 59 with a 6-letter and 101 with an 8-letter target word. See Table 3.1 for frequency and length measures as well as acceptability ratings and cloze probabilities. The procedure was identical to the one used in Experiment 3.1, except that in addition to preview morpheme order the availability of preview for each of the morphemes was also manipulated. While fixating to the left of the invisible boundary, subjects therefore received an identical or a dissimilar preview of the first (e.g. *cowboy* vs. *vnrboy*) or the second morpheme (e.g. *cowboy* vs. *cowhrg*) comprising the target word.

Table 3.3: Experiment 1 – LMM analyses on the pretarget word. *b*: Regression coefficient, SE: standard error, *t*: test statistic (b/SE). All $|t| \geq 1.96$ are marked in bold.

			First fixation duration			Gaze duration			Total viewing time			
		b	SE	*b*	SE	*t*	*b*	SE	*t*	*b*	SE	*t*
Fixed	(Intercept)	213.44	6.32	226.05	7.74	**29.22**	259.67	13.75	**18.89**	254.78	12.38	**20.58**
effects	Order preview	-2.15	5.58	-9.01	6.56	-1.37	15.74	10.75	1.46	1.06	10.00	0.11
Covariates:												
Frequency	Pretarget	-10.51	2.92	-17.77	3.82	**-4.65**	-15.88	7.58	**-2.10**	-28.88	7.31	**-3.95**
	Target	-4.19	4.01	-8.41	5.25	-1.60	-27.45	10.44	**-2.63**	-20.83	10.07	**-2.07**
	Posttarget	2.02	2.95	1.97	3.82	0.52	3.82	7.41	0.52	-1.53	7.13	-0.21
	Morpheme 1	1.05	5.39	5.78	6.96	0.83	10.66	13.62	0.78	9.35	13.11	0.71
	Morpheme 2	2.83	4.32	7.82	5.58	1.40	9.13	10.90	0.84	16.21	10.49	1.55
Predictability	Target	-178.05	82.16	-213.14	108.02	**-1.97**	-319.49	216.28	-1.48	-330.35	208.99	-1.58
Random	Item	172.69	13.14	390.85	19.77	NA	2047.70	45.25	NA	1982.60	44.53	NA
variance	Subject	574.82	23.98	825.73	28.73	NA	2342.40	48.40	NA	1543.10	39.28	NA
	Residual	5231.20	72.33	7135.26	84.47	NA	19219.10	138.63	NA	16656.90	129.06	NA

Table 3.4: Experiment 1 – LMM analyses on the target word. b: Regression coefficient, SE: standard error, t: test statistic (b/SE). All $|t| \geq 1.96$ are marked in bold.

		First fixation duration			Gaze duration			Go-past time			Total viewing time		
		b	SE	t	b	SE	t	b	SE	t	b	SE	t
Fixed effects	(Intercept)	239.49	8.07	**29.68**	279.36	12.42	**22.49**	308.93	15.93	**19.40**	324.98	16.89	**19.24**
	Order preview	16.22	6.88	**2.36**	22.93	8.89	**2.58**	36.29	12.80	**2.83**	22.46	12.18	1.84
Covariates:													
Frequency	Pretarget	-13.00	3.97	**-3.27**	-6.49	5.79	-1.12	-5.45	8.46	-0.64	-10.63	9.53	-1.12
	Target	-12.00	5.46	**-2.20**	-18.75	7.97	**-2.35**	-25.61	11.66	**-2.20**	-29.18	13.14	**-2.22**
	Posttarget	-1.75	3.94	-0.44	-7.19	5.66	-1.27	-5.83	8.28	-0.70	-12.64	9.19	-1.38
	Morpheme 1	-6.30	7.25	-0.87	3.79	10.44	0.36	-11.37	15.26	-0.75	-5.30	17.04	-0.31
	Morpheme 2	3.44	5.77	0.60	-6.06	8.34	-0.73	-0.02	12.16	0.00	-4.74	13.56	-0.35
Predictability	Target	-225.73	111.57	**-2.02**	-339.20	163.60	**-2.07**	-499.61	239.47	**-2.09**	-657.61	272.30	**-2.42**
Random variance	Item	396.97	19.92	NA	1045.70	32.34	NA	2288.90	47.84	NA	3519.80	59.33	NA
	Subject	856.62	29.27	NA	2583.80	50.83	NA	3156.90	56.19	NA	3575.50	59.80	NA
	Residual	7226.93	85.01	NA	11923.50	109.19	NA	24843.60	157.62	NA	22904.80	151.34	NA

Table 3.5: Experiment 1 – LMM analyses on the posttarget word. *b*: Regression coefficient, SE: standard error, *t*: test statistic (b/SE). All $|t| \geq 1.96$ are marked in bold.

		First fixation duration			Gaze duration			Go-past time			Total viewing time		
		b	SE	*t*	*b*	SE	*t*	*b*	SE	*t*	*b*	SE	*t*
Fixed effects	(Intercept)	225.54	10.29	**21.91**	238.57	12.72	**18.76**	276.41	20.02	**13.81**	259.66	16.46	**15.77**
	Order preview	19.81	9.23	**2.15**	23.65	10.35	**2.29**	45.14	18.72	**2.41**	17.00	13.48	1.26
Covariates:													
Frequency	Pretarget	7.06	5.07	1.39	8.72	6.67	1.31	4.12	11.70	0.35	5.04	8.90	0.57
	Target	1.30	7.29	0.18	-3.80	9.55	-0.40	-5.17	16.77	-0.31	0.07	12.38	0.01
	Posttarget	-11.33	5.27	**-2.15**	-24.17	6.85	**-3.53**	-30.40	11.98	**-2.54**	-43.08	9.02	**-4.77**
	Morpheme 1	4.71	9.36	0.50	14.60	12.07	1.21	-9.14	21.25	-0.43	6.58	16.07	0.41
	Morpheme 2	10.29	8.07	1.27	6.51	10.40	0.63	-5.75	18.26	-0.31	-1.69	13.53	-0.13
Predictability	Target	66.42	146.09	0.45	41.31	194.99	0.21	-332.32	341.29	-0.97	-265.88	258.73	-1.03
Random variance	Item	471.34	21.71	NA	1211.80	34.81	NA	3540.90	59.51	NA	2385.80	48.84	NA
	Subject	1048.54	32.38	NA	1668.50	40.85	NA	1999.20	44.71	NA	2575.70	50.75	NA
	Residual	6841.22	82.71	NA	8430.00	91.81	NA	28027.90	167.41	NA	16173.40	127.17	NA

In addition, there was a condition in which the previews of both the first and the second morpheme were dissimilar. Dissimilar letter previews were generated by replacing the letters of the target morpheme with random letters while maintaining word shape. Additionally, the morpheme order in the preview could be either normal or transposed, as in Experiment 3.1. Note that first morpheme preview, second morpheme preview, and preview morpheme order were manipulated independently, resulting in a total of eight preview conditions (see Figure 3.1 for an example of each condition). As in Experiment 3.1, 9 additional subjects who reported seeing more than 5 display changes were excluded from the experiment.

Correct morpheme order

Morpheme 1 preview	Morpheme 2 preview	Example sentence	
available	available	Everyone scattered as the infamous	cowboy drew his gun.
available	denied	Everyone scattered as the infamous	cowtxg drew his gun.
denied	available	Everyone scattered as the infamous	enzboy drew his gun.
denied	denied	Everyone scattered as the infamous	enztxg drew his gun.

Reverse morpheme order

Morpheme 1 preview	Morpheme 2 preview	Example sentence	
available	available	Everyone scattered as the infamous	boycow drew his gun.
available	denied	Everyone scattered as the infamous	txgcow drew his gun.
denied	available	Everyone scattered as the infamous	boyenz drew his gun.
denied	denied	Everyone scattered as the infamous	txgenz drew his gun.

Figure 3.1: Examples of the preview conditions used in Experiment 3.2. After readers crossed the boundary (vertical line), the target preview was always replaced with the correct target word (*cowboy*)

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3.2.2 Results and Discussion

We obtained first pass fixation times for each of the critical words. Trials with track losses or display changes that had completed after fixation onset were eliminated (34.72% of the data[3]), as were trials on which a blink occurred either during or imme-

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[3] Again, due to the high rate of data loss we also performed an analysis with the more lenient criterion which included data when the display change was completed up to 9 ms after the saccade ended and resulted in a data loss of only 9.8%. Again, the pattern of results was identical for both criteria. The

diately before or after a fixation on the target word (3.72 % of data). Also, fixations shorter than 80 ms or longer than 800 ms (less than 1% of all fixations) were removed. Finally, we only report means and analyses of those trials during which the pretarget word had received at least one first-pass fixation (62.6 % of the total remaining trials)[4]. All subjects answered at least 85% of the comprehension questions correctly. Table 3.6 shows the mean first fixation duration, gaze duration, go-past time and total viewing time for each experimental condition.

We analyzed the same measures as in Experiment 3.1, again fitting LMMs to the data and using the $|t| \geq 1.96$ significance criterion. In doing this, we employed a $2x2x2$ factorial design: apart from the preview order condition (correct vs. transposed) which corresponded to the conditions used in Experiment 3.1, each initial model included the letter identity preview condition of the first morpheme (identical vs. dissimilar) and the letter identity preview condition of the second morpheme (identical vs. dissimilar) as well as all two-way interactions[5]. Additional predictors added to the model were target word length (six vs. eight letters), log word frequency of the pretarget, target, and posttarget word and of the first and second morphemes of the target word, and target word predictability estimates we calculated from the results of the cloze task. Frequency estimates were obtained from an unlemmatized frequency list generated from the British National Corpus (Kilgarriff, 2006).

In Tables 4.2 through 4.9, we report the coefficients, standard errors, and *t*-values obtained from the LMMs for each word and each dependent measure. In order to make sure that the effects found in the models are not due to violations of normality, we fitted

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only exception was the analysis of log-transformed gaze durations on the target word in Experiment 3.2, which, under the more lenient data exclusion rules, yielded a significant effect of Morpheme 1 preview availability even in the transposed morpheme preview order condition ($b = 0.03$, SE = 0.014, $t = 2.02$).

[4] As in Experiment 3.1, including those trials in which the pretarget word was skipped during first-pass reading did not lead to a major change in the pattern of results.

[5] For each factor, the level that represented correct morpheme order preview or correct morpheme letter preview, respectively, was coded as -1, while the level that represented transposed morpheme order preview and incorrect morpheme letter preview was coded as 1.

The three-way interactions did not reach significance in any analysis except for log-transformed first fixation durations ($b = 0.08$, SE = 0.04, $t = 2.08$). We fitted separate models for the correct preview order and the transposed preview order condition in order to explore this interaction further and found that the interaction between Morpheme 1 letter identity and Morpheme 2 letter identity preview was significant only when the preview morpheme order had been correct ($b = -0.054$, SE = 0.026, $t = -2.08$). However, since this interaction was far from significance in the analysis using raw first fixation duration and is not visible in the raw fixation time means, it is unclear whether it can be interpreted.

the models for raw, log, and reciprocal transformed data. Since the resulting models were very similar, we report the coefficients based on the raw data which are more easily interpretable and only report the analyses using transformed data where their results are different from the raw fixation time analyses[6].

Pretarget word

There was a parafoveal-on-foveal effect of Morpheme 2 preview availability on first-fixation durations and go-past times on the pretarget word (see Table 3.7 for coefficient estimates, standard errors, and *t*-values). Additionally, there was a significant interaction between Morpheme 1 preview availability and preview morpheme order on go-past times. In the analysis using log-transformed first-fixation durations, we also found a significant three-way interaction between preview order and Morpheme 1 and Morpheme 2 preview availability (b = 0.1, SE = 0.038, t = 2.08). We fitted separate models for the correct preview order and the transposed preview order condition in order to explore this interaction further. We found a significant interaction between Morpheme 1 and 2 preview availability in the correct preview order condition (b = -0.05, SE = 0.026, t = -2.04), but only a significant parafoveal-on-foveal main effect of Morpheme 2 preview availability in the transposed preview order condition (b = 0.029, SE = 0.014, t = 2.09).

Since the incorrect previews consisted of random letters, this effect could be interpreted as an orthographical parafoveal-on-foveal effect caused by the presence of unusual letter sequences in the parafovea as well as an effect of very early Morpheme 2 processing. In the transposed preview order condition this effect seems to be driven by the second morpheme only (which appears first in the transposed preview), while in the correct preview order condition both morphemes seem to contribute to the effect.

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[6] In addition to the analyses reported here, we performed two supplementary analyses.

In the first analysis, we included semantic transparency (Libben, Gibson, Yoon, & Sandra, 2003) as a predictor. Specifically, we tested for effects of transparency of the first (non-head) or second (head) morpheme as well as the overall effect of transparency of the entire compound word. Since none of these predictors showed significant effects, we do not report the results from this analysis. In the second analysis, we treated the first and the second morpheme of the compound word as separate analysis regions in order to investigate whether the effects found in the main analysis were present throughout the word or only in fixations on one of the morphemes. We did not find a consistent pattern in this analysis, although there was a slight trend of preview order effects being stronger on the first morpheme and preview letter identity effects being stronger on the second morpheme.

Table 3.6: Condition means and standard deviations (in parentheses) for first fixation duration, gaze duration, go-past time and total viewing time (in ms) in Experiment 3.2.

Morpheme 1/ Morpheme 2 letter preview	Correct/transposed morpheme order previews	First fixation duration Order preview		Gaze duration Order preview		Go-past time Order preview		Total viewing time Order preview	
		correct	transposed	correct	transposed	correct	transposed	correct	transposed
Pretarget word									
identical / identical	cowboy / boycow	207 (72)	214 (67)	248 (117)	250 (111)	304 (198)	283 (162)	313 (187)	304 (168)
identical / dissimilar	cowtxg / txgcow	222 (75)	219 (77)	261 (118)	256 (116)	308 (186)	303 (183)	317 (176)	322 (192)
dissimilar / identical	enzboy / boyenz	214 (72)	209 (71)	244 (105)	250 (118)	285 (163)	303 (188)	312 (183)	315 (196)
dissimilar / dissimilar	enztxg / txgenz	214 (72)	219 (84)	252 (114)	256 (121)	301 (192)	299 (187)	322 (184)	335 (198)
Target word									
identical / identical	cowboy / boycow	236 (81)	250 (89)	279 (115)	309 (121)	324 (186)	359 (173)	359 (218)	396 (212)
identical / dissimilar	cowtxg / txgcow	245 (77)	254 (85)	302 (125)	318 (128)	341 (171)	361 (178)	360 (171)	406 (212)
dissimilar / identical	enzboy / boyenz	243 (80)	249 (79)	300 (120)	319 (128)	354 (176)	369 (191)	386 (208)	399 (199)
dissimilar / dissimilar	enztxg / txgenz	248 (82)	257 (85)	322 (128)	320 (124)	376 (196)	384 (204)	400 (204)	391 (199)
Posttarget word									
identical / identical	cowboy / boycow	236 (99)	235 (89)	256 (115)	254 (108)	321 (218)	312 (179)	304 (187)	305 (191)
identical / dissimilar	cowtxg / txgcow	231 (84)	239 (100)	250 (104)	267 (123)	297 (190)	323 (211)	307 (180)	305 (174)
dissimilar / identical	enzboy / boyenz	233 (89)	233 (87)	257 (110)	260 (116)	308 (201)	319 (186)	307 (180)	305 (175)
dissimilar / dissimilar	enztxg / txgenz	234 (89)	229 (82)	254 (119)	255 (115)	297 (190)	296 (170)	295 (161)	292 (174)

For go-past times, the analogous analyses for correct and transposed preview order did not yield any significant effects of Morpheme 1 or 2 letter preview. Finally, there was a strong effect of pretarget word frequency across all measures on the target word.

Target word

All fixation time measures on the target showed a strong effect of order preview. In each case, fixation times were longer if the preview had shown the morphemes in the transposed order, suggesting that we were successful in replicating the results of Experiment 3.1 (see Table 3.8 for coefficients, standard errors, and t-values), although with reduced effect sizes, most likely due to the additional preview manipulation. As expected, we also found an effect of target word length on gaze durations, go-past times, and total viewing times. In the analysis using log-transformed values, the effect of target word length was also significant in first-fixation duration (b = 0.042, SE = 0.028, t = 2.54). All fixation time measures also showed significant effects of target word frequency (the effect on first-fixation duration was only significant in the analysis on log-transformed values: b = -0.017, SE = 0.0079, t = -2.10) and target word predictability. There also was a significant spillover effect of pretarget frequency on all fixation time measures. Morpheme 2 frequency had an effect on gaze durations only, while Morpheme 1 frequency did not have an effect on any fixation time measure.

The effects of the letter identity preview conditions for the two morphemes differed strongly between fixation time measures. In first fixation duration, the effect of preview availability for the second morpheme narrowly failed to reach significance in the analysis on raw values, but reached significance in the analysis on log-transformed values (b = 0.036, SE = 0.014, t = 2.55), with fixation durations on the target word being slightly longer when the preview for Morpheme 2 had been denied. This result in addition to the lack of interaction between morpheme order and Morpheme 2 availability suggests that readers extract information from the second morpheme early in the processing stream, even when it appears in the end of the word. In contrast, there was no effect of preview availability for Morpheme 1 on first-fixation durations. Taken together, this implies that readers might be able to extract information even from a transposed morpheme preview.

Of the four fixation time measures, gaze durations provided the most straightforward picture: both the manipulations of Morpheme 1 preview availability and Morpheme 2 preview availability led to a significant preview benefit effect. Additionally, there were significant main effects of word length and morpheme order preview, while none of the interactions between morpheme order and morpheme letter preview reached significance. This suggests that there was a preview benefit effect for both morphemes regardless of their order in the preview.

In order to confirm this we again performed separate analyses[7] of the correct preview order condition and the transposed preview order condition data, which showed that the preview benefit effects differed between the two conditions: while both the effects of Morpheme 1 and Morpheme 2 preview availability were significant in the correct preview order condition (Morpheme 1: b = 20.62, SE = 5.34 ms, t = 3.87; Morpheme 2: b = 21.06 ms, SE = 5.31 ms, t = 3.97), neither reached significance in the transposed preview order condition (Morpheme 1: b = 7.86 ms, SE = 5.58 ms, t = 1.41; Morpheme 2: b = 8.75 ms, SE = 5.59 ms, t = 1.57). In effect, we were able to replicate the standard preview benefit effect on gaze durations. However, this effect disappeared when the preview morpheme order was reversed. Importantly, the results suggest that the Morpheme 1 and Morpheme 2 are equally important, as there was a preview benefit effect for both of them. Since the interaction between Morpheme 1 and Morpheme 2 preview availability was not significant, these preview benefit effects appear to be additive.

The picture changes again slightly in the go-past time analysis. There were significant preview benefit effects for Morpheme 1, while the main effect of Morpheme 2 preview did not reach significance in the analysis with raw data, but was significant in the analysis using log-transformed data (b = 0.043, SE = 0.02, t = 2.16). None of the interactions were significant, suggesting that these effects applied both in the correct and the transposed preview order conditions. In light of the differences between preview order conditions we found on gaze durations, we again decided to fit separate models for the correct and the transposed preview order conditions. Indeed, the effect of Morpheme 2 preview was only significant in the correct preview order condition (correct: b =

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[7] These analyses included all predictors present in the full analyses with the exception of morpheme preview order and the interaction between Morpheme 1 and Morpheme 2 letter preview, as this term did not reach significance in any measure.

17.83, SE = 8.15, *t* = 2.19; transposed: *b* = 11.82, SE = 8.41, *t* = 1.41). The effect of Morpheme 1 preview, however, reached significance both in the correct and in the transposed preview order conditions (correct: *b* = 31.44, SE = 8.19, *t* = 3.84; transposed: *b* = 16.44, SE = 8.4, *t* = 2.08). This suggests that readers were able to take advantage of the availability of preview for the first morpheme, even when the preview did not show that morpheme in its correct position in the compound word.

For total viewing times on the target word, the results pattern was quite similar to the pattern for go-past times. There were, however, some important differences: The effects of Morpheme 1 and Morpheme 2 letter preview only reached significance in the analysis using log-transformed values (Morpheme 1: *b* = 0.063, SE = 0.02, *t* = 3.07; Morpheme 2: *b* = 0.042, SE = 0.02, *t* = 2.08). Additionally, the total viewing time analysis showed a significant interaction between morpheme order preview and Morpheme 1 letter preview. In order to explore this interaction further, we again fitted separate models for the correct and the transposed preview order conditions. Our analyses show that the effect of Morpheme 1 preview only reached significance in the correct preview order condition (correct: *b* = 30.59, SE = 8.65, *t* = 3.54; transposed: *b* = –3.76, SE = 8.97, *t* = –0.42), while the effect of Morpheme 2 preview did not reach significance in either condition (correct: *b* = 6.94, SE = 8.62, *t* = 0.81; transposed: *b* = 2.88, SE = 8.98, *t* = 0.32). This suggests that the effect of Morpheme 1 preview on go-past times in the transposed order condition is due to an increase in regressions and second pass fixation durations on previous words rather than an increase on second- or third-pass fixation durations on the target word itself[8].

Posttarget word

Apart from a spillover effect of target word length on gaze durations and a significant effect of posttarget word frequency on all fixation time measures, none of the predictors reached significance for the posttarget word.

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[8] There was no significant effect of morpheme order on landing position. There was a significant interaction between morpheme order and Morpheme 1 preview: When morpheme order was correct, the Morpheme 1 preview denied condition led to landing positions further towards the beginning of the word. This effect was not present in the reverse preview order condition.

Table 3.7: Experiment 3.2 – LMM analyses on the pretarget word. M1 = Morpheme 1, M2 = Morpheme 2, let = letter, freq = word frequency, predict = cloze predictability. b: Regression coefficient, SE: standard error, t: test statistic (b/SE). All $|t| \geq 1.96$ are marked in bold.

		First fixation duration			Gaze duration			Go-past time			Total viewing time		
		b	SE	*t*	*b*	SE	*t*	*b*	SE	*t*	*b*	SE	*t*
Fixed effects	(Intercept)	209.38	5.06	**41.35**	242.11	8.25	**29.35**	277.31	13.18	**21.04**	301.10	13.73	**21.92**
	Morpheme order	3.38	4.17	0.81	-0.05	6.20	-0.01	-14.85	9.94	-1.49	-8.84	9.91	-0.89
Preview	Morpheme 1 let	0.54	3.38	0.16	-0.61	5.03	-0.12	5.16	8.06	0.64	9.20	8.03	1.14
	Morpheme 2 let	8.96	3.38	**2.65**	9.11	5.03	1.81	16.47	8.07	**2.04**	14.44	8.04	1.80
	Compound length	2.43	3.58	0.68	6.78	6.80	1.00	13.50	10.53	1.28	1.57	10.76	0.15
Covariates	Pretarget freq	-6.68	1.15	**-5.79**	-20.71	2.17	**-9.56**	-21.98	3.36	**-6.54**	-34.73	3.43	**-10.13**
	Target freq	-0.55	2.06	-0.27	0.06	3.95	0.02	-4.27	6.12	-0.70	-0.82	6.24	-0.13
	Posttarget freq	0.40	1.47	0.27	-0.42	2.77	-0.15	-0.91	4.30	-0.21	-3.62	4.39	-0.82
	Target predict	22.25	38.17	0.58	-27.21	73.92	-0.37	-69.56	114.16	-0.61	-110.63	116.80	-0.95
	Morpheme 1 freq	-1.50	2.36	-0.64	2.06	4.49	0.46	4.41	6.97	0.63	2.11	7.11	0.30
	Morpheme 2 freq	0.61	2.13	0.29	4.35	4.06	1.07	5.80	6.30	0.92	9.11	6.43	1.42
Interactions	Order : M1 let	-4.71	4.77	-0.99	8.07	7.10	1.14	27.33	11.39	**2.40**	13.19	11.35	1.16
	Order : M2 let	1.64	4.77	0.34	-1.26	7.10	-0.18	1.06	11.37	0.09	14.39	11.33	1.27
	M1 let : M2 let	-3.09	4.77	-0.65	-1.42	7.10	-0.20	-9.50	11.38	-0.84	-0.99	11.34	-0.09
Random variance	Item	172.82	13.15	NA	940.36	30.66	NA	2168.50	46.57	NA	2329.00	48.26	NA
	Subject	505.68	22.49	NA	1073.85	32.77	NA	2925.90	54.09	NA	3392.40	58.24	NA
	Residual	4743.34	68.87	NA	10419.90	102.08	NA	26828.50	163.79	NA	26644.80	163.23	NA

Table 3.8: Experiment 3.2 – LMM analyses on the target word. M1 = Morpheme 1, M2 = Morpheme 2,let = letter, freq = word frequency, predict = cloze predictability. *b*: Regression coefficient, SE: standard error, *t*: test statistic (b/SE). All $|t| \geq 1.96$ are marked in bold.

		First fixation duration			Gaze duration			Go-past time			Total viewing time		
		b	SE	*t*	*b*	SE	*t*	*b*	SE	*t*	*b*	SE	*t*
Fixed effects	(Intercept)	245.76	5.76	**42.68**	276.77	10.28	**26.92**	321.82	14.75	**21.82**	342.81	16.77	**20.44**
	Morpheme order	11.88	4.66	**2.55**	29.72	6.81	**4.36**	31.84	10.25	**3.11**	44.85	10.88	**4.12**
Preview	Morpheme 1 let	3.49	3.78	0.92	16.77	5.52	**3.04**	20.79	8.32	**2.50**	17.09	8.82	1.94
	Morpheme 2 let	7.37	3.79	1.95	17.46	5.52	**3.16**	10.87	8.32	1.31	8.06	8.83	0.91
	Compound length	-6.22	3.45	-1.80	20.34	6.95	**2.93**	22.11	10.65	**2.08**	42.76	13.11	**3.26**
Covariates	Pretarget freq	-8.63	1.13	**-7.61**	-11.44	2.22	**-5.16**	-12.59	3.40	**-3.71**	-14.86	4.16	**-3.57**
	Target freq	-3.58	1.96	-1.83	-11.43	4.01	**-2.85**	-17.29	6.15	**-2.81**	-22.49	7.61	**-2.95**
	Posttarget freq	-1.35	1.42	-0.95	-2.60	2.84	-0.92	-3.69	4.34	-0.85	-6.71	5.34	-1.26
	Target predict	-106.26	36.62	**-2.90**	-186.16	74.78	**-2.49**	-239.00	114.86	**-2.08**	-384.82	143.25	**-2.69**
	Morpheme 1 freq	-0.36	2.27	-0.16	1.16	4.57	0.25	2.89	7.01	0.41	-0.59	8.65	-0.07
	Morpheme 2 freq	-0.76	2.04	-0.37	-11.23	4.15	**-2.71**	-8.23	6.35	-1.30	-13.98	7.84	-1.78
Interactions	Order: M1 let	-5.60	5.33	-1.05	-11.91	7.78	-1.53	-14.82	11.73	-1.26	-33.94	12.46	**-2.72**
	Order: M2 let	0.69	5.33	0.13	-12.59	7.77	-1.62	-6.02	11.72	-0.51	-4.43	12.45	-0.36
	M1 let : M2 let	-1.09	5.33	-0.20	-4.75	7.77	-0.61	7.16	11.71	0.61	-6.06	12.43	-0.49
Random variance	Item	91.03	9.54	NA	877.57	29.62	NA	2104.10	45.87	NA	3787.90	61.55	NA
	Subject	786.84	28.05	NA	2445.94	49.46	NA	4552.60	67.47	NA	5343.30	73.10	NA
	Residual	5686.85	75.41	NA	11839.81	108.81	NA	27260.80	165.11	NA	31136.40	176.46	NA

Table 3.9: Experiment 3.2 – LMM analyses on the posttarget word. M1 = Morpheme 1, M2 = Morpheme 2, let = letter, freq = word frequency, predict = cloze predictability. *b*: Regression coefficient, SE: standard error, *t*: test statistic (b/SE). All $|t| \geq 1.96$ are marked in bold.

		First fixation duration			Gaze duration			Go-past time			Total viewing time		
		b	SE	*t*	*b*	SE	*t*	*b*	SE	*t*	*b*	SE	*t*
Fixed effects	(Intercept)	230.76	7.81	**29.55**	243.77	9.78	**24.92**	301.92	15.96	**18.91**	287.62	14.08	**20.43**
	Morpheme order	3.71	7.24	0.51	3.70	8.92	0.41	4.91	15.73	0.31	2.27	12.80	0.18
Preview	Morpheme 1 let	-0.79	5.87	-0.13	4.79	7.23	0.66	-5.57	12.76	-0.44	-0.60	10.37	-0.06
	Morpheme 2 let	-0.55	5.92	-0.09	2.67	7.29	0.37	-14.03	12.86	-1.09	-2.16	10.40	-0.21
	Compound length	-8.69	6.06	-1.43	-16.74	7.72	**-2.17**	-11.24	14.00	-0.80	-23.09	11.98	-1.93
Covariates	Pretarget freq	-1.27	1.97	-0.64	-2.06	2.51	-0.82	0.47	4.54	0.10	-6.09	3.89	-1.56
	Target freq	0.79	3.59	0.22	-1.75	4.57	-0.38	-12.74	8.28	-1.54	-4.93	7.06	-0.70
	Posttarget freq	-10.66	2.46	**-4.33**	-25.59	3.14	**-8.16**	-28.15	5.68	**-4.95**	-43.32	4.86	**-8.91**
	Target predict	-41.90	67.32	-0.62	-65.81	85.49	-0.77	-180.38	154.64	-1.17	-219.03	132.79	-1.65
	Morpheme 1 freq	-6.05	4.06	-1.49	-2.99	5.16	-0.58	0.10	9.33	0.01	2.37	7.90	0.30
	Morpheme 2 freq	0.68	3.53	0.19	-0.65	4.51	-0.14	-0.50	8.18	-0.06	-5.38	7.10	-0.76
Interactions	Order : M1 let	-12.24	8.35	-1.47	-12.14	10.29	-1.18	-5.89	18.15	-0.32	-10.08	14.64	-0.69
	Order : M2 let	5.03	8.32	0.60	13.05	10.25	1.27	9.94	18.08	0.55	3.41	14.58	0.23
	M1 let : M2 let	-1.09	8.34	-0.13	-5.55	10.28	-0.54	-1.56	18.13	-0.09	-8.06	14.58	-0.55
Random variance	Item	365.12	19.11	NA	652.37	25.54	NA	2303.70	48.00	NA	2074.30	45.54	NA
	Subject	861.82	29.36	NA	1329.86	36.47	NA	2159.00	46.47	NA	2286.20	47.81	NA
	Residual	6819.93	82.58	NA	10295.54	101.47	NA	31969.90	178.80	NA	24923.20	157.87	NA

3.3 General Discussion

In the present studies, we examined how morpheme order affects the parafoveal processing of compound words in natural reading using the gaze-contingent display change boundary paradigm. In Experiment 3.1, we tested how a transposed morpheme preview affected parafoveal processing, with the results indicating that readers obtained a clear benefit from the availability of a correct morpheme order preview. In Experiment 3.2, we compared the effect size of this morpheme order preview benefit to the letter identity preview benefit effect reported in numerous previous studies. In particular, we attempted to test whether readers were able to make use of correct letter previews from one or both morphemes if the preview did not have the correct morpheme order. The letter identity preview manipulation also allowed us to determine whether readers processed only one or both of the morphemes in the compound word preview.

On gaze durations, we found a significant interaction between preview order and preview letter identity for the first morpheme. When we analyzed the data from the correct and transposed preview order conditions separately, preview benefit effects only emerged in the correct preview order condition. This suggests that as far as later processing is concerned, reversing the morpheme order in a compound word is just as disruptive as changing the letter identities in the preview. Importantly, preview availability for both morphemes seemed to be associated with a similar amount of preview benefit, with the preview benefit for the whole compound word being the sum of the preview benefit effects of its constituents.

Critically, this picture changes when we consider early processing as evidenced by first fixation duration and late processing as evidenced by go-past times. In both cases, we were able to demonstrate that readers obtained some benefit from the availability of letter identity preview of one of the morphemes even when the morpheme order in the preview had been reversed. This finding contradicts results from an earlier parafoveal naming study by Inhoff and Tousman (1990) who reported that subjects were only able to benefit from a prime containing the final trigram of a six-letter target word if the letters appeared in the correct position (i.e. if the prime was *XXXTER* for *BITTER*). However, the letter trigrams that Inhoff and Tousman used were not morphemes but rather part of a monomorphemic six-letter word. Additionally, they presented single items and did not record eye movements, but instead analyzed naming times. This may explain the divergent results. In spite of the differences pointed out above, both Inhoff and Tousman's finding and our finding that readers benefit equally from preview of the first and the second morpheme in a compound word suggest that, to some degree, readers of English process morphemes in compound words in parallel.

Such a finding would appear, at first, to contradict the findings of Drieghe et al. who suggested that the morphemes in compound words are processed serially. There is, however, an important distinction between the effects examined in the two studies. Drieghe et al.'s study focused on the effect of availability of preview of the second morpheme during fixations on the first morpheme, while the present study investigates the parafoveal processing of both morphemes during fixations on the pretarget word. Drieghe et al. hypothesized that compound word processing takes place in multiple stages. At first, a reader has to determine that a word is a compound word. During this stage of processing, all the letters of the word would have to be processed in parallel for a certain amount of time.

Since such processing must necessarily occur very early, it might overlap with the parafoveal processing which is the focus of the present study. Once it is determined that the word is a compound word, however, the constituents could well be identified in serial. Since this serial stage would occur at a slightly later point than the parallel stage, it is quite possible that preview of the second morpheme is no longer important once the first morpheme has been fixated, which corresponds to the findings reported by Drieghe et al. Importantly, while it seems clear that the foveal and likely serial processing of words is affected by their morphological structure, the initial parafoveal processing stage proposed by Drieghe et al. may not involve any morphological processing, and processing during this stage could be purely orthographical.

Crepaldi et al.'s (2013) finding that transposed morpheme order primes can facilitate lexical decisions for compound words suggests that foveal morphological processing occurs relatively quickly (that is, within the prime duration of 48 ms). However, this may not necessarily be true for parafoveal processing. In this context, it is important to point out that findings from a number of studies (Bertram & Hyönä, 2007; Inhoff, 1989a, 1989b; Kambe, 2004; Lima, 1987) suggest that morphological boundaries do not play a role in parafoveal preview benefit. However, there are some substantial differences between some of these studies and the current study. Lima (1987) and Kambe (2004) investigated prefixed words, which might conceivably be processed differently from compound words. While the target words in Bertram and Hyönä (2007) were compound words, they were considerably longer than the words used in the current study, which could also cause differences in processing.

In contrast, the target words used in Inhoff (1989a) were very similar to the target words used in this study. The fact that Inhoff (1989a) found equal amounts of preview benefit for compound (*cowboy*) and pseudocompound words (*carpet*) does suggest that there is an orthographical component to the effects observed in the present study. Specifically, the morphological manipulations we used resulted in differing amounts of orthographical overlap. At least the preview benefit effect found for the first morpheme in the correct preview order condition could also be explained with the initial letter overlap implicit in these conditions.

Given that Johnson (2007) found that up to five letters can be pre-processed parafoveally and that, during this pre-processing stage, letter identity information may not be strictly position-specific, this warrants further study. Specifically, it should be investigated whether monomorphemic 6- and 8-letter words show similar effects when the first and last 3- or 4- letter blocks are transposed (e.g. *carpet* vs. *petcar* and *fountain* vs. *tainfoun*) in order to verify that the effects are morphological in nature. However, a pure orthographical account of our findings would not be able to explain why we found letter identity preview benefit effects for the first morpheme even when the morpheme order was reversed, unless it assumes that absolute letter position is less important than relative letter order.

An alternative possibility is that both the initial orthographic analysis involving all letters and the subsequent morpheme extraction can be performed parafoveally. In this case, the preview benefit effects we found could be related to both of these processes. In the correct morpheme order condition, the effects might be driven by both the orthographic and the morpheme-based process, while the effect in the transposed morpheme order condition might be driven mostly by the morpheme-based process. This would also explain why the effects in the transposed morpheme order condition appear only in the later measure of go-past time. Which of these alternatives is correct remains to be tested by further research. In either case our results suggest that readers can, under some circumstances, process up to eight letters in the parafovea. This goes beyond the limits estimated in earlier research (Inhoff, 1990; Johnson et al., 2007).

The time course of compound word processing as presented so far is as follows: there is an orthographic pre-processing stage which involves both of the morphemes and during which the morpheme boundary is established. This is followed by serial processing of the first and the second morpheme. Most of our results fit in quite well with this view. However, some aspects of our data suggest that the second morpheme might sometimes be processed before the first one. Specifically, preview for Morpheme 2, but not Morpheme 1, had a significant effect on fixation times on the pre-target word and on first-fixation durations on the target word. On the other hand, Morpheme 1 seemed to have a stronger influence on later fixation time measures such as total viewing time than on early measures. This could be due to the fact that, in most cases, Morpheme 2 determined the meaning of the compound word. A similar finding was reported by Inhoff, Starr, Solomon, and Placke (2008), who found that the frequency of the semantically dominant morpheme in a compound word had a strong effect even on early fixation time measures.

Finally, the notion that there is at least some parallel parafoveal morpheme processing fits in well with the findings of Yang (2010), who performed an experiment similar to the present study in Chinese, manipulating the character order of the previews Chinese readers received for two-character target words embedded in a sentence. For all of the words, reversing the character resulted in a different lexical word. However, some of the transposed-character words had a meaning that was identical to the original target words, while others had a meaning that was quite different from the meaning of the original target words. Yang found a clear benefit of correct order preview for those target words whose meaning changed as their characters were transposed, but no benefit of correct order preview at all for those words whose character order could be reverted without changing the meaning. In a second experiment, she found that there was no benefit of correct order preview even when the transposition resulted in preview words that had a different meaning but still plausibly fit into the sentence context. In

Chinese, therefore, the characters comprising two-character words seem to be processed in parallel by default. There only appears to be a cost of identifying the characters in the wrong order when this affects the meaning or the plausibility of a word in its sentence.

In the present experiment, reversing the morpheme order always resulted in a nonword with a meaning that was unclear at best (what is a *boycow*?). Such a word is always highly implausible by default, which might be the reason why we found a clear cost of having a transposed morpheme order preview in all conditions. Despite the inevitable disruptive effect of a transposed morpheme order in English, we found indications that readers of English, too, might be able to process morphemes constituting a compound word in a parallel fashion. It remains to be determined which of the processing stages take place in parallel and which can only be performed serially, as well as when the disruptive effects of changes in semantics and plausibility come into play.

In summary, our study suggests that processing of compound words in English and processing of multi-character words in Chinese might have some similarities. Of course, processing in Chinese is quite different from processing in English. For example, there is some evidence that Chinese readers obtain much more semantic information from the words to the right of fixation than English readers (Yan, Richter, Shu, & Kliegl, 2009; Yang, Wang, Tong, & Rayner, 2012). As a consequence, there is a possibility that Yang's findings reflect the effects of semantic overlap and plausibility as well as morphological processing (see also Yen, Tsai, Tzeng, & Hung, 2008). In contrast, our findings could also be explained solely by orthographic processing. Further research is needed in order to distinguish between orthographic and morphological factors of compound word processing. However, the findings of Crepaldi et al. (2010) suggest that a morphological basis for our effects is not completely implausible.

Chapter 3, in full, is a reprint of the material as it appears in Eye movements and parafoveal preview of compound words: Does morpheme order matter? Angele and Rayner (2013a) The dissertation author was the primary investigator and author of this paper.

Chapter 4

Processing *the* in the parafovea: Are articles skipped automatically?

Readers do not fixate every single word in a sentence, but occasionally skip a word. Words are especially likely to be skipped if they are short, highly frequent, and predictable from the preceding sentence context (Koriat & Greenberg, 1994; [for a summary of research on skipping effects, see Rayner, 1998, 2009). Some word skipping can also be explained by mislocated fixations (i.e. readers attempting to fixate a short word, but overshooting it and landing on the subsequent word instead; see Nuthmann et al., 2005). It is also clear that word skipping is influenced by parafoveal processing (Fitzsimmons & Drieghe, 2011; Rayner, Slattery, Drieghe, & Liversedge, 2011; Schotter et al., 2012). The phenomenon of word skipping has the potential of providing insight into the time course of word identification and syntactic integration. More specifically, since the decision to skip a word has to be made relatively early during a fixation (within about $75-125$ ms of fixation onset[1]), readers must make their decision quickly and may not take information from higher levels of processing into account. The definite article the is an ideal candidate for studying word skipping, since it is short, highly frequent, and

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[1] Most sources estimate the minimum time to program a saccade at 150-175 ms (Abrams & Jonides, 1988; Rayner, 1978). E-Z Reader assumes a saccade programming time of around 125 ms (Reichle et al., 2006). Given that the average fixation duration in reading is around 250 ms (Rayner, 1998), that leaves only the first 75-125 ms to make the decision to program a skipping saccade. There might be more time for saccade planning if one assumes that the target of a saccade is not decided until the very last stage of programming.

highly predictable.

Previous research by O'Regan (1979) and Carpenter and Just (1983) demonstrated that three-letter function (closed-class) words such as articles or prepositions are more likely to be skipped by readers than three-letter content (open-class) words. Gautier et al. (2000) replicated O'Regan's finding that articles are skipped much more often than other short words even when they are not predictable from the context, as did Drieghe, Pollatsek, et al. (2008). This suggests that readers use parafoveal information in order to decide whether to skip a word, and do not rely exclusively on prior context. However, the nature of the parafoveal information that leads to the increased skipping rates in the the-condition is not clear: readers may skip the because it is easy to process, or they may have learned to skip articles by default, regardless of their processing status.

Another interesting issue is whether readers skip the automatically without actually seeing the word. Specifically, some recent research (Roy-Charland et al., 2012) in which the missing-letter effect (MLE) was combined with a gaze-contingent moving window paradigm (McConkie & Rayner, 1975) suggests that this might be the case. In MLE studies (Healy, 1994; Koriat & Greenberg, 1993, 1994; Saint-Aubin & Klein, 2008), subjects have to detect a target letter in text. The well-known finding is that they miss more letters in frequent function words than in less frequent content words. In Roy-Charland et al.'s study, a moving window was used such that the fixated word was available for processing, but all words to the right of fixation were masked with *X*'s. They found that readers were able to detect a target letter embedded in a word that was skipped. In such cases, the letter could only have been identified in post-view (to the left of fixation). More critically for the present issues, they found that the was skipped slightly more often than a three-letter content word (an 8% difference).

In Dutch, Drieghe, Brysbaert, Desmet, and De Baecke (2004) investigated the influence of context-driven expectations on the skipping of short words (but not the definite article) in general. In particular, they compared target words that were highly predictable from the preceding context (e.g. "maakte het bed *op*"; English: "made the bed"; target word in italics) with neutral target words of either the same length ("maakte het bed *na*"; English: "imitated the bed") or a different length ("maakte het bed *vast*", English: "fastened the bed"). Drieghe et al. found an effect of contextual constraint on the probability of fixating the target word, with predictable words being skipped more often than unpredictable words. They claimed that the size of this effect, a nine percentage point difference, is among the largest that can be obtained with contextual constraints. Drieghe et al. also reported a main effect of word length, with short words being skipped more often than long words. There was, however, no effect of expected word length on skipping, i.e. the skipping probability of an unexpected word did not depend on whether it had the same length as the expected word. As a consequence, Drieghe et al. argued that visual features like word length and linguistic features like predictability might influence skipping separately.

In the present study, we aimed to test the hypothesis that function words are automatically skipped by using a gaze-contingent preview manipulation (Rayner, 1975). This enabled us to differentiate between effects of parafoveal information and effects of the sentence context without overtly using syntactically illegal or unusual sentences. Specifically, we provided readers with a preview of the definite article the in a position where it can be expected to always be grammatically illegal (that is, in the position of a three-letter word used as a verb, such as *ace*). If readers only consider the upcoming parafoveal letters when making a skipping decision, we expected to find higher skipping rates for target verbs which had a infelicitous *the* preview than for target verbs which had a correct preview (e.g. *ace*). On the other hand, if readers do consider context information, they should be able to detect the anomaly and, as a consequence, be more likely to fixate the problematic word.

Whether readers are able to detect the anomaly inherent in the the previews should also determine their fixation durations on the target word and the surrounding words: If readers detect the anomaly, they should show longer fixation times on the pre-target word (i.e. a parafoveal-on-foveal effect), the target word, and, possibly, a spill-over effect on the post-target word in the the preview condition compared to the correct preview condition. If readers do not detect the anomaly until after they have skipped the target word, we should expect no difference in fixation times on the pre-target word. In contrast, there should be strong effects on the post-target words after inappropriate skips of the target word as well as a higher probability for regressions out of that word. Finally, on those trials where the target word is not skipped, we might also expect an effect of the incorrect previews on the target word itself.

In order to establish a baseline for the effects of unusual parafoveal information on fixation times and word skipping, we also included a condition in which the preview consisted of random letter strings (e.g. *fda*). We expected this condition to result in immediate effects of the unusual letter strings on fixation times on the target word, as well as possible effects on the pre-target and post-target words. However, random letter previews should not cause readers to skip the target word more frequently than the correct previews—on the contrary, we expected that readers would be more likely to fixate a word with a random letter preview.

Finally, in order to make sure that any observed effects are due to letter identity and not lower-level influences such as word shape, we presented all sentences in upper case for half of the subjects. We did not expect this to have a strong influence on parafoveal processing (see Slattery, Angele, & Rayner, 2011; Slattery, Schotter, Berry, & Rayner, 2011).

4.1 Method

Subjects

Sixty University of California, San Diego students participated in this experiment for course credit. All were native speakers of English, had either normal or corrected to normal vision, and were naïve concerning the purpose of the experiment. Apparatus. An SR Research *Eyelink 1000* eyetracker was used to record subjects' eye movements with a sampling rate of 1000 Hz. Subjects read sentences displayed on an Iiyama *Vision Master Pro 454* video monitor with a refresh rate of 150 Hz. Viewing was binocular, but only the right eye was recorded. Viewing distance was approximately 60 cm, with 3.8 letters equaling one degree of visual angle.

Materials

Sixty-three experimental sentences were generated, each one containing a three-letter target word which was always used as a verb (e.g. *She was sure she would* ***ace*** *all the tests*, target word in bold; see the Appendix for all sentences). Acceptability

Case	Preview	Sentence prior to display change	
Normal	Correct	She was sure she would	ace all the tests.
Normal	Nonword	She was sure she would	fda all the tests.
Normal	Infelicitous *the*	She was sure she would	the all the tests.
All upper case	Correct	SHE WAS SURE SHE WOULD	ACE ALL THE TESTS.
All upper case	Nonword	SHE WAS SURE SHE WOULD	FDA ALL THE TESTS.
All upper case	Infelicitous *the*	SHE WAS SURE SHE WOULD	THE ALL THE TESTS.

Figure 4.1: Examples of the three preview conditions and two capitalization conditions. After a participant's gaze position crossed the boundary located to the right of the pretarget word (vertical line), all incorrect previews changed to the correct words (i.e. the sentence appeared as it did in the correct preview condition).

ratings for each of the sentences were obtained from 46 University of California, San Diego undergraduates who participated for course credit and were native speakers of English to ensure that no sentence was unacceptable to the target population. On a scale from 1 (unacceptable) to 7 (perfectly acceptable), the average rating of the experimental sentences was 5.18. In order to ensure that any effects were not primarily due to word shape, half of the subjects read sentences in lower-case, while the other half read the sentences in all caps (see Figure 4.1).

Procedure

The 63 experimental sentences were embedded in 60 filler sentences unrelated to the present study. Subjects were asked to read the sentences on the computer screen silently and press a button on the *Eyelink* button box when they were finished and felt that they understood the sentence content. During the presentation of the experimental sentences, the gaze-contingent boundary paradigm (Rayner, 1975) was used to manipulate the parafoveal preview of the target word. There were three preview conditions: The preview was correct, that is, identical to the target word (*ace*), a random-letter preview (*fda*), or a false, infelicitous preview of an article (*the*; see Figure 4.1). It is important to note that this procedure ensured that the false article preview always appeared in a position in which an article would be syntactically illegal. After 20 out of the 63 sentences (31.7%), subjects were presented with a two-alternative forced choice comprehension question and used the trigger buttons on the *Eyelink* button box to select the answer they thought was correct (see Appendix for a list of all questions used).

4.2 Results

For each of the critical words, we examined fixation time on the target word. Trials with track losses or display changes that completed after fixation onset as well as trials in which a blink occurred immediately before or during a fixation on the target word were eliminated (10.33% of the data). If a fixation was shorter than 80 ms and located within one character space (11 pixels) of another fixation, it was merged into that fixation. Otherwise, it was deleted, as were fixations shorter than 80 ms or longer than 800 ms (less than 1% of the data). All subjects answered at least 85% of the comprehension questions correctly.

Since we expected that frequent skipping of the three-letter target words and exclusion of delayed display changes would lead to unequal cell sizes, inferential statistics are reported based on linear mixed models (LMM) with subjects and items as crossed random effects (Baayen et al., 2008). In order to fit the LMMs, the `lmer` function from the `lme4` package (Bates et al., 2009) was used within the R Environment for Statistical Computing (R Development Core Team, 2013). For each factor, we report regression coefficients (b), standard errors, and t-values. For binomial dependent variables such as fixation and regression probabilities, we report regression coefficients, standard errors, and z-values from generalized LMMs using a logit-link. We do not report p-values, since it is not clear how to determine the degrees of freedom for LMMs, making it difficult to estimate p-values. However, since our analyses contain a large number of subjects and items and only a few fixed and random effects are estimated, we can assume that the distribution of the t-values estimated by the LMMs approximates the normal distribution. We will therefore use the two-tailed criterion $|t| \geq 1.96$ which corresponds to a significance test at the 5% α-level. Of course, the z-values from the generalized LMMs can be interpreted in exactly the same way.

We fitted an LMM for each of the following dependent variables on each target word: first fixation duration (FFD), gaze duration (GD), go-past time (go-past), landing position, fixation probability, and the probability of making a regression out of the word. FFD is the mean duration of the first fixation on a word, regardless of whether there are subsequent fixations on that word or not. It can be considered a measure of early processing (Rayner, 1998, 2009). Mean GD is the sum of the duration of the first fixation on a word and the durations of all subsequent refixations before leaving the word. It is still a measure of early processing, but can capture some later processing difficulties that force a reader to refixate on a word. Mean go-past time includes all the fixations used to calculate GD, but additionally considers the durations of fixations that are made to the left of the word in question from the time a reader first enters that word from the left until the reader leaves the word to the right. As such, it is sensitive to integration difficulties that require regressions. Tables 4.1, 4.4, and 4.7 show the means and standard deviations of each dependent variable in each of the experimental conditions. For fixation probability and probability of regressions out, logistic LMMs were used (Gelman & Hill, 2007).

The analyses included two fixed effects, preview (correct vs. random letter vs. infelicitous *the*) and case (normal sentence vs. upper case) as well as their interaction (a 3 × 2 design), and random intercepts for subjects and items. We used two orthogonal contrasts to further explore differences between the preview factor levels. Contrast 1 compared the random letter condition with the mean of the correct and the infelicitous *the* condition—that is, it compared the condition in which the preview was a nonword with the conditions in which the preview was a word (random letters = 1, correct = $-.5$, infelicitous *the* = $-.5$). Contrast 2 then compared the correct and the infelicitous *the* condition (random letters = 0, correct = -1, infelicitous *the* = 1). Since we expected the infelicitous *the* condition to cause the strongest disruption on the post-target word (as opposed to the pre-target and target words where the random letter preview was expected to cause more disruption), we used slightly different contrasts for the analyses of the post-target word.

In the post-target word analyses, Contrast 1 corresponds to the difference between the correct and the mean of the *the* and the random letters preview conditions (random letters = .5, correct = -1, infelicitous *the* = .5) and Contrast 2 tests for a difference between the random letters and the infelicitous *the* conditions (random letters = -1, correct = 0, infelicitous *the* = 1). The LMM analyses included random intercepts for subjects and items as well as random preview effect slopes for subject and random case effect slopes for items. Model comparisons showed that none of the other possible random slopes (i.e. random preview effect slopes for items or random slopes for the interaction terms between preview and case) were justified by the data. Tables 4.2, 4.3, 4.5, 4.6, 4.8, and 4.9 show the results for all models fitted on the pre-target, target, and post-target. We will now discuss the effects on each word in detail.

Pre-target word

Table 4.1 shows the means and standard deviations of all the dependent measures on the pre-target word. Random letter nonword previews resulted in longer GDs and Go-past times compared to the correct and the infelicitous *the* preview conditions (all coefficient estimates, standard errors *t*-values, and or *z*-values are presented in Tables 4.2 and 4.3). Compared to the other two conditions, in the random letter nonword condition there were also more regressions out of the pre-target word and there was a marginal effect indicating that the pre-target word was more likely to be fixated.

These orthographic parafoveal-on-foveal effects are caused by the presence of a nonword letter string in the parafovea and are likely unrelated to lexical processing (Schotter et al., 2012). Somewhat surprisingly, there also was an effect of the infelicitous *the* preview (compared to the correct preview) on pre-target fixation probability, with the pre-target word being less likely to be fixated when the subsequent target word was *the*. This effect could be interpreted as subjects detecting the anomaly caused by the infelicitous *the* early and making a saccade towards it and could, as such, be classified as a lexical or syntactic parafoveal-on-foveal effect (Schotter et al., 2012). It is, however, important to point out that the size of this effect is quite small (3.4 percentage points in the sentence case and 2.5 percentage points in the upper case condition). Finally, capitalization had an effect on landing positions on the pre-target word, with fixations occurring slightly further to the left of the word when the sentences were displayed in upper case. No other effects were significant.

Target word

Table 4.4 shows the means and standard deviations of all the dependent measures on the target word (the corresponding model coefficients, standard errors, and *t*-values or *z*-values are shown in Tables 4.5 and 4.6). Since the present experiment was designed to elicit skipping of the target word, we need to consider fixation probability on the

Table 4.1: Condition means on the pre-target word. Standard deviations are in parentheses.

		Fixation time measures (in ms)			Landing position	Probability	
Case	Preview	FFD	GD	Go-past	in characters	Regressions out	Fixation
Sentence case	Correct	210 (2.97)	227 (4.03)	251 (5.84)	2.16 (0.071)	0.0514 (0.00886)	0.754 (0.0173)
	Dissimilar	220 (3.11)	241 (4.36)	281 (7.47)	2.04 (0.0702)	0.0844 (0.0112)	0.773 (0.0169)
	Infelicitous *the*	214 (3.24)	232 (4.38)	268 (8.1)	2.14 (0.0719)	0.0494 (0.00865)	0.721 (0.0179)
Upper case	Correct	214 (2.85)	234 (4.1)	260 (6.26)	1.87 (0.072)	0.0526 (0.00921)	0.778 (0.0172)
	Dissimilar	214 (3.2)	240 (4.84)	275 (7.13)	1.98 (0.0737)	0.078 (0.0112)	0.789 (0.017)
	Infelicitous *the*	215 (3.54)	233 (4.49)	263 (7.33)	1.89 (0.0711)	0.0593 (0.00959)	0.753 (0.0175)

Table 4.2: Fixed effects from the LMM analyses on first fixation duration, gaze duration, go-past time, and landing position on the pre-target word word. Each column represents a model fitted to one of the dependent variables. All $|t| \geq 1.96$ are marked in bold.

	FFD			Gaze duration			Go-past time			Landing Pos.		
	b	SE	*t*	*b*	SE	*t*	*b*	SE	*t*	*b*	SE	*t*
(Intercept)	214.22	3.45	**62.04**	233.26	4.46	**52.30**	264.83	7.39	**35.83**	1.96	0.07	**27.44**
Contrast 1:												
Nonword vs. Identical/*the*	3.20	1.69	1.89	6.15	2.44	**2.52**	11.95	4.17	**2.87**	0.01	0.04	0.30
Contrast 2:												
Identical vs. *the*	0.92	1.61	0.57	0.63	2.16	0.29	3.54	3.64	0.97	0.00	0.03	-0.08
lower vs. upper case	-0.77	2.99	-0.26	-2.09	3.87	-0.54	-1.06	6.09	-0.17	0.11	0.04	**2.81**
Preview Contrast 1 x Case	2.95	1.69	1.75	1.46	2.44	0.60	2.71	4.17	0.65	-0.07	0.04	-1.68
Preview Contrast 2 x Case	0.35	1.61	0.22	1.05	2.16	0.48	1.63	3.64	0.45	-0.02	0.03	-0.59
Subject: (Intercept)	478.89	21.88	NA	688.88	26.25	NA	1788.11	42.29	NA	0.05	0.22	NA
Subject: Preview Contrast 1	1.24	1.11	NA	27.66	5.26	NA	197.14	14.04	NA	0.01	0.07	NA
Subject: Preview Contrast 2	28.77	5.36	NA	32.87	5.73	NA	158.36	12.58	NA	0.00	0.05	NA
Item: (Intercept)	198.67	14.10	NA	410.59	20.26	NA	1253.94	35.41	NA	0.22	0.47	NA
Item: lower vs. upper	15.22	3.90	NA	101.74	10.09	NA	163.84	12.80	NA	0.00	0.03	NA
Residual	3897.87	62.43	NA	7537.37	86.82	NA	19568.28	139.89	NA	2.09	1.45	NA

Table 4.3: Fixed effects from the logistic generalized LMM analyses on regression and first-pass fixation probability on the post-target word. Each column represents a model fitted to one of the dependent variables. All $|z| \geq 1.96$ are marked in bold.

		p(Regression out)			p(Fixation)		
		b	SE	*z*	*b*	SE	*z*
	(Intercept)	-3.15	0.14	**-22.25**	1.49	0.16	**9.56**
Preview	Contrast 1: Nonword vs. Identical/*the*	0.32	0.10	**3.31**	0.13	0.07	1.89
	Contrast 2: Identical vs. *the*	0.07	0.10	0.77	-0.12	0.06	**-2.11**
Case	lower vs. upper	-0.17	0.13	-1.29	-0.11	0.10	-1.14
Interactions	Preview Contrast 1 x Case	0.08	0.10	0.83	0.03	0.07	0.46
	Preview Contrast 2 x Case	-0.04	0.10	-0.43	0.00	0.06	0.02
Random effects	Subject: (Intercept)	0.52	0.72	NA	0.43	0.66	NA
	Subject: Preview Contrast 1	0.00	0.01	NA	0.04	0.20	NA
	Subject: Preview Contrast 2	0.01	0.08	NA	0.05	0.22	NA
	Item: (Intercept)	0.35	0.59	NA	0.98	0.99	NA
	Item: lower vs. upper case	0.14	0.38	NA	0.05	0.22	NA
	Residual	NA	NA	NA	NA	NA	NA

Table 4.4: Condition means on the target word. Standard deviations are in parentheses.

		Fixation time measures (in ms)			Landing position	Probability	
Case	Preview	FFD	GD	Go-past	in characters	Regressions out	Fixation
Sentence case	Correct	231 (3.62)	251 (4.11)	281 (6.06)	1.61 (0.0513)	0.0788 (0.0108)	0.711 (0.0182)
	Dissimilar	253 (4.26)	276 (5.11)	351 (9.01)	1.41 (0.0471)	0.164 (0.0149)	0.753 (0.0174)
	Infelicitous *the*	242 (4.94)	274 (6.37)	321 (9.31)	1.61 (0.0662)	0.0717 (0.0103)	0.486 (0.02)
Upper case	Correct	233 (3.84)	256 (4.76)	294 (7.38)	1.48 (0.0517)	0.0866 (0.0116)	0.75 (0.0178)
	Dissimilar	251 (4.19)	285 (5.2)	362 (9.22)	1.51 (0.0489)	0.158 (0.0152)	0.759 (0.0178)
	Infelicitous *the*	240 (5.02)	274 (6.15)	328 (10.3)	1.55 (0.0589)	0.0774 (0.0109)	0.598 (0.0199)

Table 4.5: Fixed effects from the LMM analyses on first fixation duration, gaze duration, go-past time, and landing position on the target word word. Each column represents a model fitted to one of the dependent variables. CT = Contrast. All $|t| \geq 1.96$ are marked in bold.

		FFD			Gaze duration			Go-past time			Landing Pos.		
		b	SE	*t*	*b*	SE	*t*	*b*	SE	*t*	*b*	SE	*t*
	(Intercept)	239.73	4.15	**57.78**	266.70	5.15	**51.76**	321.62	8.44	**38.11**	1.53	0.03	**50.75**
Preview	CT 1: Nonword vs. Identical/*the*	9.81	2.62	**3.75**	10.69	3.57	**3.00**	32.73	4.95	**6.61**	-0.07	0.03	**-2.00**
	CT 2: Identical vs. *the*	3.41	2.21	1.54	9.55	3.06	**3.13**	18.78	4.35	**4.32**	0.02	0.03	0.53
Case	(lower/upper)	0.06	3.89	0.02	-3.01	4.77	-0.63	-4.92	7.75	-0.63	0.02	0.03	0.61
Interactions	Preview CT 1 x Case	0.09	2.62	0.04	-2.38	3.57	-0.67	0.84	4.96	0.17	-0.07	0.03	**-2.18**
	Preview CT 2 x Case	1.56	2.21	0.71	1.26	3.06	0.41	0.87	4.35	0.20	-0.02	0.03	-0.50
Random effects	Subject: (Intercept)	803.70	28.35	NA	1203.20	34.69	NA	2965.58	54.46	NA	0.02	0.13	NA
	Subject: Preview CT 1	107.04	10.35	NA	328.31	18.12	NA	234.13	15.30	NA	0.01	0.12	NA
	Subject: Preview CT 2	31.52	5.61	NA	184.18	13.57	NA	80.39	8.97	NA	0.02	0.13	NA
	Item: (Intercept)	137.57	11.73	NA	259.07	16.10	NA	928.42	30.47	NA	0.01	0.11	NA
	Item: Case (lower/upper)	7.59	2.75	NA	20.86	4.57	NA	226.00	15.03	NA	0.00	0.04	NA
	Residual	6468.93	80.43	NA	9440.86	97.16	NA	25962.05	161.13	NA	1.11	1.05	NA

Table 4.6: Fixed effects from the logistic generalized LMM analyses on regression and first-pass fixation probability on the target word. Each column represents a model fitted to one of the dependent variables. All $|z| \geq 1.96$ are marked in bold.

		p(Regression out)			p(Fixation)		
		b	SE	*z*	*b*	SE	*z*
	(Intercept)	-2.51	0.13	**-19.21**	0.92	0.11	**8.43**
Preview	Contrast 1: Nonword vs. Identical/*the*	0.62	0.08	**7.76**	0.50	0.07	**7.04**
	Contrast 2: Identical vs. *the*	-0.01	0.08	-0.18	-0.47	0.05	**-8.90**
Case	(lower/upper)	0.03	0.11	0.28	-0.14	0.10	-1.43
Interactions	Preview Contrast 1 x Case	0.05	0.08	0.64	0.11	0.07	1.58
	Preview Contrast 2 x Case	0.00	0.08	0.03	-0.07	0.05	-1.37
Random effects	Subject: (Intercept)	0.51	0.71	NA	0.53	0.73	NA
	Subject: Preview Contrast 1	0.03	0.17	NA	0.10	0.32	NA
	Subject: Preview Contrast 2	0.01	0.11	NA	0.05	0.22	NA
	Item: (Intercept)	0.33	0.58	NA	0.14	0.37	NA
	Item: Case (lower/upper)	0.03	0.19	NA	0.03	0.16	NA
	Residual	NA	NA	NA	NA	NA	NA

target word and fixation times on the target word separately. Fixation probability on the target word is an indicator of whether the nature of the preview affected saccade target selection during the previous fixation. Our results show that this is the case: While an irregular letter preview caused readers to fixate the target word more often than in the other conditions, the infelicitous *the* preview condition led to a strong increase in skipping compared to the correct control condition—around 50% of the infelicitous *the* previews caused subjects to skip the target word when it was displayed in lower case. In the upper case condition, skipping rates were somewhat lower numerically, but the increase in skipping was still substantial. Importantly, the interaction between capitalization and preview was not significant.

It is important to keep in mind that the remaining dependent measures—FFD, GD, Go-past time, landing position, and the probability of making a regression out of the target word—are a subset of the data and reflect the consequences of NOT skipping the target word. All measures show reliable effects of the irregular letter preview, with longer fixation times and a higher probability of regressions out of the target word in the irregular preview condition. This can be considered a preview benefit effect (Rayner, 1998). The infelicitous *the* condition resulted in a somewhat smaller preview benefit in GD and go-past time. There was a numerical trend for these effects to be stronger in the upper case condition, but the corresponding interaction term was not significant. As for landing position, when the nonword previews were not skipped, subjects' fixations landed further to the left in the target word than in the correct control condition. A significant interaction with capitalization indicates that this effect was enhanced when sentences were displayed in upper case.

In summary, the fixation probabilities on the target word show that the infelicitous *the* preview manipulation had the intended effect: subjects skipped the infelicitous *the* previews more often than random letter strings, and, importantly, the actual subsequent word which fit into the sentence context. In those cases where subjects decided not to skip the target word, there was no evidence of processing disruption caused by irregular or infelicitous *the* previews beyond what is to be expected due to standard preview benefit effects. With respect to fixation time measures, first fixations on the target word following the infelicitous *the* previews were not longer than those following correct previews. GDs and go-past times following the infelicitous *the* previews were longer, however. In general, these effects were on the same order of magnitude as the effects of having had an irregular letter preview. This means that, in those cases where subjects decided not to skip the target word after an infelicitous *the* preview, its effects were comparable to a random letter preview and are essentially preview benefit effects.

Post-target word

Table 4.7 shows the means and standard deviations of all the dependent measures on the post-target word (the corresponding model coefficients, standard errors, and t-values or z-values are shown in Tables 4.8 and 4.9). There were no effects of any of the experimental manipulations on FFD, GD, and landing position on the post-target word. In go-past time, however, an effect of the target word preview manipulation emerged. First, go-past times on the post-target word were longer following a random letter or infelicitous *the* preview of the target word compared to the correct condition (a spillover effect).

Additionally, when there had been an infelicitous *th*e preview of the target word, go-past times on the post-target word were much longer than when the preview had consisted of random letters. This suggests that, while the infelicitous *the* preview did not have an effect on the early processing of the post-target word, it caused a major disruption of later processing stages, most likely on the syntactic integration of the post-target word (and the target word, if it was skipped) into the sentence structure. We observed a very similar effect on the probability of making regressions out of the post-target word, suggesting that the increase in go-past time is due to subjects re-reading earlier words in the sentence in order to arrive at a sensible interpretation of it.

Finally, we also observed significant effects of the preview manipulation on the probability of fixating the post-target word. Specifically, subjects were less likely to fixate the post-target word in the correct preview condition compared to the random letter and the infelicitous *the* condition and subjects were more likely to fixate the post-target word in the infelicitous *the* condition than in the random letter preview condition. The post-target word was also fixated more often when the sentences were displayed in upper case compared to the lower case condition. A similar effect was observed

Table 4.7: Condition means on the post-target word. Standard deviations are in parentheses.

		Fixation time measures (in ms)			Landing position	Probability	
Case	Preview	FFD	GD	Go-past	in characters	Regressions out	Fixation
Sentence case	Correct	235 (4.43)	256 (5.54)	311 (9.56)	1.99 (0.0785)	0.103 (0.0122)	0.632 (0.0194)
	Dissimilar	226 (4.36)	243 (5.27)	339 (10.9)	1.91 (0.0799)	0.167 (0.015)	0.646 (0.0193)
	Infelicitous *the*	232 (4.05)	254 (5.24)	418 (12.3)	1.58 (0.062)	0.296 (0.0182)	0.734 (0.0176)
Upper case	Correct	224 (3.91)	253 (5.47)	307 (8.94)	1.78 (0.0691)	0.114 (0.0131)	0.747 (0.0179)
	Dissimilar	223 (3.86)	251 (5.35)	327 (9.8)	1.66 (0.0676)	0.133 (0.0142)	0.737 (0.0184)
	Infelicitous *the*	224 (3.66)	257 (5.18)	402 (11.8)	1.58 (0.0623)	0.265 (0.0179)	0.779 (0.0168)

Table 4.8: Fixed effects from the LMM analyses on first fixation duration, gaze duration, go-past time, and landing position on the post-target word word. Each column represents a model fitted to one of the dependent variables. Note that the contrasts for the preview factor are different from those used for the pre-target and the target word in order to make the results easier to interpret. CT = contrast, Rand eff = random effects. All $|t| \geq 1.96$ are marked in bold.

		FFD			Gaze duration			Go-past time			Landing Pos.		
		b	SE	*t*	*b*	SE	*t*	*b*	SE	*t*	*b*	SE	*t*
	(Intercept)	226.25	3.98	**56.80**	249.17	5.06	**49.21**	347.03	10.24	**33.90**	1.66	0.07	**22.70**
Preview	CT 1: Correct vs. Nonword/*the*	-2.49	2.21	-1.12	-2.21	3.07	-0.72	42.62	6.22	**6.85**	-0.13	0.04	**-3.09**
	CT 2: Nonword vs. *the*	1.79	2.13	0.84	4.43	2.56	1.73	39.64	6.10	**6.50**	-0.09	0.04	**-2.12**
Case	(lower/upper)	2.61	3.45	0.76	-2.59	4.20	-0.62	4.10	7.44	0.55	0.06	0.03	1.85
Interactions	Preview CT 1 x Case	-1.84	2.22	-0.83	-2.77	3.07	-0.90	2.32	6.22	0.37	-0.03	0.04	-0.72
	Preview CT 2 x Case	1.84	2.13	0.86	1.95	2.55	0.76	2.17	6.10	0.36	-0.05	0.04	-1.10
Rand eff.	Subject: (Intercept)	597.14	24.44	NA	800.16	28.29	NA	2214.72	47.06	NA	0.02	0.15	NA
	Subject: Preview CT 1	0.37	0.61	NA	45.50	6.75	NA	268.11	16.37	NA	0.02	0.15	NA
	Subject: Preview CT 2	61.99	7.87	NA	12.65	3.56	NA	765.63	27.67	NA	0.06	0.25	NA
	Item: (Intercept)	266.00	16.31	NA	561.38	23.69	NA	3318.88	57.61	NA	0.27	0.52	NA
	Item: Case (lower/upper)	23.56	4.85	NA	66.58	8.16	NA	253.44	15.92	NA	0.01	0.08	NA
	Residual	6124.18	78.26	NA	10876.80	104.29	NA	42852.57	207.01	NA	1.76	1.33	NA

Table 4.9: Fixed effects from the logistic generalized LMM analyses on regression and first-pass fixation probability on the post-target word. Each column represents a model fitted to one of the dependent variables. Note that the contrasts for the preview factor are different from those used for the pre-target and the target word in order to make the results easier to interpret. All $|z| \geq 1.96$ are marked in bold.

		p(Regression out)			*p*(Fixation)		
		b	SE	*z*	*b*	SE	*z*
	(Intercept)	-1.81	0.10	**-18.08**	1.18	0.16	**7.57**
Preview	Contrast 1: Correct vs. Nonword/'The'	0.56	0.08	**6.85**	0.14	0.06	**2.48**
	Contrast 2: Nonword vs. *the*	0.47	0.07	**6.26**	0.17	0.06	**2.94**
Case	(lower/upper)	0.05	0.08	0.65	-0.28	0.08	**-3.40**
Interactions	Preview Contrast 1 x Case	0.12	0.08	1.50	0.08	0.06	1.43
	Preview Contrast 2 x Case	-0.02	0.07	-0.23	0.06	0.06	1.07
Random effects	Subject: (Intercept)	0.27	0.52	NA	0.30	0.55	NA
	Subject: Preview Contrast 1	0.08	0.29	NA	0.00	0.02	NA
	Subject: Preview Contrast 2	0.17	0.41	NA	0.06	0.24	NA
	Item: (Intercept)	0.21	0.46	NA	1.11	1.05	NA
	Item: lower vs. upper case	0.03	0.17	NA	0.04	0.19	NA
	Residual	NA	NA	NA	NA	NA	NA

on landing positions, with fixations occurring further towards the left in the post-target words in the nonword and the infelicitous *the* conditions than in the correct control condition and fixations occurring further to the left in the infelicitous *the* condition than in the nonword condition. This is likely a consequence of skipping the target word (see post-hoc analysis below).

4.2.1 Post-hoc analyses

Table 4.10: Post hoc analysis: Fixation probabilities for felicitous occurrences of *the* (fixation probabilities for the three target word preview conditions copied from Table 4.4 for comparison)

Case	Preview	p(Fixation)
Normal	Correct	0.711 (0.0182)
	Nonword	0.753 (0.0174)
	Felicitous *the*	0.466 (0.0155)
	Infelicitous *the*	0.486 (0.02)
All upper case	Correct	0.75 (0.0178)
	Nonword	0.759 (0.0178)
	Felicitous *the*	0.552 (0.0161)
	Infelicitous *the*	0.598 (0.0199)

Felicitous occurrences of *the*

The results presented above come with potential limitation: as the preceding context determines whether an occurrence of the is felicitous or infelicitous, it is impossible to compare infelicitous and felicitous instances of *the* without changing the preceding context. However, most of our sentences contained at least one felicitous instance of *the*. Using a generalized LMM, we performed a post-hoc analysis of fixation probability on these felicitous occurrences of the, comparing the probability of fixating felicitous instances of *the* to the probability of fixating the target word in the control, nonword, and infelicitous *the* conditions. Table 4.10 shows the fixation probability on the felicitous instances of *the* compared to the fixation probabilities in the experimental conditions.

It is important to note that, in this analysis, we are no longer able to keep the preceding context constant between all conditions, as the felicitous instances of the can, by design, not occur in the target position. However, this post-hoc comparison between fixation rates for felicitous and infelicitous occurrences of *the* is vastly superior to an informal comparison between fixation rates for infelicitous instances of *the* in the present experiment and skipping rates observed for felicitous instances of the in previous studies. Importantly, our analysis found no significant difference between the probability of fixating infelicitous instances of *the* in the target position and felicitous instances of *the* elsewhere in the experimental sentences (b = 0.127 SE = 0.117, z = 1.08). Also, there was no significant interaction of this contrast with case. This means that, at least as far as skipping decisions are concerned, subjects did not treat the infelicitous instances of *the* differently from felicitous instances of *the* that naturally occurred in the experimental sentences.

Finally, we tested the possibility that processing of felicitous and infelicitous instances of *the* is influenced by their position within a sentence. We performed an analysis that included word position, preview, and the interaction between those two factors. The interaction between word position and the contrast between felicitous and non-felicitous instances of the was significant (b = -.193, SE = .071, z = -2.714). However, it is not clear how to interpret this interaction, which suggests that, at the beginning of a sentence, fixation rates for felicitous *the* were lower than those following infelicitous *the* previews (felicitous *the*: M = .461, SD = .149; infelicitous *the*: M = .593, SD = .0201), while there were lower fixation rates for infelicitous *the* previews compared to felicitous instances of *the* at the end of a sentence (felicitous *the*: M = .593, SD = .0193; infelicitous *the*: M = .495, SD = 0198). This pattern of data does not easily lend itself to interpretation and will have to be addressed by future research.

Costs and benefits of skipping the target word on the surrounding words

Since the preview manipulations had a strong effect on the probability of skipping the target word, the observed effects of the preview condition on eye-movement behavior on the pre- and post-target words may be confounded with the effects of skipping. For example, Kliegl and Engbert (2005) found that fixations prior to skipping of short or high-frequency words were shorter than fixations prior to normal forward saccades (skipping benefit), while fixations prior to skipping long or low-frequency words were longer than fixations prior to normal forward saccades (skipping cost).

Kliegl (2007) reported that skipping benefits seem to be associated with skipping function words and skipping costs seem to be associated with skipping content words. We investigated this by performing a set of post-hoc LMMs on pre- and post target fixation time measures, fixation and regression probabilities, and landing positions. These LMMs included the same fixed and random main effects as the analyses (but not the interaction terms between preview and capitalization) reported above, as well as a factor indicating whether the target word was skipped in that trial (coded as -1 for fixated and 1 for skipped) and its interactions with preview and capitalization. A detailed account of the results can be found in Appendix B. In the following, we just highlight the most important result.

We found an effect of preview on go-past time, which remained highly significant even when target skipping was included as a predictor (Contrast 1: b = 34.12, SE = 5.82, t = 5.86; Contrast 2: b = 23.91, SE = 5.4, t = 4.472). This result is critical, as it shows that the effects of the infelicitous *the* preview on post-target word fixation duration associated with the-preview are not simply a consequence of the higher skipping probability associated with this condition.

4.3 Discussion

In the present study, we used the gaze-contingent boundary paradigm to present readers with previews of three-letter words which suggested that the upcoming word was the definite article *the*. This manipulation had the potential of affecting ongoing processing during fixations on the pre-target word in two ways: First, it made the parafoveal word appear to be extremely easy to process, which should increase the probability of readers skipping it. Second, since the sentences were constructed so that the target position (a verb) could never be occupied by an article, it caused the parafoveal word to be syntactically illegal given the preceding sentence context. This syntactic anomaly should make readers less likely to skip the target word. Our experiment therefore pitted parafoveal information and information about the preceding sentence context against each other.

Our results are quite straightforward: when context information and parafoveal information are in conflict, whether a reader will skip a word is decided by the parafoveal information, not by the context—readers skipped the target much more often in the infelicitous *the* condition than in the correct preview condition in which the preview was compatible with the preceding context. While there was less skipping in the upper case condition, there was no interaction between the capitalization and preview conditions, suggesting that readers relied on letter identity (that is, the letter sequence *t–h–e*), not word shape, when making skipping decisions.

As expected, the infelicitous *the* preview had a disruptive effect—but this effect occurred quite late, most likely after the identification of the post-target word was completed, leading to increased go-past times on the post-target word and an increased probability of making a regression out of the post-target word. These effects were not just consequences of the increased target skipping rate, but appear to be genuine indicators of syntactic integration difficulty. Assuming that the article the was fully identified before the skipping decision, this difficulty could be the result of readers futilely attempting to fit the article the into an incompatible sentence context. If the infelicitous *the* preview was not fully identified but just to the extent that it can trigger a skipping eye movement, the disruption could be the result of skipping the target word inappropriately and, as a consequence, having to re-read earlier parts of the sentence.

From the above results, one might conclude that the sentence context has no influence at all on the decision to skip a word. A post-hoc analysis including felicitous instances of *the* confirms this, as there was no difference in fixation probability between an infelicitous target word the and felicitous occurrences of *the* in other parts of the experimental sentences. The low skipping rate for *the* in the present study is in contrast to other studies (Angele & Rayner, 2011; Drieghe, Pollatsek, et al., 2008), which report that felicitous articles were skipped around 80% of the time. Why subjects skipped felicitous instances of *the* less in the present experiment than in previous experiments is not entirely clear.

One possible explanation is that, in the sentence materials used in the present experiment, the article *the* was simply less predictable than in some previous studies. Another possibility is that, in the present experiment, subjects employed a more conservative strategy in their skipping decisions for *the*. Since every *the*-skipping in the infelicitous *the* condition resulted in considerable disruption on the subsequent word, subjects might simply decide to skip *the* less often in general. If subjects are capable of changing their response to the presence of a the preview, this suggests that the-skipping is not due to an automatic, rigid response to the letter string *t–h–e* but rather a relatively flexible reading strategy that can be modified if it leads to processing difficulties. Future research should be able to address the question of whether *the*-skipping is a reading strategy and whether it is affected by processing difficulty.

A related question is whether this effect is specific to *the* or whether other function words might also be inappropriately skipped. Greenberg and Saint-Aubin (2004) found that subjects missed more occurrences of the letter *r* in the conjunction or than in control words even when they were presented in texts whose word order had been randomly scrambled. One possible explanation for this effect is that subjects tend to skip function words like or even when they appear in a syntactically inappropriate position. On the other hand, evidence for the hypothesis that the has a special processing status comes from a study by Koriat and Greenberg (1993) on the missing-letter effect (MLE). Koriat and Greenberg had subjects search for the Hebrew letter *“He”* (*the*). They found that detection accuracy for *“He”* was not influenced by syntactic structure, that is, subjects were just as good at detecting the within a sequence such as *“and for the”* or *“in the”* as they were at detecting the when it appeared on its own. This was in contrast to all other function words (e.g. *on* or *from*) whose letters were missed more often when they occurred in the first position (as in “*on the*”) than when they were in the second position (as in *“and on”*).

On the basis of our results, we believe that, at least in English, the definite article *the* is likely to be processed differently from any other function word due to its extremely high frequency and low semantic content, although it is possible that the indefinite article a or an might be processed in a similar way. In other languages such as French or German, which possess several different definite and indefinite articles (e.g. *le*, *la*, and *les*; *un*, *une*, and *des* in French), this may well be different. However, additional research is needed to fully settle this question.

Our finding that readers do not seem to take syntactic information into account when planning an eye movement suggests that such information may not be available while readers make their skipping decision. This could be due to the time-course of linguistic processing: perhaps syntactic information just does not become available quickly enough to inform a skipping decision. However, word predictability has long been known to have an important effect on skipping probability (Balota, Pollatsek, & Rayner, 1985; Ehrlich & Rayner, 1981; Rayner & Well, 1996).

It is possible that readers process the parafoveal word until a likely lexical candidate (given the parafoveally available letters) emerges. Due to the extremely high frequency of the, it should almost always be a likely lexical candidate. On the other hand, a less frequent content word might still emerge as a likely candidate if it is primed by the context. Further studies should investigate whether syntactic information can influence the decision to skip words other than *the*. If our hypothesis is confirmed, it might inform future models of eye-movement behavior during reading such as E-Z Reader (Reichle et al., 1998, 2006) and SWIFT (Engbert et al., 2002, 2005). Finally, we found an effect of the preview manipulation on skipping the pre-target word. It remains to be seen whether this effect can be replicated. If this is the case, it will certainly inform models of eye-movements during reading as well.

Chapter 4, in full, is a reprint of the material as it appears in Processing *the* in the parafovea: Are articles skipped automatically? Angele and Rayner (2013b). The dissertation author was the primary investigator and author of this paper.

Chapter 5

General Discussion

In Chapter 1, I identified three open questions about parafoveal pre-processing as the basis for the experiments performed as part of this dissertation. These questions concerned the number of words that can be pre-processed in the parafovea, the number of morphemes that can be processed in the parafovea, and the extent to which word skipping requires parafoveal pre-processing of the word to be skipped. I will now address each of these questions in turn and highlight how the results from the experiments presented in Chapters 2 – 4 can help answer these questions.

5.1 How many words can we pre-process at a time?

Experiments 2.1 and 2.2 showed quite clearly that, at least in normal sentence reading, there was no evidence for parafoveal preprocessing of *n+2* even when conditions were specifically designed to encourage such processing. Combined with the results from Angele et al. (2008), this paints quite a clear picture of parafoveal pre-processing (at least in English): For all intents and purposes, parafoveal pre-processing seems to be limited to the first word to the right of fixation. At first, this conclusion seems to be at odds with what we know about the size of the perceptual span as determined by McConkie and Rayner (1975) and McConkie and Rayner (1976): If the perceptual span extends up to 14 characters to the right of fixation, circumstances under which the right half of word *n*, word *n+1*, and word *n+2* all fit into this span should not be all that rare during normal reading. However, this argument ignores the deleterious effect of unusual information (such as a mask consisting of Xs) in the parafovea for foveal processing (for a detailed discussion of this phenomenon, see Angele, Tran, & Rayner, 2013). In short, the presence of unusual parafoveal information may slow down reading through a mechanism that is different from normal word identification.

Another possible objection to the above conclusion is that perhaps evidence of *n+2* pre-processing can only be found under even more specific circumstances. If this is the case, however, the proportion of fixations during which *n+2* pre-processing occurs is likely to be so small that it does not have any measurable effect on normal reading. A more important issue is that my findings may only apply to reading English. Indeed, Risse and Kliegl (2011) reported finding *n+2* preview benefit effects in German reading (the study by Kliegl et al., 2007, had also been performed in German). If these differences turn out to be reliable, then that raises the question of why word identification in English seems to take place serially in English but in parallel in German. In this context it is worthwhile to note that evidence for other effects which have proven elusive in English, such as semantic pre-processing, have been found in German (Hohenstein et al., 2010). Future research will be needed to investigate these language differences in more detail.

5.2 How many morphemes can we pre-process at a time?

Experiments 3.1 and 3.2 tested whether subjects were able to obtain parafoveal preview benefit for a target compound word (*cowboy*) even if the order of the constituent morphemes was reversed in the preview (*boycow*). The results suggested that readers were able to extract some useful parafoveal information even from a reverse preview (compared to a dissimilar control preview). This might suggest that compound words are processed as a whole at an early stage during processing (as suggested by Drieghe et al., 2010). If this is the case, then my results also suggest that letter position coding during parafoveal pre-processing is not as strict as during foveal processing. Alternatively, the results of the experiments may be taken to suggest that readers routinely process multiple morphemes at a time. A third option might place the parafoveal preview benefit effect not at the orthographic or morphological, but at the phonological level. Future experiments will have to clarify this issue. In summary, however, the answer to the above question seems to be “at least two, but the processing does not necessarily take place at the morphological level”.

5.3 To what extent does a word have to be pre-processed in order to make the decision to skip it?

Experiment 4 demonstrated that articles seem to be pre-processed in a quite shallow manner when it comes to deciding on whether to skip them or not: clearly, readers are able to recognize the letters *t–h–e* and determine that this is likely to be a skippable word. However, they do not process the articles to a point where they would attempt (and fail) to integrate them with the infelicitous context. This processing either takes place later, during the subsequent fixations (causing an integration failure, longer fixations, and a higher probability of regressions out of the post-target word). An alternative possibility is that subjects simply don’t properly identify the parafoveal word, but instead assume that it is easy enough to fill in once the subsequent sentence context is known. Of course, in the experimental condition, this strategy fails. If this is the mechanism underlying skipping, it could be considered an example of a risky reading strategy. This assumption does not explain, however, why skipping is influenced by word predictablity (see Brysbaert, Drieghe, & Vitu, 2005), which should not be available until the integration stage. A possible way to investigate this issue would be to manipulate the predictability of the target word directly. In summary, it does not seem that the parafoveal word is pre-processed beyond the orthographic level.

5.4 Consequences of the results for computational models of eye movements

Much research has been undertaken in recent years with the goal to find evidence for or against a particular model of eye movements in reading. As a consequence, there is a general tendency to interpret results in terms of how well they fit with current computational models of eye movements. In the following, I will provide a brief outline of each model before discussing each result in turn.

E-Z Reader

The E-Z Reader Model (Reichle et al., 1998, 2006; Reichle, Warren, & McConnell, 2009) assumes that readers identify words one at a time. Word identification requires both shifting attention to and (usually) fixating the word in question (serial attention shift, SAS). Since eye movements take some time to prepare, planning for the next saccade is initiated before processing of the current word is completely finished. However, usually the second part of word identification completes quite quickly, leaving time for an attention shift to (and parafoveal pre-processing of) the upcoming word. A recent extended version of E-Z Reader (Reichle, Warren, & McConnell, 2009) also allows for integration failures to occur, which stops current processing and leads to regressions in an attempt to recover from the failure.

SWIFT

In contrast to E-Z Reader, the SWIFT model (Engbert et al., 2002, 2005) assumes that readers process every word within the perceptual span at the same time, with the speed of processing determined by visual acuity (guidance by attentional gradient, GAG). Eye movements are not triggered by the completion of a processing stage, but by a random saccade timer which can be delayed to ensure that readers don't move their eyes away from difficult foveal words before identifying them. The saccade goal is probabilistically determined so that readers tend to move their eyes to those words that are difficult to process and those that have already received some parafoveal pre-processing.

Compatibility of the current results with the models

Of the three questions discussed in this chapter, only the first one, that is, the question of how many parafoveal words can be pre-processed at the same time, speaks directly to the models. While the E-Z Reader model clearly predicts that readers should not pre-process word *n+2* unless word *n+1* is skipped (or was attempted to be skipped), SWIFT would, at least in principle, predict that both *n+1* and *n+2* are processed at the same time. However, the degree to which *n+2* is actually pre-processed may not be too high—a SWIFT simulation of experiments like the ones presented in Chapter 2 may shed some light on what the actual predicted degree of pre-processing would be. In fact, SWIFT has a parameter that determines the degree of pre-processing, with the extremes being a strictly serial or a massively parafoveal mode of word identification (Engbert et al., 2005). In summary, therefore, one can say that the experiments presented in Chapter 2 had the potential to falsify the predictions of E-Z Reader, but did not, while constraining the extent of parafoveal processing that can be realistically assumed for SWIFT.

E-Z Reader and SWIFT do not differ in their predictions for the experiments presented in Chapter 3: both models would predict that a compound word is processed as a whole, with the processing speed depending on the word frequency of the whole compound word. My results and those of Drieghe et al. (2010) together could be used to inform modifications of the models, with compound words initially being (parafoveally) pre-processed as one word. In a second step, each morpheme would be processed as an individual unit, with the morpheme meanings being integrated during semantic processing.

Just like Experiments 3.1 and 3.2, Experiment 4 goes beyond the level of processing addressed by E-Z Reader and SWIFT. Both models predict that a simple word such as *the* should be skipped often. Furthermore, both models take predictability into account when making the skipping decision, which should lower the probability of skipping an infelicitous instance of *the*. Despite this, neither model can predict the strong disruption effect that was observed on the post-target word[1] In short, both E-Z Reader and SWIFT can predict the skipping of an infelicitous instance of *the*, but they cannot predict the negative consequences that skipping it has later on.

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[1] If the post-target word is assumed to have a high integration time, E-Z Reader 10 (Reichle, Warren, & McConnell, 2009) will likely predict an integration failure which will result in longer fixation times on and a higher rate of regressions out of the post-target word. Nevertheless, neither E-Z Reader nor SWIFT can independently predict where the integration failure should happen, since they do not include processing on the syntactic level.

5.5 Conclusion

In this thesis, I have reported a number of gaze-contingent boundary experiments, each designed to investigate a specific aspect of parafoveal pre-processing during reading. Overall, the results of these experiments support the idea that parafoveal pre-processing is generally quite shallow (taking place mostly on the orthographic and phonological level), not informed by higher level processing such as syntactic parsing or semantic integration, and restricted to processing of one word at a time. This fits in with the idea of parafoveal processing as *pre*-processing—an early, low-level type of processing that gives the language processing system an advantage later on, when the word in question is fixated. A surprising result from these experiments is that even a high-frequency word like the seems only to be processed to this shallow degree, raising questions about what exactly is taken as evidence by the processing system that a word can be skipped.

Appendix A

Supplemental material for Chapter 3

A.1 Experimental stimuli

Sentences 1 – 46 were used in Experiment 2.1; Sentences 1 – 152 were used in Experiment 2.2. The target compound word is marked by *asterisks*.

1. Her friends say she was a *tomboy* in her childhood.
2. The eagerly expected *tryout* was scheduled for the following week.
3. After the successful mission the *airmen* were hailed as heroes.
4. The criminal's plan to *kidnap* the mayor was foiled.
5. Native to America, the *bobcat* hunts rodents and deer.
6. Years ago, going to the *carhop* was a popular date.
7. This year, the *cutoff* date for admissions is very early.
8. After calling his teacher a *dimwit* the student was suspended.
9. The soldiers were forced to defend their *dugout* until nightfall.
10. The candidate clearly needed a new *outfit* for the debate.
11. My aunt loves to drink *eggnog* at Christmastime.

12. In humans, an *eyelid* protects the eye from small objects.

13. Maybe the *heyday* of the automobile will soon be over.

14. The country is still a *hotbed* of civil unrest.

15. The argument was *humbug* in the eyes of the jury.

16. It is hard for a *layman* to understand these laws.

17. The company’s massive *layoff* threatens the economy of the county.

18. The newspaper’s new *layout* received rave reviews from readers.

19. The crisis left the government little *leeway* for reform.

20. The legislation ran into a *logjam* when three senators died.

21. The recent profits cannot *offset* the first quarter’s losses.

22. The senator’s public statement caused an *outcry* among the voters.

23. Once again, the notorious *outlaw* had robbed the noblemen.

24. His room resembled a *pigsty* most of the time.

25. The criminals are just a *ragtag* group of thugs.

26. Every night, the *seaman* sang old shanties.

27. In the morning, the *sunlit* forest clearing looked beautiful.

28. The beautiful island *sunset* has been painted many times.

29. Michael had to *tiptoe* around the sleeping dog.

30. Many commuters take the *subway* every day.

31. John stood in line at the *hotdog* stand nearby.

32. The girl walked through a *cobweb* in the attic.

33. Kenny liked the ice cream *sundae* at the local diner.

34. A rare find, the antique *teapot* is worth a lot.

35. To enter the code, use the *keypad* at the door.

36. Many politicians have denounced *payday* loans as dangerous to consumers.

37. The smell of *catnip* is very attractive to cats.

38. In British cuisine the *potpie* is considered a delicacy.

39. John went out for *tenpin* bowling last night.

40. John could not find *anyone* who would help him.

41. In crashes an *airbag* can prevent the driver from injury.

42. Jack loved the *jigsaw* puzzle he got for his birthday.

43. Everyone scattered as the infamous *cowboy* drew his gun.

44. The beef *cutlet* is one of the restaurant’s signature dishes.

45. John cannot eat a single *peanut* without risking a rash.

46. The woman knew her lovely *suntan* would impress her friends.

47. They knew that the *mainland* could not be far away.

48. It was the computer *software* the teenager resented paying for.

49. The designer shop sold expensive *knitwear* that was very popular.

50. The books were quite *highbrow* and difficult to understand.

51. The old salesman’s battered *passport* had been stamped many times.

52. Everyone joined in a tremendous *singsong* around the piano.

53. The police knew the dangerous *madman* could be violent.

54. All the players enjoyed the *softball* game in the park.

55. They knew the electrical *output* would meet the requirements.

56. With great care he picked up the *blowpipe* and aimed.

57. Very quietly they watched the elusive *wildlife* using powerful binoculars.

58. The man was an important *bigwig* in his field.

59. Very quickly the *mainsail* unfurled and thrust the yacht forward.

60. He quickly used the plastic *ramrod* to unblock the drains.

61. Far below, the bright *runway* was visible to the pilot.

62. The journalists worried about the impending *deadline* for their stories.

63. John often used the specialized *darkroom* to develop his photos.

64. She knew that the informative *cookbook* would contain the recipe.

65. Very carefully he guided the lengthy *sailboat* into the harbor.

66. Everyone knew the frustrating *deadlock* would lead to violence.

67. The woman read the *headline* with a sense of dread.

68. The tourists enjoyed the beautiful *highland* scenery during the visit.

69. The girl wore her favorite *swimsuit* at the pool.

70. The woman had made a beautiful *hotpot* for the guests.

71. In the frantic *workshop* the engineer was very busy.

72. The mother particularly liked the delightful *snapshot* of her daughter.

73. The youngster enjoyed the crunchy *flapjack* his mother had made.

74. The mountains provided a picturesque *backdrop* for the film scene.

75. After several days the impressive *borehole* was sufficiently deep.

76. The man bought tools from the *hardware* store in town.

77. The woman hated clearing the *bindweed* from her rose garden.

78. The man struggled with the massive *dumbbell* in the gym.

79. The student misremembered his *password* and could not log on.

80. The Christmas rush meant increased *overtime* payments to the workers.

81. From the plane they saw the *icecap* many meters below.

82. The man knew his powerful *backhand* was his best shot.

83. Tensions in the city caused a *backlash* against the police.

84. The children enjoyed the *playtime* because the sun was shining.

85. The new car impressed everyone in the *showroom* this weekend.

86. The child put the battered *workbook* into his schoolbag.

87. After dark, the *tripwire* caught a prisoner trying to escape.

88. The teenager thought that the romantic *keepsake* was wonderful.

89. The student needed a new *backpack* for the school year.

90. The loud *backfire* from the truck sounded like a gunshot.

91. After he painted the front, the house’s *backside* was next.

92. The professional tennis player had strong *backspin* on his serves.

93. The banquet dinner in the *ballroom* was a fantastic success.

94. Working in a *barnyard* did not excuse his poor etiquette.

95. Despite bursts of action, *baseball* is generally a slow sport.

96. In the remodel budget, the *bathroom* received the smallest amount.

97. Watching the train, she noticed every *boxcar* was heavily graffitied.

98. Her voice resembled that of a *bullfrog* during her illness.

99. They fried the excellent *crawfish* they had caught.

100. After refusing to pay alimony, the *deadbeat* dad was sued.

101. She found the perfect *doorknob* for the new door.

102. The news predicted *overcast* skies for the week.

103. Bad grades caused the *downfall* of the student's academic career.

104. She was much better at *downhill* skiing than her brother.

105. The storm brought days of *downpour* to the dry city.

106. Looking for parking *downtown* is never easy.

107. The steep *downward* slope lead to the ocean.

108. The hotel room was *downwind* of the smelly garbage cans.

109. His lack of ambition was a *drawback* to his personality.

110. The girl cleaned out her *earwax* on a daily basis.

111. Startled, the boy realized an *earwig* was tickling him.

112. The compass directed the group *eastward* into the dense forest.

113. The boy said his last *farewell* to his girlfriend.

114. She got poor *feedback* on her rough draft.

115. The burning building was like a *fireball* against the sky.

116. The couple first kissed by the *fireside* at summer camp.

117. His chores included chopping *firewood* for the long winter ahead.

118. Living in a *fishbowl* was too cramped for the fish.

119. Jack took the *fishhook* out of the salmon’s mouth.

120. The young kids used the *flagpole* to play tetherball.

121. The company’s *flagship* store was located in London.

122. The girl always used a *flatiron* to straighten her curls.

123. The bride registered new *flatware* as her most desired gift.

124. To the boy, *football* was the most important sport.

125. The climbing rock didn’t have a *foothold* within reach.

126. The family added a *footpath* in the garden.

127. The boy couldn’t reach the *footrest* on the seat.

128. The house was so quiet a *footstep* sounded like thunder.

129. The dance required very difficult *footwork* for the woman.

130. She relied on the *forecast* to know how to dress.

131. She considered adding the *foreword* to the reading assignments.

132. The girls went as a *foursome* to every dance.

133. To the boy, turning *fourteen* wasn’t very exciting.

134. The art teacher was impressed with the *freehand* sketch.

135. After running sprints the *fullback* realized he needed more practice.

136. The boy found a *glowworm* in the dirt.

137. The parents decided a *goldfish* would be a great pet.

138. At the shooting range the *gunman* was well known.

139. The man’s receding *hairline* made him very self-conscious.

140. The quarterback knew his *halfback* would be open.

141. Because the *handbook* provided no answers he gave up.

142. She knew that *handmade* gifts make the most sincere presents.

143. She would go the farm and *handpick* the produce herself.

144. He finally skated the whole *handrail* without falling.

145. He considered himself the most *handsome* guy at the party.

146. None of the many *hangover* remedies seem to really work.

147. She used a *headband* to keep her bangs under control.

148. She wore the *heirloom* necklace with great caution.

149. She wanted to live on the *hillside* overlooking the beach.

150. The girl was known to *overcook* everything she made.

151. The defendant wished the judge would *overturn* the previous ruling.

152. He never really understood how *anyone* could survive without literature.

Appendix B

Supplemental material for Chapter 4

B.1 Sentences and questions used in Experiment 4.

B.1.1 Experimental stimuli

Target words are in *italics*.

1. The council voted to immediately *ban* cell phones in public buildings.
2. Everyone told him that he should *bow* to the emperor.
3. The members of the club will *box* every Friday to keep in shape.
4. After finishing the meal you must *bus* your table.
5. At the end of the book, all the villains will *die* when their hideout burns down.
6. The exhausted slaves must *fan* their emperor all day long.
7. If the pants don't fit we can *hem* them easily.
8. My brothers often *hum* a melody while they are working.
9. If you park here, they will *tow* your car immediately.
10. The honor student was sure she would *ace* all the tests.
11. The navy could not *man* every ship since they lacked sailors.

12. Since the grass is getting very tall, we must *mow* it next week.

13. Unfortunately, we still *owe* them a lot of money.

14. Before her illness my aunt *ran* five marathons a year.

15. They soon would *rue* their unfortunate decision.

16. On weekdays, the fast trains *run* every half hour.

17. If the button falls off we can *sew* it on again.

18. She retired after having finally *won* every prize in her field.

19. His enemies tried to *tag* him as a socialist.

20. This spring we must *lop* off all the dead branches from our trees.

21. Because the lights in their bar are bright, the owners always *dim* them at night.

22. Since it was very hot, he did not *don* his hat when he left.

23. You should not *fix* it unless it is broken.

24. The workers will *hoe* all day to prepare the field.

25. One should never *lie* about important matters.

26. Some people do not *tan* easily in the sun.

27. The crowd wanted to *tar* and feather the criminals.

28. Many people think the federal and state governments already *tax* them too much.

29. My nephew is just five years old, but he can already *tie* his shoelaces on his own.

30. When he was in town, the actor wanted to *eat* breakfast at his favorite restaurant.

31. If you are bored with hiking, you can *ski* around the area as well.

32. In order to hit the target you must *aim* very carefully.

33. Due to the growing unrest many people think they should *arm* themselves nowadays.
34. If you aren’t careful, crooks will *con* you out of your savings.
35. Even experts can *err* on some issues.
36. Many fear the new high-rise buildings would *mar* our city’s downtown.
37. In order to make the cake just *mix* all the ingredients on the list.
38. The impatient cows will *moo* when they want to be milked.
39. If they don’t open the door, we will *ram* it with a sledgehammer.
40. At the start line, the drivers always *rev* their engines.
41. If the weather permits it, we can *row* our boat out onto the lake.
42. The witness described what she *saw* at the crime scene.
43. If you trespass on their property they will *sic* their dogs on you.
44. When catholic people *sin* they have to confess.
45. Every spring farmers *sow* their crops in the fields.
46. He said he would *sue* his employer after he was laid off.
47. In order to get the total we must *sum* up all the numbers.
48. If I had money, I would use it to *buy* a house.
49. The two parents will *vie* with each other in their attempts to gain the childrens’ love.
50. In some religions, priests must *vow* to stay chaste.
51. This weekend we will finally *wax* our new car.
52. If the athlete wants a scholarship, she must *win* her next competition.

53. If you don’t succeed, you should *try* using another method.
54. My father loves to *fry* all his food.
55. Before you can put it away, you must *dry* your wet laundry.
56. If you are happy with the service, you should *tip* the waiter generously.
57. All dogs will *wag* their tails when they are happy.
58. At nightfall we will *peg* our tents in a sheltered location.
59. The wrestler must *pin* his opponent down in order to win.
60. They did not know housing prices would *top* out very soon.
61. The paper bag burst with a loud *pop* that startled everyone.[1]
62. If you need something, you should *tap* gently on the door.
63. This month our sales will *hit* a new high due to the advertising campaign.

B.1.2 Questions

Answer alternatives in parentheses. Each question corresponds to the sentence with the same number. The first alternative was shown on the left of the screen, the second alternative was shown on the right of the screen. Correct answers are marked by asterisks.

1. Did they allow cell phones? (yes, no*)
2. Who was he supposed to bow to? (emperor*, king)
3. Do the club members exercise on Friday? (no, yes*)
4. Will the waiter clean your table? (no*, yes)

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[1] Sentence was included due to experimenter error despite the target word being a noun instead of a verb. Excluding this sentence from the analyses did not result in a different pattern of effects.

5. Did the villains survive the fire? (yes, no*)
6. Did the emperor have someone fanning him throughout the day? (yes*, no)
7. Is it easy to fix the pants if they don't fit? (no, yes*)
8. Do my brothers always work in silence? (no*, yes)
9. Will they tow your car if you park here? (no, yes*)
10. Was the student nervous about the tests? (no*, yes)
11. Was the navy understaffed? (yes*, no)
12. Is the grass short? (yes, no*)
13. Do they owe us a lot of money? - (no*, yes)
14. Did my aunt exercise a lot before her sickness? (no, yes*)
15. Were they going to regret their decision? (yes*, no)
16. Does the train only run twice on weekdays? (yes, no*)
17. Can we sew the button back on? (yes*, no)
18. Is she going to delay retirement further and keep working? (yes, no*)
19. Does he have enemies? (no, yes*)
20. Will we need to prune the trees this spring? (yes, no*)

B.2 Supplemental analyses on the costs and benefits of skipping the target word

Table B1 shows mean fixation times, landing positions, and regression as well as fixation probabilities for the pre-target (Table B.1) and the post-target words (B.2) conditional on skipping the target word. As there was no evidence of an interaction between target skipping and capitalization, the means in Tables B.1 and B.2 are collapsed over the case condition. For the sake of brevity, we will only report those instances in which the pattern of effects observed in these post-hoc analyses diverged from that found in the analyses reported above.

With regard to fixation probability, skipping the target word was associated with a much higher probability of fixating the pre-target (b = 1.21, SE = .07, z = 17.26) and the post-target word (b = 1.29, SE = .07, z = 18.69). Since readers rarely skip two words at once, this is not unexpected. On the pre-target word, we also observed a skipping cost on FFDs (b = 4.09, SE = 1.38, t = -2.97), which is opposite to what Kliegl and Engbert (2005) found for for single-fixation durations before short/high frequency words (see also Rayner, Ashby, Pollatsek, & Reichle, 2004; Rayner et al., 1986). This effect did not reach significance in any of the other fixation time measures. Additionally, the inclusion of target skipping as a predictor in the model caused the contrast measuring the difference between the nonword preview condition and the mean of the correct and the infelicitous the condition to reach significance with regard to pre-target fixation probability (b = -.33, SE = .06, z = -5.22), which can be interpreted as another orthographic parafoveal-on-foveal effect. There was a significant relationship between target skipping and landing position on the pre-target word, with fixations that preceded target skips seeming to be located further towards the beginning of the pre-target word (b = .41, SE = .03, t = 13.88). However, this could simply be due to variations in the length of the pre-target word, as subjects tend to fixate a position several characters into a longer pre-target word and subjects are also more likely to initiate a target skip from a short pre-target word than from a long pre-target word. Interestingly, after including target skipping in the model, the main effect of preview on landing position became significant. Specifically, the nonword preview condition was associated with landing positions further into the pre-target word compared to identical and infelicitous *the*.

Additionally, the infelicitous the condition was associated with landing positions further towards the beginning of the target word. On the post-target word, there was a significant main effect of skipping the target word on GD, go-past time, landing position, regression probability, and fixation probability, with GDs being slightly lower when the target word had been skipped (b = 6.78, SE = 2.32, t = 2.92). A significant interaction between capitalization and target word showed that presentation of the sentence in upper case was only related to longer GDs when the target word had been skipped (*b* = -5.27, SE = 2.26, *t* = -2.33). In contrast, while there was no main effect of either capitalization or target skipping on FFD, the significant interaction indicated that lower case presentation was associated with longer FFDs, but only when the target had not been skipped. There was no such interaction for go-past times, which were substantially higher in that case (*b* = 74.75, SE = 4.41, *t* = 16.97). This effect was in addition to the effect of preview on go-past time, which remained highly significant even when target skipping was included as a predictor (Contrast 1: b = 34.12, SE = 5.82, t = 5.86; Contrast 2: *b* = 23.91, SE = 5.4, *t* = 4.42). The same was true for the increase in regression probability due to target skipping (*b* = 1.18, SE = .06, *t* = 20.75). A significant interaction term between capitalization and target skipping showed that capitalization only had an on regression probability when the target word had been skipped, with skips in the normal condition being more likely to be followed by regressions than skips in the upper case condition (*b* = .14, SE = .06, *z* = 2.45).

The effect of preview on the probability of fixating the target word disappeared once target skipping was taken into account. Surprisingly, skipping the target word was associated with a lower fixation probability on the post-target word (*b* = 1.29, SE = .07, *z* = 18.69). It is not quite clear what caused this, although it is possible that, given that both the target and the post-target word were frequently only three letters long, saccades which were intended to skip the target word only overshot and skipped the post-target word as well. Finally, target skipping also had an effect on landing positions on the post-target word, with subjects fixating further towards the beginning of the post-target word when the target word had been skipped (*b* = .64, SE = .03, *t* = -23.85). In summary, target skipping was associated with a variety of changes in eye-movement behavior both on the pre- and the post-target word. Despite this, effects due to target skipping cannot explain the principal effects of the preview manipulation, especially the processing disruption effect on the post-target word.

Table B.1: Condition means on the pre-target word conditional on skipping the target word (collapsed over capitalization conditions).

		Fixation time measures (in ms)			Landing position	Probability	
Target skipped	Preview	FFD	GD	Go-past	Characters	Fixation	Regressions out
No	Correct	202 (3.1)	228 (5.19)	255 (7.92)	2.58 (0.0922)	0.939 (0.0133)	0.055 (0.0126)
	Dissimilar	209 (4.19)	242 (7.18)	266 (9.43)	2.72 (0.101)	0.907 (0.017)	0.055 (0.0134)
	Infelicitous *the*	208 (2.85)	227 (3.91)	251 (6.49)	2.31 (0.0694)	0.892 (0.013)	0.0494 (0.00911)
Yes	Correct	217 (2.64)	232 (3.45)	256 (5.06)	1.74 (0.0574)	0.701 (0.0154)	0.0509 (0.0074)
	Dissimilar	221 (2.63)	240 (3.53)	283 (6.16)	1.73 (0.0551)	0.739 (0.0146)	0.0898 (0.00952)
	Infelicitous *the*	223 (4.02)	239 (5.09)	283 (9.15)	1.65 (0.0699)	0.605 (0.0189)	0.0584 (0.00908)

Table B.2: Condition means on the post-target word conditional on skipping the target word (collapsed over capitalization conditions).

		Fixation time measures (in ms)			Landing position	Probability	
Target skipped	Preview	FFD	GD	Go-past	Characters	Fixation	Regressions out
No	Correct	226 (3.99)	258 (6.11)	351 (12.1)	0.965 (0.0685)	0.881 (0.018)	0.229 (0.0233)
	Dissimilar	220 (4.98)	243 (6.85)	429 (15.4)	0.919 (0.0727)	0.931 (0.0149)	0.44 (0.0291)
	Infelicitous *the*	226 (3.28)	255 (4.76)	481 (12.2)	1.2 (0.0568)	0.882 (0.0136)	0.485 (0.021)
Yes	Correct	231 (3.97)	253 (5)	286 (7.49)	2.36 (0.0616)	0.617 (0.0164)	0.0633 (0.0082)
	Dissimilar	227 (3.56)	249 (4.49)	286 (7.1)	2.2 (0.0618)	0.612 (0.0162)	0.0576 (0.00777)
	Infelicitous *the*	230 (4.5)	256 (5.72)	330 (10.6)	2.02 (0.0621)	0.65 (0.0185)	0.108 (0.012)

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