Eye Movements and Processing of Semantic Information in the Parafovea During Reading

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Doctoral Thesis

Submitted to the Faculty of Human Sciences at the University of Potsdam (Department of Cognitive Psychology) in partial fulfillment of the requirements for the degree of Doctor of Philosophy

Submission: July 1, 2013 Defense: December 4, 2013

Reviewers: Prof. Dr. Reinhold Kliegl, Prof. Dr. Jukka Hyönä

ABSTRACT

When we read a text, we obtain information at different levels of representation from abstract symbols. A reader's ultimate aim is the extraction of the meaning of the words and the text. The reserach of eye movements in reading covers a broad range of psychological systems, ranging from low-level perceptual and motor processes to high-level cognition. Reading of skilled readers proceeds highly automatic, but is a complex phenomenon of interacting subprocesses at the same time. The study of eye movements during reading offers the possibility to investigate cognition via behavioral measures during the excercise of an everyday task.

The process of reading is not limited to the directly fixated (or *foveal*) word but also extends to surrounding (or *parafoveal*) words, particularly the word to the right of the gaze position. This process may be unconscious, but parafoveal information is necessary for efficient reading. There is an ongoing debate on whether processing of the upcoming word encompasses word meaning (or *semantics*) or only superficial features. To increase the knowledge about how the meaning of one word helps processing another word, seven experiments were conducted. In these studies, words were exachanged during reading. The degree of relatedness between the word to the right of the currently fixated one and the word subsequently fixated was experimentally manipulated. Furthermore, the time course of the parafoveal extraction of meaning was investigated with two different approaches, an experimental one and a statistical one.

As a major finding, fixation times were consistently lower if a semantically related word was presented compared to the presence of an unrelated word. Introducing an experimental technique that allows controlling the duration for which words are available, the time course of processing and integrating meaning was evaluated. Results indicated both facilitation and inhibition due to relatedness between the meanings of words. In a more natural reading situation, the effectiveness of the processing of parafoveal words was sometimes time-dependent and substantially increased with shorter distances between the gaze position and the word. Findings are discussed with respect to theories of eye-movement control. In summary, the results are more compatible with models of distributed word processing. The discussions moreover extend to language differences and technical issues of reading research.

ZUSAMMENFASSUNG

Wenn wir einen Text lesen, erfassen wir Informationen auf verschiedenen Repräsentationsebenen anhand abstrakter Symbole. Das oberste Ziel des Lesers ist das Erfassen der Bedeutung der Worte und des Textes. Die Erforschung der Blickbewegungen beim Lesen umfasst verschiedene Verarbeitungsebenen, die von Warhnehmung über motorische Prozesse bis hin zu Kognition auf übergeordneter Ebene reichen. Das Lesen geübter Leser verläuft zum großen Teil automatisch, ist aber gleichzeitig ein komplexes Phänomen interagierender Teilprozesse. Die Untersuchung von Blickbewegungen beim Lesen eröffnet die Möglichkeit, kognitive Prozesse bei der Ausübung einer alltäglichen Aufgabe anhand von Verhaltensmaßen zu untersuchen.

Der Leseprozess ist nicht beschränkt auf das direkt fixierte (oder *foveale*) Wort, sondern umfasst auch umgebende (oder *parafoveale*) Wörter, insbesondere das Wort rechts der Blickposition. Obgleich dies nicht notwendigerweise bewusst geschieht, ist die parafoveale Information dennoch wichtig für effizientes Lesen. Es wird darüber diskutiert, ob die Verarbeitung des nächsten Wortes die Wortbedeutung (*Semantik*) oder nur oberflächliche Eigenschaften umfasst. Um ein besseres Verständnis zu erhalten, ob die Bedeutung eines Wortes bei der Verarbeitung eines anderen Wortes hilft, wurden sieben Experimente durchgeführt. In diesen Studien wurde ein Wort im Satz während des Lesens ausgetauscht. Der inhaltliche Zusammenhang zwischen einer parafoveal präsentierten Vorschau und dem anschließend fixierten Zielwort wurde experimentell manipuliert. Außerdem wurde der zeitliche Verlauf der Bedeutungserfassung aus parafovealen Wörtern mit zwei Ansätzen untersucht, einem experimentellen und einem statistischen.

Als primärer Befund zeigte sich, dass die Fixationszeiten durchweg kürzer waren, wenn ein semantisch verwandtes Wort als Vorschau präsentiert wurde, verglichen mit einem Wort ohne Verwandtschaft. Mit der in dieser Arbeit verwendeten experimentellen Vorgehensweise konnte zudem der zeitliche Verlauf des Verarbeitens und Integrierens von Bedeutung ermittelt wurde. Dabei ergaben sich kürzere Fixationszeiten auf dem Zielwort bei ähnlichen Wortbedeutungen und längere Fixationszeiten bei unterschiedlichen Wortbedeutungen. Die Ergebnisse zeigten sowohl leichtere als auch schwerere Verarbeitung in Folge der Ähnlichkeit von Wortbedeutungen. In einer natürlicheren Lesesituation war die Wirksamkeit der Verarbeitung nachfolgender Wörter teilweise abhängig von der Dauer der Vorschau, und sie war deutlich größer bei kürzerer räumlicher Distanz zwischen der Blickposition und der Vorschau. Die Befunde werden mit Blick auf Theorien der Blickbewegunskontrolle diskutiert. Die Ergebnisse sind stärker mit Modellen verteilter Wortverarbeitung vereinbar. Die Diskussion erstreckt sich außerdem auf Sprachunterschiede und technische Aspekte der Leseforschung.

CONTENTS

1 INTRODUCTION

Reading is an everyday task and, at the same time, a complex phenomenon involving the interaction of perceptual, cognitive, and motor processes. The ultimate goal is the extraction of meaning from a string of abstract symbols. During reading the gaze moves to obtain information of the text. Both the "where" and "when" of eye movements are functions of a multitude of word features and contextual conditions.

Processing is not limited to the words in the center of vision, but rather comprises surrounding words. In this thesis, I investigate the extraction of meaning from upcoming words and aim at contributing to our understanding of the time course of reading.

1.1 BASIC CHARACTERISTICS OF THE EYES AND THEIR MOVEMENTS

The retina is a light-sensitive area in the inner surface of the eye, and it consists of about 120 millions of photoreceptor cells. Due to the heterogeneous density of these cells, the visual field is divided into three areas: The *fovea centralis* is located in the center of the retina and comprises the central 2° of the visual angle. The fovea is responsible for sharp central vision and thereby allows processing detailed visual input. The *parafovea* extends to the central 10° of visual angle. The area of the visual field beyond fovea and parafovea is the *periphery* and delivers visual information of very low resolution. Visual acuity declines monotonically from the center of the fovea to the periphery. These acuity constraints require moving the eyes to obtain visual information of interesting areas (e.g., words) with high resolution in foveal vision (cf. Findlay & Gilchrist, 2003).

During reading, the eyes do not smoothly move across the text but perform short and very fast ballistic movements. These fast movements, which are known as *saccades*, serve to foveate interesting regions in the text. Typical saccades in reading last about 30 ms and cover a distance between seven and nine letters. Interestingly, the number of letters traversed is a more appropriate metric than degrees of visual angle, since the distances measured in the number of letters are virtually unaffected by the distance between the reader and the text (Morrison & Rayner, 1981; O'Regan, 1983; O'Regan, Lévy-Schoen, & Jacobs, 1983). This invariance may be related to the spaces between words in alphabetic languages: In Chinese, an unspaced writing system, saccade size decreases with increased font size (Shu, Zhou, Yan, & Kliegl, 2011). Between saccades the eyes remain relatively still in *fixations*. During saccades, only very limited visual information can be extracted. This phenomenon is known as *saccadic suppression* (Matin, 1974). Therefore, our visual perception is similar to a slide show of pictures extracted during fixations. Fixation durations typically last between 60 and 500 ms. The average fixation duration in reading is about 250 ms. Both saccade and fixation durations are subject to strong variation, mainly associated with the reader and the complexity of the text (cf. Liversedge & Findlay, 2000; Rayner, 1998, 2009).

Most saccades are executed in the direction of the writing system. In, for example, German and English texts, the majority of saccades are directed rightwards. About 10% to 15% of all saccades move backwards in the text (cf. Rayner, 1998, 2009). These movements are called *regressions*. Some short regressive saccades are due to oculomotor error, such that the preceding saccade was too long and therefore a shorter saccade in the opposite direction is employed to dissolve the mismatch between intended and actual fixation position (O'Regan, 1990; Vitu, McConkie, & Zola, 1998). These corrective movements are more likely after long forward saccades. Furthermore, comprehension problems can cause regressions and thereby result in rereading of difficult parts of the sentence (Frazier & Rayner, 1982; Meseguer, Carreiras, & Clifton, 2002). This is supported by the finding of a higher number of regressions in difficult texts compared to simpler texts (Rayner, 1998). Readers often have good spatial memories for the regions causing comprehension problems and show high accuracy in targeting saccades back to these regions (Frazier & Rayner, 1982).

About 15% of all words are fixated more than once in reading before a saccade to another word is executed (cf. Rayner, 1998). These *refixations* are infrequent when the center of a word is fixated, but their probability increases towards its edges (McConkie, Kerr, Reddix, Zola, & Jacobs, 1989; Vitu, O'Regan, & Mittau, 1990). Long words receive more refixations than short words (Rayner, Sereno, & Raney, 1996; Vitu et al., 1990). Moreover, word difficulty influences refixation probability: Infrequent and unpredictable words are refixated less than frequent and highly predictable words (Balota, Pollatsek, & Rayner, 1985; Rayner et al., 1996; Vitu et al., 1990).

The complexity of the paths formed by eye movements during reading allows computing different metrics of fixation duration, i.e., the time the eye rests on a word. I will briefly mention and define the most common measures used in eye-movement research (for a more detailed discussion, see Inhoff & Radach, 1998). Typically, first-pass reading is distinguished from more-pass reading. Fixations are classified as first-pass as long as neither the fixated word nor the preceding words have been the target of regressive saccades. All fixations which are not in the first pass, are classified as more-pass fixations. Typically, first-pass fixations compromise the majority of fixations in reading. The duration of the first fixation on a word is known as *first-fixation duration*. This measure is independent of whether the word was fixated exactly once or multiple times. For the subset of words receiving only one fixation, *single-fixation duration* can be computed. *Gaze duration* is defined as the sum of all fixation durations on a word before another word is fixated. The duration of a fixation depends on the difficulty of the fixated word (see below). Fixation durations are regarded as indicators of word processing (Just & Carpenter, 1980; Rayner & Duffy, 1986).

1.2 FOVEAL PROCESSING

Inherently, the fixated word is present in foveal vision, allowing most efficient visual information extraction. Many characteristics of the fixated word influence its processing difficulty and thereby how long it is fixated. There is a large body of evidence for the major impact of the three variables length, frequency, and predictability (Hyönä, 2011; Rayner, 1998, 2009).

Word length correlates negatively with fixation duration: Longer words receive longer gaze durations, partly due to increased refixation probability, and longer single-fixation durations (Calvo & Meseguer, 2002; Joseph, Liversedge, Blythe, White, & Rayner, 2009; Just & Carpenter, 1980; Kliegl, Grabner, Rolfs, & Engbert, 2004; Kliegl, Nuthmann, & Engbert, 2006; Pollatsek, Juhasz, Reichle, Machacek, & Rayner, 2008; Rayner et al., 1996). Recent work indicates the word-length effect on fixation times is driven by the number of letters rather than the spatial width of a word (Hautala, Hyönä, & Aro, 2011).

The effect of frequency on eye movements is very robust in the literature. Although multiple kinds of frequencies can be computed, the frequency of a word is usually defined as the number of occurrences of this word relative to the total number of words in a text corpus. Highly frequent words are processed faster and are fixated shorter than low-frequency words (Inhoff & Rayner, 1986; Kliegl et al., 2004; Pollatsek et al., 2008; Schilling, Rayner, & Chumbley, 1998). Though long words are typically of low frequency, the frequency effect remains if word length is controlled (Rayner & Duffy, 1986).

Higher-level linguistic processing also influences fixation times. A word's predictability given the preceding words has a strong impact on fixation times. Predictability measures are assessed via cloze tasks: Subjects are presented the beginning parts of sentences and they are then asked to predict the next word. The probability of a correct answer, defined as the number of correct predictions relative to the total number of answers, is interpreted as predictability. If a word is highly predictable from the sentential context, fixation durations are shorter compared to low-predictable words (Balota et al., 1985; Calvo & Meseguer, 2002; Ehrlich & Rayner, 1981; Kliegl et al., 2004; Staub, 2011).

1.3 PARAFOVEAL PROCESSING

Though the fixated word—the foveal word—has a major impact on reading, sentence processing is also based on parafoveal information (see Schotter, Angele, & Rayner, 2012, for a review). The region from which effective visual information is acquired during a fixation in reading is known as perceptual span. The significant influence of parafoveal vision on the reading process has been demonstrated in studies with the classic moving-window technique (McConkie & Rayner, 1975).

This paradigm employs gaze-contingent display-changes during reading, i.e., the presentation of the text is continuously updated as a function of the gaze position (see Figure 1.1). Only a part of the text around the fixation location is available whereas the surrounding part of the visual field is masked and, for example, replaced with chains of `x` or different letters. By varying the sizes of both the left and the right part of the window, it is possible to determine how large the window has to be before reading is close to normal. The resulting minimum window size, under which reading behavior is similar to reading without a mask, is interpreted as the region providing useful information during reading. In a corpus of studies with the moving-window technique it has been shown that the perceptual span extends from three to four characters left of the fixation up to 14 to 15 characters right of the fixation (McConkie & Rayner, 1976; Rayner & Bertera, 1979; Rayner, Inhoff, Morrison, Slowiaczek, & Bertera, 1981; Rayner, Well, & Pollatsek, 1980; Rayner, Well, Pollatsek, & Bertera, 1982). If only the actually fixated word is available, reading time is inflated in comparison to reading with larger windows (Ashby, Yang, Evans, & Rayner, 2012; Rayner et al., 1982). These results demonstrate that fluent reading also relies on the processing of parafoveal information.

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       ★
Information is pxxxxxxx xxxxxx xxx xxxxxx xxxx.

                     ★
Xxxxxxxxxxx xs provided within xxx xxxxxx xxxx.

                                ★
Xxxxxxxxxxx xx xxxxxxxx within the window xxxx.

                                           ★
Xxxxxxxxxxx xx xxxxxxxx xxxxxx xxx window area.
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Figure 1.1. The moving-window paradigm. The stars indicate the fixation positions. The text is available within a specified area around the fixation location. Outside the window, the text is masked.

The region for the identification of words and letters, however, is smaller than the perceptual span. It has been demonstrated that the span in which replaced letters can be detected does not exceed seven to nine letters to the right of fixation (Häikiö, Bertram, Hyönä, & Niemi, 2009; McConkie & Zola, 1987; N. R. Underwood & McConkie, 1985). This span is even smaller for beginning readers and increases with reading skill (Häikiö et al., 2009; Rayner, 1986).

The size of both the perceptual span and the letter-identification span indicate that information from the upcoming parafoveal word, word *n* + 1, may be extracted while fixating word *n*, the foveal word. In the following sections, I will review the empirical evidence for parafoveal processing. The first part of this review focuses on tasks requiring subjects to read sentences for comprehension. It illustrates eye-movement measures and techniques which allow evaluating the role of parafoveal information in reading. Processing of word *n* + 1 can manifest in (a) word skipping, (b) landing positions, (c) parafoveal-on-foveal effects, and (d) preview benefit effects. It will be highlighted to what extent semantic properties of word *n* + 1 can be extracted. In the second part of this review, I will illustrate parafoveal processing in reading-like and non-reading tasks.

1.3.1 WORD SKIPPING

Although most words are fixated during reading, about one third is skipped, i.e., not fixated in first pass (cf. Rayner, White, Kambe, Miller, & Liversedge, 2003). This finding suggests that these words have been (at least partly) identified and processed parafoveally. Most skipped words are very short, such as the definite article *the*. Word length is one important factor for whether a word is fixated or not. It has often been demonstrated that long words are skipped less frequently than short words (Blanchard, Pollatsek, & Rayner, 1989; Rayner & McConkie, 1976; Rayner et al., 1996; Rayner, Slattery, Drieghe, & Liversedge, 2011; Vitu, O'Regan, Inhoff, & Topolski, 1995). The inverse relationship between word length and skipping probability per se does not provide sufficient information for the question whether a word has been preprocessed linguistically or whether low-level visual information has guided oculomotor control. The question which kind of information can influence skipping of words has been addressed in several studies.

The predictability of a word from the prior context also influences word skipping. In many studies (Balota et al., 1985; Drieghe, Brysbaert, Desmet, & De Baecke, 2004; Drieghe, Rayner, & Pollatsek, 2005; Ehrlich & Rayner, 1981; Kliegl et al., 2004; Rayner, Binder, Ashby, & Pollatsek, 2001; Rayner & Well, 1996; Staub, 2011) it has been demonstrated that highly constrained words are skipped more frequently than unpredictable words. Furthermore, words that disambiguate the meaning of the prior context are skipped less often than words without such functionality (Drieghe, Desmet, & Brysbaert, 2007; Vonk, 1984).

The frequency of a word also influences its skipping probability (Angele, Laishley, Rayner, & Liversedge, 2014; Choi & Gordon, 2013; Inhoff & Topolski, 1994; Kliegl et al., 2004; O'Regan, 1979; Pynte & Kennedy, 2006; Rayner & Fischer, 1996; Rayner & Raney, 1996; Rayner et al., 1996; White, 2008). Highly frequent words are fixated less often than words with a low frequency. Both predictability and frequency are related to the processing difficulty of a word. Rayner, Ashby, Pollatsek, and Reichle (2004) simultaneously manipulated these two variables and demonstrated that the effect of predictability on skipping is limited to relatively high-frequent words. For low-frequent words, predictability appears to be negligible.

More recently, Fitzsimmons and Drieghe (2011) employed sentences with mono- and disyllabic target words, which were matched in length, frequency, and predictability. Readers skipped monosyllabic words (*grain*) more often than disyllabic words (*cargo*). In general, the findings of skipping effects corroborate the view that eye movements in reading are influenced by higher-level processing of parafoveal words.

1.3.2 LANDING POSITION

If a word is not skipped, the location of the first fixation on this word, i.e., the landing position, can reveal parafoveal processing. Inherently, the landing position of the saccade was programed before the word was fixated and therefore based on information extracted parafoveally. Rayner (1979) showed that when a saccade is directed towards the word to the right, the location of the succeeding fixation will most probably be located between the beginning and the center of the word. This region is defined as preferred viewing location. Therefore, landing positions are farther away from the beginning of a word word as length increases. In other studies (McConkie, Kerr, Reddix, & Zola, 1988; Radach & McConkie, 1998; Rayner et al., 1996), this result was replicated and, in addition, it was demonstrated that the landing position varies with the distance to the target word and its length (for a more detailed review of low-level visual influences on initial fixation position, see Findlay and Gilchrist, 2003).

The influences of linguistic aspects on landing positions are less clear because experimental results are different. Such effects would denote an influence of parafoveal preprocessing of word *n* + 1 on saccade programing. Lavigne, Vitu, and d'Ydewalle (2000) showed that the landing position on highly predictable words is significantly shifted towards the end of the words in comparison to words which are less constrained from the prior context. Neverthelss, Rayner et al. (2001), Vainio, Hyönä, and Pajunen (2009), and Vonk, Radach, and van Rijn (2000) could not find a predictability effect.

Inhoff, Briihl, and Schwartz (1996) studied morphological influences on initial fixation locations. They compared the landing positions on compound words (*blueberry*), bimorphemic suffixed words (*ceaseless*), and monomorphemic words (*arthritis*). Fixation locations on compound words were closer to the word center, compared to the other conditions (see also Hyönä & Pollatsek, 1998; but see Andrews, Miller, & Rayner, 2004).

In a series of experiments, Underwood and colleagues (Everatt & Underwood, 1992; Hyönä, Niemi, & Underwood, 1989; G. Underwood, Bloomfield, & Clews, 1988; G. Underwood, Clews, & Everatt, 1990; G. Underwood, Clews, & Wilkinson, 1989) examined the influence of semantic factors, i.e., the meaning of a word, for the landing position on long words composed of redundant and informative halves. For example, *vulnerable* can be identified on the basis of its five initial letters whereas the beginning of *underneath* is shared by many English words (in contrast to its ending). Landing positions were shifted towards the end (and closer to the center) if the informative half was at the end of the word than at the beginning. Underwood and colleagues suggested that semantic preprocessing of parafoveal words was responsible for this effect. However, the effect was sometimes nonsignificant and could not be replicated in a more carefully controlled experiment by Rayner and Morris (1992).

Saccade amplitudes to a parafoveal word or nonword appear to increase with the frequency of initial letters and thereby influence landing positions in the targets (Hyönä, 1995; Plummer & Rayner, 2012; Radach, Inhoff, & Heller, 2004; Vonk et al., 2000; White & Liversedge, 2004, 2006a, 2006b). It is very likely that orthographic regularity (i.e., the commonness of the initial letter sequence in the written language) significantly affects landing position. For example, White and Liversedge (2006b) used sentences with orthographically regular and familiar beginnings[1] (*infection*) and irregular beginnings (*oestrogen*). The eyes initially moved further into words with regular than with irregular initial letter sequences. Furthermore, they showed that this effect does not rely on visual properties since it holds for both lowercase and visually less distinctive uppercase text.

Both skipping rates and landing positions are related to *where* the eyes fixate. Results indicate that saccade programing is not based on visual properties only but is sensitive to the lexical information extracted from word *n* + 1. In the next two sections, I will illustrate how parafoveal preprocessing can influence *when* a saccade is executed.

1.3.3 PARAFOVEAL-ON-FOVEAL EFFECTS

The question whether characteristics of the parafoveal word can influence how long the eyes stay on the fixated word is currently discussed controversially (Murray, Fischer, & Tatler, 2013). The impact of a parafoveal word on fixation times is known as *parafoveal-on-foveal* effect. Whereas evidence of parafoveal-on-foveal effects has been found in some studies, others failed to demonstrate an influence of word *n* + 1 on fixation

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[1] Orhographic regularity and familiarity were confounded in these studies. Whereas regularity refers to the number of words sharing an initial letter sequence, familiarity is the cumulated type frequency of words with the same initial letters.

duration. Furthermore, there have been reports of effects in opposed directions despite similar experimental manipulation (see Schotter et al., 2012, for a discussion).

In several experimental studies (Inhoff, Starr, & Shindler, 2000; Plummer & Rayner, 2012; Pynte, Kennedy, & Ducrot, 2004; Rayner, 1975; Starr & Inhoff, 2004; G. Underwood, Binns, & Walker, 2000; White, 2008), it has been shown that orthographic familiarity—the sum of frequencies of words containing a particular letter sequence—of word *n* + 1 influences fixation duration on word *n*. For example, White (2008) compared words with high (*dart*) and low mono-, bi-, and trigram frequencies[2] (*oboe*), which were matched referring to frequency. She obtained deflated fixation durations if the parafoveal word was orthographically highly familiar, compared to unfamiliar initial letter sequences. However, the effects of familiarity could not be replicated in other studies (Rayner, Juhasz, & Brown, 2007; White & Liversedge, 2004). Although there is evidence of an influence of unusual letters in parafoveal vision on fixation times, the impact of higher-order lexical word features is less clear.

There is some evidence of an influence of semantic properties of word *n* + 1 on how long the eyes stay at word *n*. In an experiment by Murray and Rowan (1998; see also Murray, 1998), subjects were presented two sentences. The task was to decide whether the sentences were physically identical or not. If they were unequal, the two sentences differed by one word. Importantly, this somewhat artificial task differs from natural reading for comprehension. Some sentences were implausible, e.g., "*The expedition wore the costumes*". Murray and Rowan found that the fixation time on word *n* (*expedition*) was inflated if word *n* + 1 (*wore*) resulted in implausible reading. Whereas Kennedy, Murray, and Boissiere (2004) replicated this result with the artificial task, Rayner et al. (2003) could not replicate it in a natural reading situation.

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[2] These are the frequencies of sequences of one, two, and three letters, respectively, in their exact order. In White's (2008) experiment both conditions differed with regard to position specific and nonposition specific comparison of orthographic familiarity.

Inhoff, Radach, Starr, and Greenberg (2000) found some evidence for semantic preprocessing of word *n* + 1. They presented sentences such as "*Did you see the picture of her mother's mother at the meeting?*" and compared fixation duration on word *n* (*mother's*) when the next word was identical (*mother*), related (*father*), or unrelated (*garden*). Fixation time was shorter if word *n* + 1 was either related or identical, compared with the unrelated condition. However, in another experiment, Inhoff, Starr, et al. (2000) failed to replicate these findings. More recently, Angele, Tran, and Rayner, (2013), and Dare and Shillcock (2013) also found evidence of an influence of a repetition of word *n* at position *n* + 1 on fixation durations. Nonetheless, the effect of semantic relatedness could not be replicated (Angele, Tran, et al., 2013).

Parafoveal-on-foveal effects of word frequency are highly controversial. Studies in which experimental manipulations were used, have not shown support for an influence of the frequency of the next word on the fixation time at the currently fixated word (Angele, Slattery, Yang, Kliegl, & Rayner, 2008; Carpenter & Just, 1983; J. M. Henderson & Ferreira, 1993; Inhoff, Starr, et al., 2000; Rayner, Fischer, & Pollatsek, 1998; White, 2008) or obtained inconsistent effects (Hyönä & Bertram, 2004).

However, considerable evidence of parafoveal-on-foveal frequency and predictability effects derives from analyses of large corpora of sentences. These corpus analyses differ from experimental studies with regard to the presence of a critical target region. Experimental studies employ a critical target region in which word features are manipulated while the sentence frame remains the same and therefore effects can be attributed to the experimental manipulation. In contrast, corpus analyses lack experimental control, but rather make use of almost all words in regression analyses including potentially important word features. In corpus studies, effects from the frequency of word *n* + 1 on fixation duration at word *n* have been reported (Fernández, Shalom, Kliegl, & Sigman, 2014; Kennedy, Pynte, Murray, & Paul, 2013; Kennedy & Pynte, 2005; Kliegl et al., 2006; Pynte & Kennedy, 2006). Furthermore, there has been evidence of parafoveal-on-foveal predictability effects (Fernández et al., 2014; Kennedy et al., 2013; Kliegl et al., 2006). Corpus studies have been criticized for the use of correlational analyses lacking control over confounding variables (Drieghe, 2011; Rayner, Pollatsek, Drieghe, Slattery, & Reichle, 2007). However, Kliegl (2007) demonstrated the reliability of the effects across multiple samples with an advanced statistical model including several additional predictors. From a more general perspective, also Baayen (2010) showed evidence for the reliability of regression analysis including continuous covariates, and he strongly argued for the use of these analyses when predictors are part of a complex correlational structure.

In the following section, I will review a widely accepted way of measuring parafoveal processing in which the critical conditions are under experimental control. It allows examining relatively late effects of parafoveal processing.

1.3.4 PARAFOVEAL PREVIEW BENEFIT

1.3.4.1 PARAFOVEAL PREPROCESSING AND FOVEAL PROCESSING

A measure of parafoveal preprocessing of a word is the time the eyes stay at this word when it is fixated. Compared to skipping, landing position, and parafoveal-on-foveal-effects, this is a relatively late measure, but it is unique in allowing direct assessment of how the parafoveally extracted information is integrated into subsequent foveal processing. When we read a text, the duration a word is fixated is inherently a function of (a) information extracted parafoveally—before the word was fixated—and (b) information extracted foveally—when the word is in foveal vision. Hence, different word features in parafoveal vision potentially facilitate subsequent foveal processing. Since visual acuity drops with increasing distance from the fovea, visual processing is less efficient in the parafoveal region. With the moving-window paradigm, it has been demonstrated that the denial of parafoveal information slows down reading (e.g., Rayner et al., 1982). The extent to which the denial of parafoveal information disrupts reading can be compared with cases in which foveal information is masked. Rayner and Bertera (1979) and Rayner et al. (1981) employed a variation of the moving-window technique, the moving-mask paradigm, in which letters in the fovea are masked while retaining parafoveal letters. Subjects' reading rate was severely reduced and they showed errors in reporting the sentences. Compared to reading on the basis of foveal information only (moving window), reading is disrupted to a much higher degree if it is solely based on parafoveal information (moving mask).

Parafoveal and foveal influences on word processing can be distinguished. I will describe a technique which allows manipulating the type of parafoveal information being available to the reader before discussing different (foveal and parafoveal) word features and their role for parafoveal processing.

1.3.4.2 THE BOUNDARY PARADIGM

The most frequently employed technique for the investigation of parafoveal preprocessing in reading is the *boundary paradigm* developed by Rayner (1975), which, like the moving-window technique, is based on gaze-contingent display-changes. Yet in the boundary paradigm, only a critical target word in a sentence is initially mutilated (see Figure 1.2).

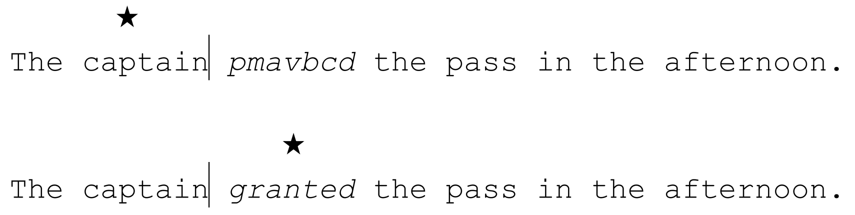

Figure 1.2. The boundary paradigm. The stars indicate the fixation positions. Initially, a preview occupies the target location (in italics). When the gaze crosses the invisible boundary (indicated by the vertical bar), the target replaces the preview.

The name of the paradigm derives from an invisible boundary located directly prior to the space preceding the target. When the sentence is presented, the target word is occupied by, for example, an unrelated word or a nonword. During the saccade crossing the boundary, the actual target word replaces the preview and the sentence remains in this final form. Hence, the reader fixates the correct form of the target, whereas the preview has been only available in parafoveal vision. Usually, the pretarget word before the boundary and the target word are referred to as words *n* and *n* + 1, respectively. Trials in which the target word is masked, can be compared with trials in which the target is persistently available (i.e., without display change). Differences in fixation durations on the target word $n + 1$ allow assessment of the influence of parafoveal information on later word processing. Typically, the fixation duration on the target word is shorter if parafoveal preview was available than if preview was denied. The difference between both conditions is known as *preview benefit* and is interpreted as evidence of facilitation due to parafoveal preprocessing.

The information shared between parafoveal previews and targets is under experimental control. Therefore, the boundary paradigm is a sophisticated tool for the assessment of what types of information can be extracted parafoveally and integrated in later foveal processing. In the following, I will discuss which variables determine the size of the preview benefit as well as the word features that have been demonstrated to affect parafoveal word processing.

1.3.4.3 WHAT MODULATES PREVIEW BENEFIT?

Features of both the parafoveal target word and the foveal word determine the processing of parafoveal information provided by the preview and the integration into the processing of the subsequently fixated target.

Balota et al. (1985) examined the role of contextual constraint for preview benefit. The size of the preview benefit was larger for high- than low-predictable targets, indicating a more effective use of parafoveal information matching expectations. Similarly, Inhoff and Rayner (1986; see also Reingold, Reichle, Glaholt, & Sheridan, 2012) employed targets of low (*traitor*) and high frequency (*teacher*) and found more effective preview benefit for high-frequent words.

There is evidence that the difficulty of the fixated word, the *foveal load*, influences parafoveal processing. J. M. Henderson and Ferreira (1990; Exp. 2) manipulated syntactic difficulty of the foveal pretarget word. If the fixated word was difficult to integrate into the sentence structure, parafoveal processing was less effective. Most likely, the ease of processing of the foveal word determines the size of the processing span and how much parafoveal information can be processed. Effects of foveal load have also been demonstrated by manipulating the frequency of the foveal word (J. M. Henderson & Ferreira, 1990; Kennison & Clifton, 1995; White, Rayner, & Liversedge, 2005a). For example, J. M. Henderson and Ferreira (1990; Exp 1) presented identical (*despite*) and different (*zqdioyv*) parafoveal previews for target words. The frequency of the pretarget was either high (*chest*) or low (*trunk*). Highly frequent foveal words yielded greater preview benefit than low-frequent words.

Furthermore, preview benefit also appears to depend on the position of the pretarget and the target in the sentence. Payne and Stine-Morrow (2012) investigated the degree to which semantic integration processes modulate preview benefit. The foveal pretarget occurred in sentence-internal, clause-final, or sentence-final position. Fixation durations on the target revealed greater preview benefit in the sentence-internal position than in the other conditions. Likewise, White, Warren, and Reichle (2011) found larger preview benefit when the target word occurred in sentence-internal or sentence-final position, compared to targets at sentence-initial position. These results indicate that the workload associated with semantic integration reduces parafoveal processing across syntactic boundaries.

1.3.4.4 TYPES OF PREVIEW BENEFIT

There is a large corpus of studies in which the boundary paradigm was employed. The manipulation of information provided by the preview ranges from sub-lexical visual and orthographic codes to higher-level semantic features. Preview benefit is not limited to the comparison of nonidentical and identical parafoveal previews, but rather can be assessed with different preview conditions all of which are not identical to the target.

Orthographic processing

The integration of information is based on orthographic features. McConkie and Zola (1979) presented sentences in alternating case (lIkE tHiS). On each saccade the case of every letter changed (LiKe ThIs). Although this manipulation has a massive influence on the visual appearance of words, the reading behavior was equivalent to a control condition in which the case alternation was constant throughout the whole trial. More recently, this finding was replicated for a single critical target word (Slattery, Angele, & Rayner, 2011): Fixation durations did not reliably differ between identical-preview and case-change conditions. These findings indicate that no overlapping of visual features is required for the integration of information obtained during fixations on word *n* and *n* + 1. This process is rather based on abstract letter codes extracted parafoveally.

Moreover, solid evidence of an impact of orthographic features on parafoveal preview benefit is derived from a large corpus of studies in which a subset of letters is shared between preview and target (Angele & Rayner, 2013; Balota et al., 1985; Bélanger, Mayberry, & Rayner, 2013; Briihl & Inhoff, 1995; Drieghe et al., 2005; J. M. Henderson & Ferreira, 1990; Inhoff & Tousman, 1990; Inhoff, 1987, 1989a, 1989b, 1990; Lima & Inhoff, 1985; Rayner et al., 1982). The availability of a word's first two or three letters in parafoveal vision facilitates reading. For a critical target word (e.g., *money*), Balota et al. (1985) used orthographically related previews (*moncg*), which preserved the initial letters, and unrelated previews (*toohz*). Fixation times on the target were shorter if the initial letters of the parafoveal word were available, compared to the condition in which all letters were different.

However, the availability of a word's final letters (e.g., *puit* as a preview for *quit*) does not consistently facilitate reading (Angele & Rayner, 2013; Briihl & Inhoff, 1995; Inhoff, 1989a, 1989b, 1990; Johnson, Perea, & Rayner, 2007). Furthermore, preview benefits from final letters are (if at all) smaller than benefits from initial letters. Briihl & Inhoff (1995) tested the effect of preserving the letters of the orthographic body (*xxundxx* as a preview for *thunder*) and found no evidence of a benefit for target processing. Taken together, the first letters of a word play a major role in parafoveal preprocessing. Evidence of preview benefit due to final letters is more pronounced and more consistently reported in recent studies (Angele & Rayner, 2013; Johnson et al., 2007) compared to the seminal studies (e.g., Inhoff, 1989b, 1990). Drieghe et al. (2005) discussed this discrepancy and concluded that the improvements of cathode ray tube monitors may have allowed greater precision in the presentation of the experimental texts and therefore more efficient parafoveal processing.

Further evidence for the assumption that parafoveal word representation is based on orthographic codes rather than on visual features is derived from a series of studies in which letter order was changed (Johnson & Dunne, 2012; Johnson et al., 2007; Johnson, 2007; Masserang & Pollatsek, 2012). Johnson et al. (2007) employed different previews for a parafoveal target word (*magic*). The transposed-letter condition involved a transposition of two internal and adjacent letters (*maigc*). Compared to the control condition, in which letters were replaced (*mayoc*), parafoveal preview of transposed letters resulted in shorter fixation durations. Preview benefit obtained from transposed internal letters was similar to preview benefit from transposed final letters (*magci*) in five-letter words. When seven-letter targets (*dolphin*) were employed, internal transposed letters (*dolhpin*) yielded more benefit than final transposed letters (*dolphni*). Interestingly, replacing the fifth and the sixth word-internal letters (*dolpukn*) led to longer target fixations than replacing the final two letters (*dolphra*). Taken together, the results indicate that the first five letters and the final letter can be extracted in parafoveal vision.

Johnson (2007) demonstrated that readers also obtain preview benefit if the transposed letters are not adjacent (*flewor* as a preview for *flower*). Furthermore, Johnson and Dunne (2012) examined the processing of transposed-letter neighbors, i.e., transposed-letter previews representing actual words. Both words (*beats* as a preview for *beast*) and nonwords (*besat*) facilitated target processing.

Finally, Williams, Perea, Pollatsek, and Rayner (2006) examined the influence of the frequency of a parafoveal preview on orthographic preprocessing. They previewed target words (*spice*) with orthographic neighbor words (*space*), orthographically matched nonwords (*spuce*), and orthographically unrelated nonwords (*zqeoc*). In the first experiment, the target was a high frequent word and the corresponding neighbor was a low-frequent word. Target fixation durations revealed that a high-frequent neighbor was as better preview than the nonword preview. In the reverse situation, i.e., when high-frequent neighbors previewed low-frequent targets, neighbors provided no greater preview benefit than nonwords. This pattern of results indicates that parafoveal extraction of letters is facilitated by partial lexical activation of high-frequent words.

Phonological processing

The orthographic representation of a word constitutes the basis for the extraction of phonological units. Phonology refers to the organization of sounds in languages. In several studies, it has been shown that phonological information is extracted parafoveally (Ashby, Treiman, Kessler, & Rayner, 2006; Bélanger et al., 2013; Chace, Rayner, & Well, 2005; Miellet & Sparrow, 2004; Pollatsek, Lesch, Morris, & Rayner, 1992). In Pollatsek et al.'s (1992) experiment, a parafoveal target word (*beach*) was previewed by a homophone preview (*beech*) or an orthographically matched control condition (*bench*). Target fixation durations were shorter if a homophone was presented parafoveally, compared to the nonhomophonic control condition (see also Chace et al. 2005, for a replication of this result). Similarly, Miellet and Sparrow (2004) employed French sentences and did not find a difference in fixation durations on the target when either a pseudo-homophone (*maurçots*), i.e., a phonologically related nonword, or an identical preview (*morceaux*) was available in the parafovea. In Ashby et al.'s (2006) study, target words (*flirt*) were preceded by pronounceable nonword previews whose vowel phoneme was concordant (*flurn*) or discordant (*flarn*) with that of the target. In the first experiment, preview and target vowels were not identical. Target fixation durations were shorter in the concordant than in the discordant condition. In the second experiment, the vowel concordance effect was replicated with identical vowels whose following consonant determined whether the vowel phoneme was concordant (*chean* as a preview for *cheap*) or discordant (*chead*). Recently, Bélanger et al. (2013) examined preview benefit in hearing and deaf readers. While orthographic preview facilitated target reading for both groups of subjects, parafoveal processing of phonological codes was only found for hearing readers.

A strong relation to the examination of phonological parafoveal processing is present in studies by Ashby (2006; Ashby & Rayner, 2004) on prosodic information extraction. Prosody refers to intonation in languages. Words in alphabetic languages consist of syllables, which consist of consonants and vowels. Ashby and Rayner (2004) manipulated previews for critical targets whose initial syllable had a consonant-vowel structure (*device*) or a consonant-vowel-consonant structure (*balcony*). Fixation durations on the target were shorter when parafoveal previews matched the syllable information of the target (*de_πxw*, *bal_πxw*) than when previews provided one letter more or one letter less than the initial syllable (*dev_πx*, *ba_πxwx*).

In summary, studies on eye movements reveal evidence of parafoveal extraction of phonological and prosodic word features. This information facilitates reading when the target word is finally fixated.

Morphological processing

In contrast to orthographic and phonological preview benefit, the pattern of findings concerning parafoveal extraction of morphological information—morphemes constitute the smallest grammatical units in languages—in alphabetic scripts is mixed. Whereas there is no definite evidence of the preprocessing of morphological codes in Roman writing systems (Bertram & Hyönä, 2007; Inhoff, 1989a; Juhasz, White, Liversedge, & Rayner, 2008; Kambe, 2004; Masserang & Pollatsek, 2012), morphologically related previews facilitate reading in Hebrew (Deutsch, Frost, Pelleg, Pollatsek, & Rayner, 2003; Deutsch, Frost, Pollatsek, & Rayner, 2005). Kambe (2004) and Lima (1987) investigated prefixed words in English and failed to find morphological preview benefit. Targets were either prefixed words (*revive*) or pseudoprefixed words (*rescue*). Benefit from nonword previews sharing the prefix (*reXXXX*) was not larger than orthographic benefit. Moreover, morphological parafoveal processing has been studied with two-noun compound words in English (Inhoff, 1989a; Juhasz et al., 2008) and Finnish (Bertram & Hyönä, 2007). For example, Juhasz et al. (2008) compared preview benefit for compounds (*mailbox*) and monomorphemic words (*shuttle*). In the preview conditions, a space replaced a single letter. The first string of the previews either constituted a lexeme (*mail ox*, *shut le*) or a nonword (*mai box*, *shu tle*). There was no difference in preview benefit for compounds, compared to monomorphemic words. Masserang and Pollatsek (2012) used transposed-letter previews in which the adjacent letters either crossed a morpheme boundary (*ovelroad* as a preview for *overload*) or not (*toelrate* as a preview for *tolerate*), and found no reliable difference in preview benefit. However, there is some evidence of morphological preprocessing from a recent study by Angele and Rayner (2013). They previewed compounds (*cowboy*) with the morphemes in reversed order (*boycow*) and visually similar nonwords (*enztxg*). Target fixation durations were reduced by the availability of the morphemes suggesting there is a preview benefit due to parafoveal extraction of both morphemes.

In contrast to English and Finnish, morphological preview benefit has been demonstrated in several studies in Hebrew. For example, Deutsch et al. (2003) presented identical, morphologically related, and orthographically related previews for target nouns. When the target word was fixated, fixation durations were shorter in the identical and morphologically related condition than in the orthographic condition. Moreover, fixation times yielded no reliable difference between identical and morphologically related conditions. The results are evidence of parafoveal preprocessing of morphological codes in Hebrew. The discrepancy between studies with Hebrew and Roman languages most likely reflects differences in the structure of these languages. Most nouns in Hebrew consist of two basic morphemes: The root carries the semantic meaning of the word whereas the word pattern defines grammatical features. In languages based on the Roman writing system, morphemes are separated, but in Hebrew the root and the word pattern are interwoven. The different results of morphological preview benefit between languages reveal the impact of structural characteristics of writing systems on parafoveal preprocessing.

Researchers have also studied *semantic* preview benefit. Semantics and the extraction of parafoveal semantic information will be discussed in the next section.

1.4 SEMANTIC PROCESSING

In this thesis, I focus on the processing of semantic code. After a brief introduction to semantics and semantic relatedness, I will review studies on parafoveal semantic preview benefit in reading. This review comprises both alphabetical and nonalphabetical writing systems: Differences between languages are a major key of understanding experimental results.

1.4.1 SEMANTIC RELATIONS

When we read a text, the ultimate goal is the extraction of meaning. The processing of visual, orthographic, phonological, and morphological word features is used to access the lexical representation of a word. *Lexical semantics* refer to the meaning of words. Words can be regarded as the names of concepts. Following Cruse (1986), the meaning of a word is constituted by its contextual relations. Although there are numerous theories of lexical semantics (see Geeraerts, 2010, for a review), it should be noted that semantic processing refers to the extraction of word meaning. Different semantic dimensions—like imageability, body-object interaction, and valence—have been shown to affect word recognition (see Pexman, 2012, for a discussion).

For the study of parafoveal processing, previews related with the target and unrelated previews are employed. For example, orthographic previews share letters with the target and phonological previews have a similar sound like the target word. What is semantic relatedness? In a large corpus of *priming* studies, researchers investigated foveal semantic processing: A semantically related prime word (*cat*) improves the speed or accuracy of a response to an isolated target word (*dog*), compared to an unrelated prime (*table*). The subjects' task most often is either the naming of the target word or lexical decision, i.e., deciding whether the target is a real word. The results from these kinds of experiments imply that the relations of meaning between the words *cat* and *dog* produce priming effects (see McNamara, 2005, and Neely, 1991, for extensive reviews).

One of the most influential models of semantic priming is spreading activation (e.g., Anderson, 1983; Collins & Loftus, 1975) in which concepts are represented as nodes in a semantic network. The perception of the preview activates its representation, and the activation spreads to related concepts. When the target is presented, residual activation at its node helps retrieving the concept of the target. In distributed network models (e.g., Masson, 1995), concepts are represented by patterns of activity over a large number of interconnected units. Semantically related words are represented by similar pattern of activation. The presentation of the prime results in a certain pattern of activation which facilitates the creation of the target representation. An extension of the interactive activation model (J. L. McClelland & Rumelhart, 1981) can also explain semantic priming (Stolz & Besner, 1996). Words are processed at a letter level, a lexical level, and a semantic level. Connections between levels are excitatory and thus help activating related concepts. Within one level, connections are inhibitory. Semantic priming is explained by the activation of concepts at different levels of representation. There are further models of semantic priming, which are beyond this brief overview. Some of these models are explicitly designed for explaining how semantic priming helps distinguishing words from nonwords in a lexical-decision task. Inherently, these models are inappropriate for parafoveal semantic preprocessing during reading for comprehension. For further discussions of models of semantic priming, see Jones and Estes (2012), and McNamara (2005).

How can two words be related at a semantic level? Several kinds of semantic relatedness can be distinguished. *Synonymy* between two words occurs if their meanings are very similar or identical, e.g., *sofa* and *couch*. Full synonyms, which are identical in every sense, are relatively rare and limited to words with a very specific meaning. Most synonyms are so-called near-synonyms which share some senses but differ in others.

Words are *antonyms* or opposites if they share most semantic qualities but differ in a significant feature, e.g., *fast* and *slow*, *life* and *death*. Whereas these examples are morphologically unrelated, most antonyms in English and many other languages have a morphological base in common. Opposite meanings can be created with negating affixes like *non-*, *un-*, *in-*, or *dis-*, for example *happy* and *unhappy*. Antonymy is a binary subtype of *contrast*. The aggregate states *solid*, *liquid*, and *gaseous* are an example of non-binary contrast. Synonymy, antonymy, and contrast are nonhierarchical and symmetric relations, i.e., the relation between *sofa* and *couch* is identical to the relation between *couch* and *sofa*, and thus, the relation between these two words is bidirectional.

In contrast to symmetric relations, hierarchical relations between words occur if a hierarchy qualifies their semantic relatedness. These relations are *hyponymy* (subordination) and *hyperonymy* (superordination). For example, *cat* is a hyponym of *mammal* and *mammal* is a hyponym of *animal*. *Cat* is a subordinate category of the category *mammal*. In the other direction, *mammal* is a hyperonym of *cat*. Unlike synonymy and antonymy, these hierarchical relations are unidirectional. The meanings of the subordinate words include all meanings of the superordinate words, but not vice versa. Every cat is a mammal, but not every mammal is a cat. The subordinate words are more specific and include additional features (e.g., a cat has protractible claws). Whereas *mammal* and *cat* are in a taxonomic relation, hyponymy (and hyperonymy) also exist for functional relations, e.g., *cat* as a hyponym of *pet*. In contrast to taxonomic relationship, functional relationship is not logically necessary (not every cat is a pet). If two words are hyponyms of the same superordinate term, they are *co-hyponyms*. For example, *cat* and *dog* are co-hyponyms of *mammal*.

Another type of branching lexical hierarchies are *meronymy* and *holonymy*. Meronymy is a part-of-a-whole relation, for example, *head* is a meronym of *body*. Conversely, *body* is a holonym of *head*. Meronymy and holonymy are unidirectional terms. Furthermore, the meronymy between *head* and *body* is necessary: Every body has a head (even if it is removed). Necessary meronymy can be distinguished from optional meronymy, e.g., *handle* and *door*. A handle is not necessarily a part of a door.

These are the most widely accepted types of semantic relatedness. There are several other types of specific lexical relations and associations. Cruse (1986) and Murphy (2003) provide extensive discussions of semantic relatedness.

Although these types of relatedness appear obvious, the overlap between meanings of words is not due to these relations per se. Mental representations of meaning can exist at different levels. The meaning of a word could directly refer to something in reality in a perceptual symbol system (Barsalou, 1999). In different approaches, words are meaningful due to their relationship with other words (for a discussion, see Kintsch, 2008). According to this view, contextual relations of words stored in memory are used to construct semantic information. A word's meaning is characterized by co-occurring words. For example, latent semantic analysis (Landauer & Dumais, 1997), a statistical model, represents semantic relatedness of words as the similarity between their multidimensional vectors based on text corpus information.

1.4.2 SEMANTIC PREVIEW BENEFIT

There have been several studies on semantic parafoveal processing in reading. In these studies, the boundary paradigm in reading was applied while subjects read sentences for comprehension. The employed experiments differ with respect to writing system and relation between previews and targets. Table 1.1 displays an overview of semantic preview benefit (i.e., the fixation-duration difference between the unrelated preview condition and the semantically related preview condition).

Rayner, Balota, and Pollatsek (1986) used English sentences. The presentation of the target word (*tune*) was preceded by an identical (*tune*), an orthographically related (*turc*), a semantically related (*song*), or an unrelated preview (*door*). Compared to the unrelated condition, fixation times revealed identity preview benefit (44 ms) and orthographic preview benefit (39 ms). However, there was no reliable difference between the semantically related and unrelated conditions (4 ms).

Altarriba, Kambe, Pollatsek, and Rayner (2001) used another approach. They did not employ semantically related previews, but translations in English and Spanish sentences. Bilingual subjects were asked to read sentences in which the target preview was either identical to the target word (*sweet* for *sweet*), a cognate translation of similar orthography (*crema* for *cream*), an orthographically similar pseudo-cognate of different meaning (*grasa* for *grass*), a non-cognate translation (*dulce* for *sweet*), or an unrelated control word (*torre* for *cream*). The identical and several orthographic preview types resulted in shorter target fixation durations, compared to the control condition. In contrast, there was no reliable preview benefit due to the non-cognate translation for English or Spanish sentences.

Table 1.1

Semantic Preview Effects (in Milliseconds) for Gaze Duration (GD), First-Fixation Duration (FFD), and Single-Fixation Duration (SFD) in Sentence-Reading Studies

				Preview effect		
Study	Language	Previews	Condition/details	GD	FFD	SFD
Rayner et al., 1986	English	Related vs. unrelated		4		
Altarriba et al., 2001	English/ Spanish	Translation vs. unrelated (opposite language)	English targets	11	4	
			Spanish targets	0	1	
Hyönä & Häikiö, 2005	Finnish	Neutral vs. emotional[a]		−4	−2	
White et al., 2008	Finnish	Related vs. unrelated (within-word boundary[b])	Second constituent (target region)	12	5	
			Whole compound[c]	33		
Yan et al., 2009	Chinese	Related vs. unrelated		27	17	
Kim et al., 2012	Korean	Correct vs. mismatch[d]		25	13	
Tsai et al., 2012	Traditional Chinese	Related vs. unrelated		20	10	22
Yan, Zhou, et al., 2012	Chinese	Related vs. unrelated	Transparent previews	25	14	18
			Opaque previewss	12	12	14
Yang, Wang, et al., 2012	Chinese	Related vs. unrelated	Unplausible previews	−1		3
			Plausible previews	1		9
Cui et al., 2013	Chinese	Related vs. unrelated[e]	High-frequency first constituent	34		
			Low-frequency first constituent	48		

Note. Studies are ordered by the year of publication and the name of the first author. The preview effect at the target for previews in conditions x vs. y is calculated as fixation-duration difference $(y - x)$. See text for further details on studies.

[a] The direction of the effect is based on the authors' expectations. [b] The preview of the second constituent of a two-constituent compound was manipulated. The boundary was located between both constituents. [c] Gaze duration on the whole compound, including all fixations after crossing the boundary. [d] In the incorrect condition, the preview resulted in a syntactic and semantic mismatch between preview and target. [e] The preview of the second character of a two-character compound was manipulated.

Typically, effects of semantic relatedness are examined with semantically related words and neutral (or at least semantically unrelated) control words. However, Altarriba et al. (2001) contrasted translations of the target and unrelated control words of different language. The use of a translation as a semantically related preview is a sophisticated approach. Although translation priming has been demonstrated in some foveal priming studies (e.g., Chen & Ng, 1989; Schoonbaert, Duyck, Brysbaert, & Hartsuiker, 2009), Altarriba et al.'s (2001) approach entails potential interference due to the change from one language to another. Indeed, language-switching costs have been reported in several studies (Costa & Santesteban, 2004; Costa, Santesteban, & Ivanova, 2006; Hernandez & Kohnert, 1999; Jackson, Swainson, Cunnington, & Jackson, 2001; Meuter & Allport, 1999; Soares & Grosjean, 1984). For example, in the experiment by Meuter and Allport (1999), bilingual subjects were asked to name numerals in a determined language. Reaction times on trials in which the language changed from the previous trial were longer than on trials in which the language did not change. In the study by Altarriba et al. (2001), the language changed two times in each trial. The first change emerged due to attention shift from the beginning of the sentence and the fixated word to the preview word in a different language; the display change from preview to target word depicts the second change. Thus, potential semantic representations from parafoveal information extraction may have been negated by language-switching costs, reflecting the fragility of semantic priming effects (Dagenbach, Carr, & Wilhelmsen, 1989).

Hyönä and Häikiö (2005) examined the influence of emotional words in parafoveal vision during reading of Finnish sentences. For a critical target (*pentu*; cub), the preview was either a neutral (*penni*; penny) or an emotional word (*penis*; penis). In each case, the words shared the initial three letters. Most emotional words were sex-related or threat-related. Neither emotional nor neutral previews were semantically related to the target. The authors expected longer target fixations following emotional previews, but the results did not show the expected difference: There was no reliable difference in target fixation times between both preview conditions. Hyönä and Häikiö referred to a parafoveal priming study by Calvo & Castillo (2005b), in which threat-related identity primes facilitated lexical-decision times for foveal probes. There is, however, a potentially important difference. Hyönä and Häikiö (2005) did not use identity previews but unrelated emotional ones. Indeed, in a more extensive priming study in which the influence of threat-related parafoveal words was examined, Calvo and Castillo (2005a) affirmed that emotional words in parafoveal vision are effective for reaction times on identical probes, but could not demonstrate an influence of emotional words on unrelated probes. Thus, the semantically unrelated previews by Hyönä and Häikiö (2005) may have been too weak for parafoveal semantic effects on target reading. Moreover, since the previews shared the initial three letters, differences between these previews were limited to a region that was relatively far from the fixation location.

More recently, parafoveal semantic processing has been demonstrated for Finnish. White, Bertram, and Hyönä (2008) employed the boundary paradigm but placed the boundary *within* words. The preview for the second constituent of a Finnish compound noun (*vaniljakastike*; vanilla sauce) was either semantically related (*sinappi*; mustard) or unrelated (*rovasti*; priest) to the second constituent (*kastike*; sauce). When the reader's gaze crossed the boundary located between both constituents, the target replaced the preview. Whereas fixation times on the second constituent did not reveal reliable preview benefit, the gaze duration on the whole compound (measured from the time of the first fixation on the second constituent until the eye left the word) was shorter if the parafoveal preview was semantically related to the target, compared to the unrelated condition. This result indicates that semantic information can be extracted in parafoveal vision and facilitates processing of the fixated word. Generally, preview benefit within words appears to be greater than preview benefit between words (Häikiö, Bertram, & Hyönä, 2010; Juhasz, Pollatsek, Hyönä, Drieghe, & Rayner, 2009).

While there is no definite evidence of semantic preview benefit across word boundaries in Roman writing systems, recent studies demonstrated preprocessing of parafoveal semantic information in Chinese (Cui et al., 2013; Tsai, Kliegl, & Yan, 2012;

Yan, Richter, Shu, & Kliegl, 2009; Yan, Zhou, Shu, & Kliegl, 2012; Yang, Wang, Tong, & Rayner, 2012) and Korean (Kim, Radach, & Vorstius, 2012).

Semantic preview benefits have been consistently reported for reading Chinese, a logographic writing system that is very different from alphabetic scripts (see Tsang & Chen, 2012, for a review). Written Chinese is formed by strings of equally spaced complex characters. Two differences between Chinese and alphabetic script facilitate the detection of semantic preview benefit in Chinese. Firstly, Chinese characters are more directly connected to meaning than alphabetic characters (Hoosain, 1991). In contrast to English, the pronunciation of Chinese characters is largely opaque: Since the number of different syllables is much lower than the number of different characters, there are many homophones. Hence, phonological information most likely does not play a major role for the extraction of lexical information. Secondly and more importantly, most Chinese words are only one or two characters long (Yu et al., 1985). Therefore, the mean distance between the current fixation position and the next word is smaller than in alphabetic script, and the next word covers less space in the parafoveal field. Hence, more information may be visible during a fixation.

Employing the boundary paradigm with simple non-compound characters, Yan et al. (2009) established a significant preview benefit of semantically related characters, compared to unrelated previews. They manipulated the preview of the first character of a two-character compound word, but neither related nor unrelated preview formed a real word with the following character. Furthermore, Yan et al. (2009) used simplified Chinese, the orthography used on the Chinese mainland. Recently, Tsai et al. (2012) replicated Yan et al.'s (2009) results with traditional Chinese characters used in Taiwan.

There was a question whether the results based on visually simple non-compound characters would generalize to representative Chinese compound characters. Most compound characters contain two components, a semantic and a phonological radical, which code the category of the word and its pronunciation, respectively (Yin & Rohsenow, 1994). Semantic radicals are usually located at the left side of characters, conducive to a semantic preview benefit. Preview benefit for compound characters has been examined in three studies. First, Yang, Wang, et al. (2012) demonstrated a reliable semantic preview benefit with such characters, but they did not accept their own result as completely convincing because of a potential confound with plausibility of target words. Second, Cui et al. (2013) used two-character compounds and manipulated the frequency of the first character and the preview of the second character. Semantically related preview of the second character reliably reduced fixation durations compared to an unrelated character when the first character was of low frequency. Finally, Yan, Zhou, et al. (2012) used two types of semantically related compound previews: transparent characters, whose constituent radicals were semantically related to the meaning of the whole character, and opaque characters, whose meanings were unrelated to the meanings of their radicals, both resulted in significant preview benefit. In addition, character transparency increased the semantic preview benefit for gaze durations.

Parafoveal semantic processing has also been studied for reading Korean (Kim et al., 2012). Korean combines features of both alphabetic and syllabic writing. The orthography is based on phonology, and alphabet letters, representing phonemes, are organized in syllable blocks rather than strings of letters. The syllabic structure is similar to Chinese. However, unlike Chinese, Korean is based on alphabet letters. Case markers are used to signify syntactic functions of words and thereby provide semantic information about thematic roles. Kim et al. (2012) employed correct and incorrect case markers in terms of syntactic category as parafoveal previews. The incorrect preview led to a syntactic and semantic mismatch between the initially visible case marker and the one presented after the display change. Target fixation durations were inflated in the incorrect preview condition, indicating that the processing of parafoveal syntactic and semantic information occurs in reading of Korean text.

Whereas there is clear evidence of semantic preview benefit in Chinese and Korean, there has been no definite demonstration of the extraction of semantic code from the next word in Roman orthographies. Semantic effects of words presented in parafoveal vision have, however, been found under controlled experimental conditions.

1.4.3 PARAFOVEAL SEMANTIC PROCESSING BEYOND NATURAL SENTENCE READING

The processing of semantic information in parafoveal vision has also been studied in other paradigms than sentence reading. The employed material consisted of isolated words or lists of words. Surely, preview benefit during natural reading for comprehension is the most direct assessment of how readers extract and integrate semantic features across word boundaries. Nonetheless, results from these paradigms, in which alphabetic languages were used, may provide additional insight into parafoveal processing of semantic information.

Effects of primes in parafoveal vision on reaction times to subsequently presented semantically related foveal target words have been demonstrated in several priming experiments (e.g., Di Pace, Longoni, & Zoccolotti, 1991; Fuentes & Tudela, 1992), but not in others (e.g., Paap & Newsome, 1981). Coulson, Federmeier, Van Petten, and Kutas (2005) presented a prime in foveal vision and asked subjects to name a briefly presented parafoveal target. Both naming accuracy and event-related brain potentials yielded effects of semantic relatedness. In these studies, no eye movements were required and stimulus presentation times were under experimental control.

Recently, Barber, Van der Meij, and Kutas (2013) employed a reading-like task in which sentences were presented serially, i.e., word by word, at fixation position. Each word was visible for a constant period and was flanked bilaterally by the previous and the next word to its right and its left, respectively. The right flanker was either semantically congruent or semantically incongruent in the sentential context. Subjects were asked to read for comprehension. Event-related brain potentials revealed evidence of the extraction of semantic information from parafoveal vision.

Semantic parafoveal information extraction has not been found in studies in which subjects had to move the eyes. Rayner, McConkie, and Zola (1980) asked subjects to fixate and name an isolated parafoveal stimulus. Employing the boundary paradigm, the parafoveal preview of the target was manipulated. Naming latencies did not reveal semantic preview benefit. Dimigen, Kliegl, and Sommer (2012) manipulated preview in lists of words. The subjects' task was to report whether an animal-word is present.

Neither event-related brain potentials nor fixation durations exhibited reliable semantic parafoveal processing.

In summary, effects of semantic processing of parafoveal words have been demonstrated in experiments in which preview presentation times were under experimental control. However, the similarity between these tasks and natural reading for comprehension is relatively low. Eye movements were not necessary and most often subjects were not asked to read for comprehension. Due to te lower ecological validity, the generalizability of these results is limited. They however constitute an indication of time-dependent effects of parafoveal processing.

1.5 MOTIVATION AND OVERVIEW OF THE PRESENT STUDIES

In this thesis, parafoveal semantic preview benefit during reading was examined in two studies comprising in total seven experiments (published as Hohenstein & Kliegl, 2014, and Hohenstein, Laubrock, & Kliegl, 2010). In the studies, subjects were asked to read German texts for comprehension while their eye movements were recorded. Critical targets were previewed with semantically related or unrelated words.

So far, no study on any kind of preview benefit of word $n + 1$ in German has been published. There is evidence of semantic preprocessing of parafoveal information in Chinese and Korean. The representation of meaning in these languages is very different from languages based on the Roman writing system. Chinese characters are more directly connected to meaning. The orthography in Korean is highly transparent rendering easier extraction of phonological information. Results from reading in Roman writing systems are less clear. Semantic within-word preview benefit has been demonstrated for Finnish whose orthography is also highly transparent (White et al., 2008). In two further studies, no semantically related previews of the same language were used, but rather translations (Altarriba et al., 2001) or unrelated emotional words (Hyönä & Häikiö, 2005). Hence, the only direct assessment of semantic parafoveal processing across word boundaries in Roman script with semantically related and unrelated previews has been conducted by Rayner et al. (1986), who found no reliable preview benefit in English. Most of the current knowledge about reading is based on studies with English speakers reading in their native tongue, but differences between languages might be important (see Share, 2008, for a critical discussion). English and German share many similarities since they are West Germanic languages (like Dutch) and therefore have the same origin (see Harbert, 2007, for an overview). However, compared to German and other European languages, English has a highly irregular orthography (Seymour, Aro, & Erskine, 2003). Language differences most likely affect parafoveal processing. There is clear evidence of preview effects of the word after the next one, word *n* + 2, in German (Kliegl, Risse, & Laubrock, 2007; Risse & Kliegl, 2011, 2012), but not in English (Angele & Rayner, 2011; Angele et al., 2008; Rayner, Juhasz, et al., 2007; but see Radach, Inhoff, Glover, & Vorstius, 2013). In summary, a test of semantic preview benefit in German appears to be promising with respect to the understanding of how information in the parafovea is processed in alphabetic languages.

Furthermore, effects of semantic relatedness from words in parafoveal vision have been shown in priming paradigms and related task, in which the prime duration was under experimental control. The extraction of semantic code appears to be time-dependent. In Chapter 2, a new paradigm, parafoveal fast priming, is introduced. In four experiments, this technique was used to present previews for a specified set of durations. Previews were either semantically related or unrelated to the target. The target replaced the preview during pretarget viewing. With prime durations of 35 ms, 80 ms, and 125 ms, semantic preview benefit was reliable at 125 ms in the first and the second experiment. With a salient preview in the third experiment, preview benefit was found at the 80-ms condition, but not at the 125-ms condition, indicating time-dependent facilitation and inhibition due to semantic relatedness. No reliable influence of relatedness was obtained with short prime durations ranging from 20 ms to 60 ms in the fourth experiment. Implications on the time course of parafoveal processing will be discussed.

In Appendix A, I present a reanalysis of the experiments in Chapter 2. In the original analyses, untransformed fixation duration was used as the dependent variable.

Although this practice is in agreement with the vast majority of preview-benefit studies, it is associated with statistical problems. Comparisons between untransformed and log-transformed fixation durations revealed different effects on the distribution of residuals and random effects. The results reported in Chapter 2 were confirmed with the transformed variable. Interestingly, a weak but significant preview effect at 80 ms prime duration in Experiment 2 was found in the reanalysis.

In Chapter 3, semantic parafoveal processing was investigated in three experiments with the classic boundary paradigm. Semantic preview benefit was found in the first experiment. Since preview time was not under experimental control but identical with pretarget fixation time, the duration of the pretarget fixation was used as continuous covariate. In some analyses, preview benefit was reliably modulated by preview time. Furthermore, preview benefit was independent of display-change awareness. Previews and targets in experimental sentences were nouns. Critically, all nouns are spelled with an initial capital letter in German. The influence of German spelling was examined in the second experiment, in which semantic preview benefit was also found when all words were presented in lowercase. Additional previews, identical and pronounceable nonword, were used in the third experiment. Target fixations were shorter if the preview was unrelated, compared to a nonword preview, indicating semantic preview benefit was not due to costs from unrelated words, but rather semantic facilitation. Moreover, in contrast to semantic preview benefit, the preview benefit from an identical vs. related condition was modulated by the awareness of display changes. Finally, meta-analyses with the data of the three experiments and therefore increased power were run to examine whether semantic preview benefit could be due to display-change awareness or mislocated fixations, and preview benefit remained reliable. Implications for models of eye-movement control will be discussed.

Inter-individual differences are addressed in Appendix B. Subjects and items were used as crossed random effects in the statistical models in Chapter 3. Analyses of random variance revealed interesting patterns, for example a negative relationship between the time an item is fixated and the size of the preview benefit. Random effects extend the insight gained from reading studies.

In Appendix C, I present an extensive assessment of the delay of display changes in gaze-contingent experiments. Since display-change paradigms were used in all experiments in Chapters 2 and 3, it appears critical to ensure that the exchange of words was not artificially delayed. A technical configuration was created which allows measuring the whole delay from a (virtual) eye movement to the actual change on the screen. The display-change delay was less than 10 ms and therefore not exceptionally long. Technical implications for gaze-contingent paradigms and the interpretation of eye-movement data will be discussed.

The results of the experiments are discussed in the corresponding sections (Discussions, General discussions). Three general considerations are addressed in Chapter 4. Firstly, I will review the evolution of gaze-contingent display-change paradigms with a focus on awareness of display changes and the paradigms used in Chapters 2 and 3. Secondly, additional considerations on computational models and the time course of parafoveal semantic processing will be discussed. Finally, I will discuss language differences in word processing and sentence parsing as well as the implications for parafoveal preview benefit.

2 SEMANTIC PREVIEW BENEFIT DURING EYE MOVEMENTS IN READING: A PARAFOVEAL FAST-PRIMING STUDY

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Running Head: Semantic preview benefit and parafoveal fast-priming

Hohenstein, S., Laubrock, J., & Kliegl, R. (2010). Semantic preview benefit in eye movements during reading: A parafoveal fast-priming study. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 36*, 1150–1170.

doi:10.1037/a0020233

ABSTRACT

Eye movements in reading are sensitive to foveal and parafoveal word features. Whereas the influence of orthographic or phonological parafoveal information on gaze control is undisputed, there has been no reliable evidence for early parafoveal extraction of semantic information in alphabetic script. Using a novel combination of the gaze-contingent fast-priming and boundary paradigms, we demonstrate semantic preview benefit when a semantically related parafoveal word was available during the initial 125 ms of a fixation on the pre-target word (Experiments 1 and 2). When the target location was made more salient, significant parafoveal semantic priming occurred only at 80 ms (Experiment 3). Finally, with short primes only (20, 40, 60 ms) effects were not significant but numerically in the expected direction for 40 and 60 ms (Experiment 4). In all experiments, fixation durations on the target word increased with prime durations under all conditions. The evidence for extraction of semantic information from the parafoveal word favors an explanation in terms of parallel word processing in reading.

Keywords: eye movements, reading, parafoveal preview, semantic priming

2.1 INTRODUCTION

When we read a text, we sample the visual input during a sequence of fixations, connected by rapid, jump-like eye movements called *saccades*. How our cognitive and oculomotor systems interact during this sequential sampling process is an important psychological question. Analysis of the properties of the text around fixation can be used to investigate cognitive and perceptual influences on fixation duration and saccade target selection. During the last 35 years much has been learned about what properties of fixated (i.e., foveal) and upcoming (i.e., parafoveal) words are important for eye guidance in reading and how they influence the dynamics of word recognition. Today, there is no doubt that not only foveal, but also parafoveal information is used to decide when and where to move the eyes during reading (see Rayner, 1998). Different types of parafoveal information vary in their degree of influence on eye-movement control in reading. The extraction of *phonological* and *orthographic* information is well documented for many languages and many variations of script (Rayner et al., 2003, for a review). There is also recent evidence for a semantic effect from non-compound (i.e., the most simple) characters during reading Chinese (Yan et al., 2009). There is, however, no undisputed evidence that *semantic* information can be processed parafoveally in alphabetic scripts (Rayner et al., 2003, for a review). Possibly, the failure to demonstrate a semantic preview effect is linked to the fact that so far, previews have always been available or denied for the entire prior fixation duration. Here we test the hypothesis that a semantic preview benefit may become visible if the critical information is presented only for a limited amount of time in the parafovea. The rationale is that presentation of a semantically related preview all of the time may actually interfere with the lexical access of the target word. Such a possible dissociation has a parallel in basic sensorimotor research, where the meaning of a stimulus can have a qualitatively different influence on behavior depending on whether it is consciously or subconsciously perceived (Eimer & Schlaghecken, 1998; Sumner, Tsai, Yu, & Nachev, 2006).

2.1.1 PARAFOVEAL PREVIEW BENEFITS

There is considerable evidence that a valid preview of the word to the right of fixation results in shorter fixations on that word if compared with a preview of an unrelated control word or a random string of letters. This effect is called *preview benefit* and is typically measured with the *boundary paradigm* (Rayner, 1975). In this paradigm, while subjects read, a single critical target word location is initially occupied by another word or a nonword. When the gaze crosses an invisible boundary, typically located directly prior to the space preceding the target word, the initially displayed stimulus is replaced by the target word. Subjects are generally unaware of the display change when it occurs during a saccade. Because the reader finally fixates a word that could not have been preprocessed parafoveally, one can calculate preview benefit by subtracting the fixation duration when the preview was identical to the target (or related to it in some way) from the fixation duration when the preview was unrelated to the target.

What properties of the preview facilitate reading? An important finding is that for the integration of information obtained during fixations on word *n*[3] and *n* + 1 no overlapping visual features are required. For example, alternating the case between fixations (McConkie & Zola, 1979; Rayner, McConkie, et al., 1980) or change of letter positions (Johnson, 2007; Johnson et al., 2007) does not affect eye movements, suggesting that processing is not based on low-level visual features but appears to rely on abstract letter codes. Moreover, orthographic codes in the form of initial letters of words are an effective parafoveal preview (Balota et al., 1985; Inhoff, 1989b; Rayner, McConkie, et al., 1980; Rayner, 1978).

Aside from orthographic codes, phonological information (i.e., the sound of a word) can also be processed parafoveally (Ashby et al., 2006; Chace et al., 2005; J. M. Henderson, Dixon, Petersen, & Twilley, 1995; Miellet & Sparrow, 2004; Pollatsek et al., 1992). Strong evidence for the existence of phonological parafoveal processing comes

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[3] In our notation word *n* is the word directly fixated (i.e., the foveal word). The word following it to the right is defined as word *n* + 1.

from studies by Ashby and colleagues (Ashby & Martin, 2008; Ashby & Rayner, 2004; Ashby, 2006) showing that prosodic information can be extracted parafoveally. Morphological information, on the other hand, does not seem to be a source for parafoveal preview benefit (Bertram & Hyönä, 2007; Inhoff, 1989a; Kambe, 2004; Lima, 1987).

Of special concern for the present study, however, is the controversial role of semantic information extraction from word *n* + 1. To date, the existence of semantic parafoveal preview benefit effects could not be demonstrated despite several attempts (Altarriba et al., 2001; Hyönä & Häikiö, 2005; Rayner et al., 1986; Rayner, McConkie, et al., 1980). Rayner, McConkie, et al. (1980) used a parafoveal word naming task in which the preview for a target word (*table*) was (among other conditions) either related (*chair*) or unrelated (*chore*). Reaction times exhibited no facilitation from semantically related previews. In contrast, orthographically related previews (*talks*) containing the initial two letters of the target produced shorter latencies for target word naming.

In the three other studies cited, the boundary paradigm was used during natural reading. In Rayner et al.'s (1986) experiment, target word (*tune*) presentation was preceded either by an identical, an orthographically related (*turc*), a semantically related (*song*), or an unrelated preview (*door*). Although fixation times revealed orthographic preview benefit (39 ms), there was no statistically reliable difference between the semantically related and unrelated conditions (4 ms).

Altarriba et al. (2001) used target words in English and Spanish. Bilingual subjects were asked to read sentences in which the target preview was either identical to the target word (*sweet* for *sweet*), a cognate (i.e., an orthographically similar translation; *crema* for *cream*), an orthographically similar pseudo-cognate of different meaning (*grasa* for *grass*), a non-cognate translation (*dulce* for *sweet*), or an unrelated control word (*torre* for *cream*). Although the different types of orthographic preview led to reduced fixation times, semantic previews did not (4 ms). In addition, Altarriba et al. employed a naming paradigm in which the same pattern of results was found.

More recently, Hyönä and Häikiö (2005) examined the influence of emotional words (i.e., sex- and threat-related and curse words) in parafoveal vision during reading of Finnish sentences. In each case the words shared the initial three letters. The results did not reveal reliable differences between emotional and neutral preview conditions.

Although semantic preview benefit has not been found for word *n* + 1, White et al. (2008) demonstrated that semantic information can be processed parafoveally *within* words. In their study, the preview for the second constituent of a Finnish compound noun was either semantically related or unrelated to the second constituent. This preview was replaced by the target word when the subjects' eyes crossed the boundary located between both constituents. Results indicate that the within-word parafoveal previews can be processed semantically.

There are a few studies by Murray and colleagues (Kennedy et al., 2004; Murray & Rowan, 1998; Murray, 1998) reporting some support for influences of the parafoveal semantic information upon the fixation on the preceding word in a sentence-matching task. These findings could not be replicated in a natural reading situation (Rayner et al., 2003).

Inhoff, Radach, et al. (2000) did find some evidence for semantic *parafoveal-on-foveal effects*. Fixation time on the foveal word was shorter when word *n* + 1 was related than when it was unrelated. However, in another experiment, Inhoff, Starr, et al. (2000) could not corroborate these findings. Taken together, studies using the boundary paradigm have so far failed to show preview benefit effects of semantic preprocessing of word *n* + 1 in alphabetic reading.

2.1.2 PRIMING STUDIES

Although the work of Altarriba et al. (2001), Rayner, McConkie, et al. (1980), and Rayner et al. (1986) suggests that effects of a semantically related parafoveal preview is not expressed in fixation times on the foveal target word in natural reading, several priming studies do report an influence of a semantically related word presented in parafoveal vision on reaction times to foveal words (Abad, Noguera, & Ortells, 2003; Di Pace et al., 1991; Fuentes, Carmona, Agis, & Catena, 1994; Fuentes & Tudela, 1992; Lupiáñez, Rueda, Ruz, & Tudela, 2000; Ortells, Abad, Noguera, & Lupiáñez, 2001; Ortells & Tudela, 1996). In these studies, a parafoveal prime is presented along with another word in foveal or parafoveal position, disappears after 30 to 150 ms, and is followed by a short interstimulus interval and the presentation of a foveal target. Results indicate that under time-controlled conditions (e.g., for the duration of stimulus presentation) and without eye movements, semantic information can be extracted from the parafoveal position and can be integrated with the processing of a foveal word. Recently, C. Lee and Kim (2009) showed that naming a foveal word can be influenced by the semantic relatedness of a simultaneously presented and subsequently masked parafoveal word.

What might cause the differences between priming studies and studies of natural reading in which the boundary paradigm has been used? Earlier results of this kind (Bradshaw, 1974; Marcel, 1978) were criticized for various methodological problems (Inhoff & Rayner, 1980; Inhoff, 1982; Paap & Newsome, 1981). At least some of the problems (i.e., lack of control of fixation position, no mask between prime and response) were present in the recent studies as well. Leaving these problems aside for now, we see at least three other differences: (1) control over prime duration, (2) correspondence between location of the prime and locus of attention, and (3) the degree to which the dependent variable is influenced by events before stimulus presentation. In priming studies, prime duration is controlled, attention is probably centered on the foveal word, and reaction time is largely unaffected by the state of the system before stimulus presentation. In boundary studies of reading, on the other hand, prime duration (i.e., preview) is positively correlated with gaze duration on the foveal word, attention is shifted in the reading direction, and the dependent variables (fixation duration and location, skipping probability, and so on) reflect the state of the system from reading the prior part of the sentence, as saccade programs are planned and programmed in advance, before any effects of stimulus manipulations can operate. These differences could combine to render evidence for semantic preview weaker in boundary than in priming experiments.

2.1.3 TIME COURSE OF PARAFOVEAL INFORMATION EXTRACTION

The type of information that can be obtained parafoveally has been dealt with in a large number of studies, but the *time course* of information extraction from the parafovea has been examined in only a few studies. In other words, we still do not know much about when during reading parafoveal information exerts its influence. There are, however, a few pieces of evidence. Note that these studies examined the time course of parafoveal processing generally and not for semantic previews. In studies with gaze-contingent control of parafoveal word preview, investigators have sought to determine the time frame of parafoveal information extraction by manipulating the temporal interval within which useful information is available in the parafovea (Morrison, 1984; Rayner et al., 1981; Rayner & Pollatsek, 1981). For example, Rayner et al. (1981) masked visual information within a window of seven or 17 characters at various times between 0 and 150 ms after fixation onset. Fixation durations systematically decreased from the 0-ms to the 50-ms delay where they reached an asymptote, indicating most of the relevant information had been extracted after 50 ms.

Morris, Rayner, and Pollatsek (1990) manipulated availability of parafoveal information by delaying its appearance (and not its masking). In one condition, a fixated word and all words to its left were visible throughout each fixation, but all parafoveal words to the right of fixation were replaced with a length-matched string of lowercase *x*s until 0, 50, 100, or 150 ms after fixation onset (Experiment 2). Under these conditions, fixation durations were increased with a masking duration as short as 50 ms. Thus, this study showed parafoveal information extraction starts at least as early as 50 ms from the onset of fixation.

Likewise, Rayner, Liversedge, and White (2006) manipulated the type of disruption of word *n* + 1. The word disappeared or was masked with uppercase *X*s 60 ms after the onset of fixation. The word only reappeared once a saccade was made to another word. In contrast to a control condition in which word *n* + 1 was permanently available, fixation durations were longer and regression rate was higher if parafoveal information was disrupted. These results demonstrate the importance of the continued presence of the parafoveal word, at least beyond the first 60 ms, for fluent reading.

In these studies, the manipulation of the temporal availability of a parafoveal target preview presumably hampered the reading process since visually distinct strings of *x*s or blank space were presented. As a result, attention shifts to the parafoveal word might have been somewhat different from normal reading. In a recent series of experiments by Inhoff, Eiter, and Radach (2005) examining the time course of parafoveal information extraction, the configuration of parafoveal presentations was less salient. In their first experiment temporal availability of a target word *n* + 1 was systematically manipulated. While fixating the pretarget word *n*, a parafoveal nonword was replaced by the target word. This change took place either 70, 140, or 210 ms after fixation onset; in the 0-ms control condition the target word was continuously available during sentence reading. Note that Inhoff et al.’s study did not involve semantic manipulation of preview. Gaze durations on the target word increased linearly by approximately 40 ms from the 70-ms to the 140-ms and from the 70-ms to the 140- to the 210-ms condition, respectively. Furthermore, there were virtually identical gaze durations in the control and the 70-ms delay conditions. These results suggest that parafoveal information extraction affecting abstract, letter-based representations starts only between 70 and 140 ms after fixation onset. Our experiments will allow us to replicate and further specify these timelines of parafoveal accrual of information.

2.1.4 TIME COURSE OF SEMANTIC INFORMATION EXTRACTION

As we have reviewed, there have been no reports so far of significant semantic peview benefits from parafoveal words in reading of alphabetic scripts. One approach to track the time course of semantic information extraction from the *foveal* word was introduced by Sereno and Rayner (1992) who developed the so-called *fast-priming paradigm*. In this procedure, when the eyes are to the left of an invisible boundary, a preview of random letters (*gzsd*) occupies the target location to prevent parafoveal preprocessing. During the saccade crossing the boundary, the prime, which can be semantically related (*love*) or unrelated (*rule*) to the target (*hate*), replaces the preview for a specified time. The target then replaces the prime and remains in place while the subject finishes reading the sentence. Using prime durations of 30, 45, and 60 ms, Sereno and Rayner (1992) found an effect of prime type at the 30-ms duration level only: In comparison to an unrelated prime, gaze duration was reduced by 28 ms if a related prime preceded the presentation of the target word. In their second experiment, Sereno and Rayner (1992) further explored the priming effect with prime durations of 21, 30, and 39 ms. Again, a priming advantage of 31 ms for related primes was only found at the 30-ms duration level. Semantic priming effects with similar prime durations were also reported by Sereno (1995; at 35 ms) and H.-W. Lee, Rayner, and Pollatsek (1999; at 32 ms). Apparently, the extraction of semantic information is limited to a narrow time frame within the initial 30−35 ms during the fixation of the foveal (i.e., directly fixated) word.

Interestingly, the time frame for semantic priming does not generalize to other types of information extracted from the foveal word during reading. Rather, investigators employing the fast priming paradigm (Ashby & Rayner, 2004; H.-W. Lee et al., 1999; H.-W. Lee, Kambe, Pollatsek, & Rayner, 2005; H.-W. Lee, Rayner, & Pollatsek, 2002; Y.-A. Lee, Binder, Kim, Pollatsek, & Rayner, 1999; Rayner, Sereno, Lesch, & Pollatsek, 1995) have indicated that different durations and broader time frames are effective for orthographic and phonological information.

In summary, some information is available on the time course of foveal semantic processing, but, to our knowledge, little is known about the time course of parafoveal semantic processing. As fast priming has yielded useful results about the time course of *foveal* semantic information extraction during sentence reading, we employ *parafoveal* fast priming to examine whether and when semantic information from word *n* + 1 facilitates its subsequent lexical access.

2.2 EXPERIMENT 1

According to previous results from the fast-priming paradigm, the effects of semantic properties of the fixated word are visible during a narrow time interval. We hypothesized this might also be true for the semantic properties of a parafoveal word.

One problem with the use of a semantically related preview for a parafoveal word in the boundary paradigm is the implied lack of temporal control of prime duration, leading to a preview being visible during the whole duration of the fixation on the word before it. Given that prime durations can be too short as well as too long in the fast-priming paradigm, the temporally uncontrolled parafoveal preview in the boundary paradigm may actually be the reason for the nonsignificant results in earlier boundary experiments.

To our knowledge, semantic preview benefit has not been studied with temporal control over a parafoveal word *n* + 1. We propose such an examination requires a combination of the boundary and the fast-priming paradigms with two gaze-contingent display changes, one during the saccade from word *n* − 1 to word *n* and the other during the fixation on word *n* (see Figure 2.1). The first invisible boundary after word *n* − 1 changes a consonant string at the location of the target word *n* + 1 to the prime for the target word while the eye moves from word *n* − 1 to the pretarget word *n*. The second display change (from prime to target) is triggered by a timer starting at the beginning of a fixation on the pretarget word *n* and takes place during this fixation. We manipulated the preview time of the parafoveal target word *n* + 1 using prime durations of 35, 80, and 125 ms.

The selection of the short duration (35 ms) was based on studies revealing foveal semantic priming in a time window of 30−35 ms. If extraction of semantic information occurs in parallel for the foveal and the parafoveal word, parafoveal priming effects might already occur at this prime duration. As the rapid decline of visual acuity with eccentricity may cause some delay between the availability of foveal and parafoveal information, we also included prime durations of 80 and 125 ms. In addition, we used high-frequency pretarget words *n* to induce a wide perceptual span and thereby increase the chance of observing distributed processing and parafoveal priming effects (e.g., J. M. Henderson & Ferreira, 1990; Kliegl et al., 2006).

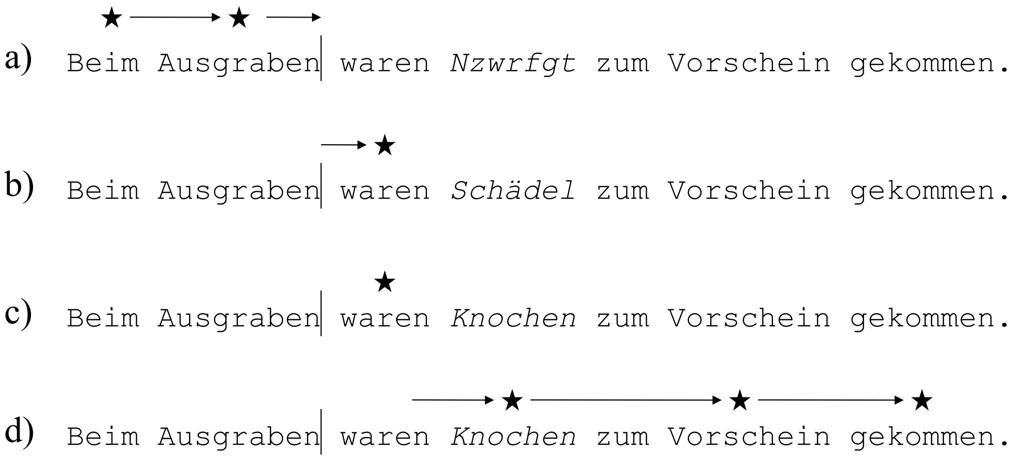

Figure 2.1. An example of the display changes during one trial: (a) before crossing the boundary (vertical line); (b) after crossing the boundary, but during the prime duration; (c) and (d) after the prime duration. Stars indicate fixations and arrows indicate saccades. Translation: "With the excavation skulls/bones had shown up." Unrelated prime: "Stiefel" ("boots").

Note that in this paradigm, all display changes occur at the location of the target word *n* + 1. They are completed during the saccade to the pretarget word and during the fixation on the pretarget word. Thus, any differential effects of prime type and prime duration on fixations on the target word cannot be attributed to visual changes during target word fixation.

2.2.1 METHOD

2.2.1.1 SUBJECTS

Thirty-six students (30 women, 6 men) of the University of Potsdam participated in the experiment. Their age was between 19 and 38 years (*M* = 24, *SD* = 4.7). They were paid €6 or received course credit. All were native speakers of German with normal or corrected-to-normal vision. The experiment lasted between 30 and 40 minutes.

2.2.1.2 APPARATUS

Subjects were seated at a distance of 60 cm (23.62 in.) in front of an Iiyama Vision Master Pro 514 Monitor (Iiyama Seiki Co., Nagano, Japan; 1024 × 786 pixels; 53.34 cm [21 in.]; vertical refresh rate 150 Hz; Courier New bold font). One character covered 20 pixels vertically and 12 pixels horizontally (0.45 degrees of visual angle). All sentences were presented in black on a light gray background. We conducted the experiment in MATLAB (The MathWorks, Natick, MA) using the Psychophysics toolbox (Brainard, 1997; Pelli, 1997) and the Eyelink toolbox (Cornelissen, Peters, & Palmer, 2002). Both eyes were monitored using an EyeLink II system (SR Research, Osgoode, ON, Canada) with a sampling rate of 500 Hz, an instrumental spatial resolution of 0.01°, and an average accuracy of better than 0.5°. Heads were positioned on a chin rest to minimize head movements.

2.2.1.3 MATERIAL

Experimental sentences

The 102 experimental sentences were constructed around a target region of foveal pretarget word *n* and parafoveal target word *n* + 1 and ranged from 6 to 13 words. Word lengths ranged from 2 to 18 characters, but we chose pretarget and target words that were all between 4 and 8 letters long to maximize single-fixation probabilities. All frequency norms are based on the Digitales Wörterbuch der deutschen Gegewartssprache [Digital Dictionary of Contemporary German Language] corpus (Geyken, 2007; Heister et al., 2011; database version from November 2007), a German text corpus based on more than 100 million tokens. We used lemma frequencies (i.e., the frequency of occurrence of words with the same root) because the end of a word can barely be identified in parafoveal position. Table 2.1 shows details about these frequencies for target words and related and unrelated primes.

Table 2.1

Means and Standard Deviations of the Untransformed and the Log_{10} Lemma Frequencies for Target Words, Related Primes (RP), and Unrelated Primes (UP) and the Absolute Differences Between the Prime Types

	Target		RP		UP		|RP − UP|	
Frequency	M	SD	M	SD	M	SD	M	SD
Untransformed	42.9	75.5	37.8	63.7	37.8	61.9	2.23	9.53
Log_{10}	1.2	0.6	1.2	0.6	1.2	0.6	0.02	0.07

Foveal pretarget words

We selected pretarget words that were between 4 and 8 letters long and of high type frequency (range: 84−6,552 per million) to increase the possibility of having a broad perceptual span and gaining information from the parafoveal target word. Mean of the base-10 logarithmic frequency was 2.5 (*SD* = 0.4). The pretarget words covered different word classes (e.g., verbs, adjectives) but no nouns (which were used as targets). Each of the 102 experimental sentences contained a different word; thus, there was no overlap that could produce distortion.

Parafoveal target words and related primes

Target words were between 4 and 8 characters long (*M* = 5.3, *SD* = 1.0) and their token frequencies ranged from 0.12 to 207 per million; related primes were of the same length and their frequencies ranged from 0.29 to 243 per million. Semantically related primes originated from different sources. Some were taken from word production tasks (Hasselhorn & Grube, 1994; Hasselhorn & Hager, 1994; Riedlinger, 1994; Schmuck, 1994), others from judgments of semantic relatedness of word pairs (Hasselhorn, 1994; Schütz, 2007), and the rest (46%) were selected by the first author. Six persons independently rated them as semantically related; that is, they judged each of the simultaneously presented “related prime/target” combinations as semantically related (yes/no answer). Furthermore, we evaluated primes and targets in a pretest using a classical priming paradigm (500-ms forward mask, 300-ms prime duration, prime-target interstimulus interval of 0 ms, lexical decision task) and found that semantic relatedness significantly reduced reaction times (semantic priming effect of 29 ms). One major constraint in generating the stimuli, given the display changes in the study, was that primes had to be of the same length as target words and that the related primes fit into the sentence frame. All target words and related primes were unique between sentences, leading to a total of 204 different stimuli (target word and related prime in each sentence).

Unrelated primes

We constructed unrelated primes using three criteria: (a) same length as the target word, (b) identical overlap of characters with the target word as the related prime, and (c) the frequency differences between related and unrelated primes minimized. The first criterion—the same word length—was met at the item level. The second criterion (character overlap) was also met at the item level. It was implemented to equate the amount of orthographic information shared between the target word and both primes. For example, the related prime *Nerz* (translated: mink) and the associated target word *Pelz* (fur) share the character *e* at second position and the character *z* at fourth position. The unrelated prime *Lenz* (springtime) covers this overlap but has no further overlap with the target word. The third criterion was to minimize differences between lemma frequencies of related and unrelated primes. Unrelated primes ranged in frequency between 0.03 and 182 per million. Mean lemma frequency was identical between lists for both prime types; the mean absolute difference at the item level was 2.2 per million. Unrelated primes had been constructed with regard to orthography, frequency, and length, but 47% of them did not fit into the sentence syntactically. Finally, unrelated primes were used only once and did not overlap with the set of targets or related primes.

Filler and training sentences

In addition to the experimental sentences, there were 12 training and 24 filler sentences with target words as well as related and unrelated primes. In the filler sentences, target words were selected from different word classes (e.g., adjectives, adverbs, verbs, but not nouns). This measure was taken to reduce subjects' anticipation that a change would occur on a noun. Training sentences also contained target words of different word classes.

2.2.1.4 DESIGN

The experimental design implemented six conditions with 102 trials per subject. Conditions mapped onto two orthogonal factors, prime type (related vs. unrelated) and prime duration (35 vs. 80 vs. 125 ms). Each experimental condition was presented equally often, rendering 17 experimental sentences per condition and subject. The mapping of experimental condition to sentences was counterbalanced with the constraint that each sentence occurred equally often in each of the six conditions. As 36 subjects were tested, each sentence was read six times in each condition. The presentation order of sentences, and hence of experimental conditions, was randomized. We will refer to the three prime-duration conditions as D35, D80, and D125, respectively.

2.2.1.5 PROCEDURE

Subjects were naive concerning the purpose of the experiment. They were instructed to read single sentences for comprehension. They were also told they might see flashes while they read but try to read as normally as possible. Their field of vision was calibrated with a standard nine-point grid for both eyes and recalibrated after every 15 sentences or if the system failed to identify a fixation at a spot on the left side of the monitor within 2 seconds. If the eye tracker identified a fixation, the fixation point disappeared, and a sentence was presented such that the center of the first word replaced the initial fixation point. Participants ended presentation of a sentence by looking into the lower right corner of the screen.

A random sample of one third of the sentences was followed by a three-alternative multiple-choice question that subjects answered by clicking on one of the response alternatives. A large portion of questions required comprehension at the semantic level, wich rendered unsuccessful an answering strategy based on superficial visual comparison between sentence and possible solutions (Bohn & Kliegl, 2007). Ninety-five percent of all questions were answered correctly, indicating no serious comprehension problems.

Subjects read six training sentences to become familiar with the procedure, followed by the experimental sentences. Figure 2.1 illustrates the sequence of display changes during one trial. When a sentence was initially presented, a string of random consonants occupied the target location (Figure 2.1a) to prevent information extraction before fixation of the pretarget word. An invisible boundary located directly after the last letter of word $n - 1$ before the pretarget word n was present in each sentence. When the eyes crossed the boundary, target word $n + 1$ was replaced with the prime (Figure 2.1b). The prime word remained in the target location for 35, 80, or 125 ms (measured from the onset of fixation, not from when the eyes crossed the boundary) and was then replaced by the target word $n + 1$ (Figure 2.1c). The sentence remained in this final form until the end of the trial (Figure 2.1d). After the eye tracker had signaled crossing of the boundary, display changes were accomplished within a mean time of 3.33 ms depending on the position of the cathode ray at the moment of the initialization of a particular change. Since the prime was not displayed until the eyes left word $n - 1$, parafoveal information extraction from the prime in position $n + 1$ was limited to the specified prime duration during fixation of word n.

2.2.1.6 DATA ANALYSIS

Measures and selection criteria

Data from sentences with a blink or loss of measurement were only used until the point in time preceding the first loss and only if the loss occurred after the target region. Saccades were detected with a binocular velocity-based algorithm (Engbert & Kliegl, 2003; improved version by Engbert & Mergenthaler, 2006). Small saccades (i.e., microsaccades) were considered part of a fixation if they covered a distance of less than the width of two characters.

As this study is similar to the one by Inhoff et al. (2005) with respect to the manipulation of the temporal delay of a target word, we adopted their procedure for data filtering. All trials in which the pretarget word was skipped (which happened occassionally, due to its high frequency) and trials with first-fixation durations shorter than the prime duration on the pretarget word were eliminated because, in this case, the change from prime to target could not be implemented during that fixation This filter left us with 72% and 69% valid trials for the left and right eye, respectively. Trials were included only if pretarget and target words were fixated in sequence (valid trials remaining: 66% and 64%, respectively). In addition, the saccade landing on pretarget word *n* and the saccade leaving the target word *n* + 1 had to be right-directed so that the reading of this sentence segment was strictly unidirectional (valid trials remaining: 56% and 54%, respectively).

At this level of data filtering, prime duration was confounded with the shortest possible fixation duration on the pretarget. To equate all remaining conditions for the duration of the shortest eligible pretarget viewing, which was 125 ms in the D125 condition, we adpoted a lower level cutoff of 125 ms. After application of all criteria, approximately 55% valid trials for the left eye and 54% for the right eye remained. For comparison, Inhoff et al. (2005) recorded only the right eye and obtained 60% valid trials. As data from both eyes were available in the present study, the remaining trials were validated binocularly (i.e., we excluded trials when at one point in time the eyes fixated different words). This resulted in 49% valid trials, equally distributed over the six experimental conditions (range: 48−51%). The exclusion of trials did not change the general pattern of effects. For these trials, gaze durations (the sum of all first-pass fixations; see Inhoff & Radach, 1998, for a definition of these measures), first-fixation durations, and refixation probabilities were computed for words *n* and *n* + 1. In addition, landing position in word *n* + 1 (i.e., the position of the first fixation) was computed. For the computation of skipping probability of word *n* + 1, we used trials in which word *n* was fixated during the entire prime duration and was left with a right-directed saccade. Sixty-two percent of all trials remained for this measure after binocular validation.

Statistical analysis

We analysed the experimental conditions (two prime types × three prime durations) with linear and quadratic trends across prime durations and three contrasts testing prime type within each of the prime durations. Inferential statistics for fixation durations are based on linear mixed models (LMMs) specifying subjects and sentences as crossed random effects (Baayen, Davidson, & Bates, 2008; Kliegl, Masson, & Richter, 2010). We analysed refixation and skipping probabilities with generalized linear mixed models using the binomial distribution with a logit link function. In the LMM analyses, differences between subjects and differences between sentences (items) are accounted for in a single analysis, rather than in two separate analyses of variance (F_1 and F_2); LMMs also lose much less statistical power with unbalanced designs (Baayen, 2008; Quené & van den Bergh, 2008)—typical of eye-movement experiments.

All effects are estimated with the lmer program from the lme4 package (Bates & Maechler, 2009) in the R environment for statistical computing (version 2.10.0; R Development Core Team, 2009). We report regression coefficients and standard errors (*SE*). There is no clear definition of “degree of freedom” for LMMs, and therefore precise *p* values cannot be estimated. In general, however, given the large number of observations, subjects, and items entering our analyses and the comparatively small number of fixed and random effects estimated, the *t*-distribution is equivalent to the normal distribution for all practical purposes. Therefore, the contribution of the degrees of freedom to the test statistic is negligible. The normal distribution is also conventionally assumed for the LMM test statistics. For all tests, we use the two-tailed criterion (LMM: $t \geq 1.96$ *SE;* generalized LMM: $z \geq 1.96$ *SE*), corresponding to a 5% error criterion for significance.

2.2.2 RESULTS

2.2.2.1 PRETARGET WORD

Table 2.2 reports means and standard deviations for gaze durations, first-fixation durations, and refixation probabilities, broken down by the experimental conditions, for the pretarget word *n*. Gaze durations revealed no significant priming effects, either globally nor at a certain prime duration (all $|t|$s < 1.14). First-fixation durations revealed a significant difference between unrelated and related primes at the D80 condition (b = 17 ms, *SE* = 8 ms, t = 2.1). There were no priming or duration-related effects on refixation rates.

Table 2.2

Means and Standard Deviations of Pretarget Reading as a Function of Prime Duration and Prime Type (Experiment 1)

	35 ms		80 ms		125 ms	
Prime	M	SD	M	SD	M	SD
Gaze duration [ms]						
related	277	117	271	124	268	129
unrelated	282	127	274	125	258	114
First-fixation duration [ms]						
related	265	115	247	111	244	116
unrelated	259	113	261	115	242	103
Refixation probability						
related	0.078	0.016	0.105	0.018	0.097	0.017
unrelated	0.128	0.019	0.069	0.014	0.088	0.016

Note. Refixation probability ranged from 0 to 1.

Both gaze and first-fixation durations decreased with increasing parafoveal prime duration (linear trend for gaze: *b* = −0.23, *SE* = 0.07, *t* = −3.4; linear trend for first fixation: *b* = −0.27, *SE* = 0.06, *t* = −4.3). In all analyses, the regression coefficient (*b*) for the linear trend is equivalent to the slope; that is, the value of *b* is the mean increase in the dependent variable (e.g., milliseconds of fixation duration) given an increase of 1 ms in prime duration. In summary, the later the parafoveal display changes occurred at word *n* + 1, the faster the saccade program originating from word *n* was executed.

2.2.2.2 TARGET WORD

Table 2.3 contains means and standard deviations for skipping probabilities, gaze durations, first-fixation durations, refixation probabilities, and landing positions associated with the target word *n* + 1, that is, at the location of the visual changes, for the six experimental conditions. The two display changes had occurred on this word, before the word was fixated. Thus, during actual fixations, the same word was displayed in all experimental conditions. In other words, we measured effects originating in processes during the last fixation. The analyses are based on 1,804 observations.

Figure 2.2 shows gaze durations on the target for the six experimental conditions. Contrasts revealed significant priming effects in the D35 condition (*b* = 12.5 ms, *SE*= 6.3, ms, *t* = 1.97) and in the D125 condition (*b* = 22.8 ms, *SE* = 6.4, *t* = 3.6) but no significant difference in the D80 condition (*b* = 6.8 ms, *SE* = 6.3 ms, *t* = 1.1). The overall prime effect was also significant (*b* = 13 ms, *SE*= 3.8 ms, *t* = 3.5). As is also evident from Figure 2.2, gaze durations increased significantly across prime durations (*b* = 0.55, *SE* = 0.05, *t* = 11.1, for the overall linear trend). First-fixation durations followed a pattern similar to that observed for gaze durations with a significant overall priming effect (*b* = 7.1 ms, *SE* = 3.5 ms, *t* = 2.02). Contrasts revealed a significant priming effect in the D125 condition only (*b* = 18 ms, *SE* = 5.9 ms, *t* = 3.0; D35: *b* = 4 ms and D80: *b* = 2 ms). Durations increased significantly with prime duration (*b* = 0.55, *SE* = 0.05, *t* = 11.9, for the overall linear trend).

Table 2.3

Means and Standard Deviations of Target Reading as a Function of Prime Duration and Prime Type (Experiment 1)

	35 ms		80 ms		125 ms	
Prime	M	SD	M	SD	M	SD
Skipping probability						
related	0.037	0.188	0.019	0.138	0.033	0.179
unrelated	0.041	0.197	0.028	0.166	0.024	0.153
Gaze duration [ms]						
related	219	68	245	76	261	79
unrelated	229	86	251	79	285	115
First-fixation duration [ms]						
related	208	65	229	73	250	78
unrelated	209	62	231	66	268	111
Refixation probability						
related	0.085	0.279	0.125	0.331	0.070	0.256
unrelated	0.135	0.342	0.147	0.355	0.118	0.323
Landing position						
related	0.443	0.212	0.437	0.210	0.500	0.236
unrelated	0.408	0.215	0.428	0.214	0.469	0.218

Note. Refixation probability, skipping probability, and landing position ranged from 0 to 1.

Refixation rate of target words was relatively low at 11%. The refixation rate was a significant 4% higher for unrelated than for related primes (b = 0.38, SE = 0.16, z = 2.31). Contrasts revealed a significant priming effect of 5% in the D35 condition (b = 0.58, SE = 0.29, z = 1.97) and a nonsignificant effect of the same magnitude in the D125 condition (b = 0.46, SE = 0.30, z = 1.47). With respect to prime duration, refixation rate followed an inverted v-shape function (i.e., 11% to 13.5% to 9.4%), reflected in a significant quadratic trend (b = −0.14, SE = 0.06, z = −2.6). Skipping rate was very low at 3% and did not differ between experimental conditions ($|z|s < 1.4$).

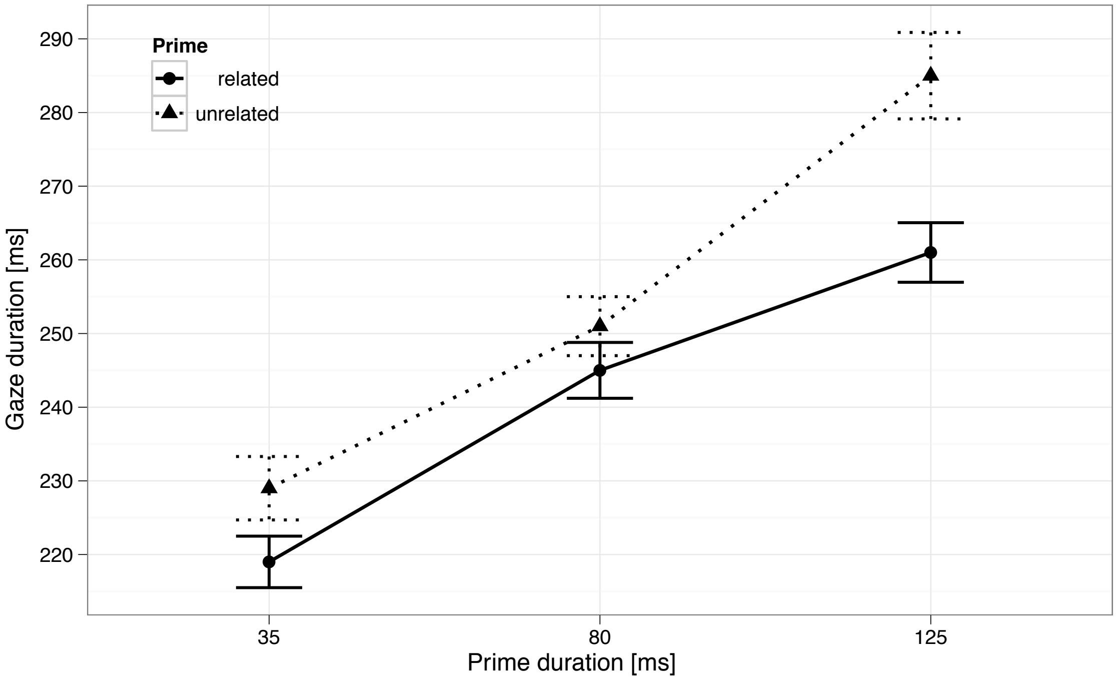

Figure 2.2. Gaze duration on the target word as a function of prime and prime duration (Experiment 1). Error bars denote standard errors computed from the residuals of the linear mixed models, that is, after removal of between-subject and between-item random effects.

Finally, we analysed the relative landing position (i.e., the absolute landing position [in characters] divided by word length [in characters]) of the first fixation on the target word. The variable ranges from 0 (for the beginning of the space preceding the word) to 1 (for the end of its last character). Mean landing position was .45 and hence slightly to the left of the word's center. This measure exhibited only a small range from .41 to .50, depending on the experimental conditions. Nevertheless, for unrelated primes the landing position was significantly further to the left than for related primes ($b = -0.021$, $SE = 0.009$, $t = -2.4$). The contrasts within durations mirrored the pattern for gaze durations, with marginal effects for D35 and D125 conditions ($t = -1.81$ and $t = -1.87$, respectively). Also, landing positions increased from the 80-ms to the 125-ms prime duration (linear trend: $b = 0.0007$, $SE = 0.0001$, $t = 5.45$; quadratic trend: $b = 0.008$, $SE = 0.003$, $t = 2.45$).

Since the application of filter criteria gave rise to the exclusion of about half of the trials, we reexamined the results with a less restrictive set of criteria. To allow the interpretation of results as a consequence of experimental manipulations, we included trials if the pretarget word was fixated for the whole prime duration and if the target was fixated when the eyes left the pretarget word. This filter left us with 66% and 64% valid trials for the left and right eyes, respectively. The focus of this study was target fixation durations. Deploying the same statistical analyses, we found the following results: First-fixation durations showed significant priming effects given durations of 125 ms (left eye: t = 2.05, right eye: t = 2.39) and a significant linear increase with prime durations (left eye: t = 11.04, right eye: t = 11.55). Gaze durations showed a significant priming effects given a duration of 125 ms (left eye: t = 2.08, right eye: t = 2.92) and a marginally significant effect at 35 ms (left eye: t = 2.06, right eye: t = 1.84) as well as a significant linear increase with prime durations (left eye: t = 10.47, right eye: t = 10.45). In summary, in this analysis, the previously barely significant D35 priming effect is significant for the left but not for the right eye. All the other results remained as before when we softened the criteria for the exclusion of trials.

2.2.3 DISCUSSION

The primary result of this experiment is statistically reliable evidence for semantic preview benefit in a combination of the boundary and parafoveal fast-priming paradigms. This priming effect was significant overall and for the prime duration of 125 ms; the effect also was numerically in the expected direction for 80-ms prime duration. In the 35-ms condition, the priming effect was ambiguous. A second set of important results relates to the increase in fixation duration on target word $n + 1$ as a function of the prime duration applied during the preceding fixation on the pretarget word n. In the following, we discuss these two sets of results.

2.2.3.1 PARAFOVEAL SEMANTIC PREVIEW BENEFIT

There were global semantic priming effects for gaze durations, first-fixation durations, landing positions, and refixations. If a related prime had been presented parafoveally, then the target word was fixated faster than when an unrelated prime had been presented. This priming effect had the size of 13 ms for gaze duration and 7 ms for first-fixation duration. Moreover, there were specific priming effects at the D35 (only in gaze durations and inconsistent for both eyes) and the D125 conditions (gaze and first-fixation durations), indicating that the extraction of semantic information from the parafovea might be biphasic, similar to semantic priming in the lexical decision task (Dagenbach et al., 1989). If one considers the D125 effect the main reliable effect, this finding also matches the pattern of results of foveal fast-priming studies showing that priming during reading becomes effective within a particular time frame. For example, Sereno and Rayner (1992) reported a priming effect of 28 ms for gaze durations, but a difference of 13 ms for first-fixation durations with a prime duration of 30 ms. Effects of similar size were also reported by Sereno and Rayner in their second experiment as well as by Sereno (1995) and H.-W. Lee et al. (1999). As expected, in general, the parafoveal fast-priming effects resembled the pattern of foveal fast priming with respect to larger effect in gaze duration compared to first-fixation duration. Such differences between gaze and first-fixation durations were also found with foveal and parafoveal priming, although the refixation in foveal fast-priming experiments was the one directly following the fixation at which the prime was present, whereas in the present study it was the next but one at the earliest.

D35 condition

In the D35 condition the effect was significant with a size of 13 ms for gaze durations, but was nearly absent (4 ms) for first-fixation durations. Furthermore, the gaze-duration effect was reliable for the left eye only. Evidently, the possible benefit of a semantically related prime presented for 35 ms needs further investigation.

D80 condition

In the D80 condition neither gaze durations nor first-fixation durations revealed significant priming effects. Possibly, disrupting processes such as a more salient stimulus change neutralized the small benefit of related primes that was present in the D35 condition. Incidentally, a similar disappearance of priming effects was reported in foveal fast-priming studies with prime durations through 60 ms (H.-W. Lee et al., 1999; Sereno, 1995; Sereno & Rayner, 1992).

D125 condition

With a long prime duration of 125 ms, the priming effect appeared reliably for both gaze durations and first-fixation durations in both eyes. Compared with foveal fast-priming experiments (H.-W. Lee et al., 1999; Sereno, 1995; Sereno & Rayner, 1992), the effective priming duration has to be longer for parafoveal fast priming, most likely due to less effective parafoveal information accrual in reading.

The similarity of results between the present experiment and the earlier foveal fast-priming experiments is quite remarkable. At the same time, our results differ from earlier boundary experiments in which investigators tried to establish a semantic preview benefit. We suspect that the lack of control over prime duration prevented the discovery of semantic priming effects in the classic boundary paradigm. In summary, to our knowledge, this is the first demonstration of preprocessing a parafoveal word semantically during natural reading of alphabetic script.

2.2.3.2 PRIME DURATION EFFECTS ON SUBSEQUENT FIXATION DURATIONS

A second result was that prime duration, applied during fixations on the pretarget word *n*, influenced fixation durations on target word *n* + 1 in such a way that longer primes led to longer subsequent fixation durations. This increase was nearly linear and replicated that found by Inhoff et al. (2005) who reported a linear increase with a slope of 0.55 in gaze duration between target delays of 70 ms and 210 ms. Our results also match Inhoff et al.'s results quantitatively: In our experiment, gaze duration increased with a slope of 0.55 between the prime duration of 35 ms and the prime duration of 125 ms.

There are two obvious explanations for this effect. First, the longer the prime duration, the more likely subjects are to notice the change from prime (unrelated or related) to target in the parafovea. Even the parafoveal visual event by itself may have caused some disruption of processing that became manifest only during the next fixation. Second, the longer the prime duration, the shorter is the preview of the target word, causing a reduction of the classic preview benefit. Obviously, these explanations are not mutually exclusive.

A potential alternative explanation, namely that earlier parafoveal changes (with shorter prime durations) might have attracted the attention to the target word when the processing of the fixated word was still incomplete, is not supported by the data. Incomplete processing should result in a higher regression probability after the target word has been fixated, but regression rates (15%) did not differ with respect to prime duration ($|z|\text{s} < 1.1$).

The most interesting finding in this context is the increase in fixation durations between the D35 and the D80 conditions, suggesting that parafoveal information extraction begins within this time window or even before 35 ms. The result is relevant because Inhoff et al. (2005) did not find any difference between the condition in which the target was delayed for 70 ms and the condition in which the target was visible throughout the whole pretarget fixation(s) (i.e., when it was not delayed at all). This result has important implications for assumptions about timelines of word recognition in current models of eye-movement control in reading. We will return to these issues in the General discussion. Clearly, at this point, the semantic preview benefit and the effects of parafoveal prime durations were important enough to warrant a second experiment that established their stability.

2.3 EXPERIMENT 2

The primary finding of Experiment 1 was a semantic preview benefit with 125 ms prime duration during fixation of the pretarget word. The effects were less clear for shorter prime durations. Therefore we replicated Experiment 1 to consolidate our conclusions.[4]

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[4] Experiment 2 was carried out upon request of the reviewers; chronologically, it occurred after Experiment 4.

2.3.1 METHOD

2.3.1.1 SUBJECTS

Thirty-six high school and university students (29 women, 7 men) from Potsdam, Germany participated in the experiment. Their age was between 19 and 41 years (*M* = 22.8, *SD* = 4.8). They were paid €6 or received course credit. All were native speakers of German with normal or corrected-to-normal vision. The experiment lasted between 30 and 40 minutes. None of the subjects participated in Experiment 1.

2.3.1.2 MATERIAL

The material of Experiment 1 was used again. Sentence frames, target words, and unrelated primes were always presented in the same typeface.

2.3.1.3 PROCEDURE

The experimental procedure was identical with the one adopted in Experiment 1. Ninety-five percent of all questions following sentence reading were answered correctly, indicating good comprehension.

2.3.1.4 DATA ANALYSIS

Data analysis also followed the procedure described for Experiment 1. After application of all filtering criteria for the target region, approximately 54% valid trials for the left eye and 52% for the right eye remained. Binocular validation resulted in the remaining 47% of all trials. For skipping probabilities for word *n* + 1, 59% of all trials remained after binocular filtering.

2.3.2 RESULTS AND DISCUSSION

2.3.2.1 PRETARGET WORD

Table 2.4 displays means and standard deviations for gaze durations, first-fixation durations, and refixation probabilities for the pretarget word *n*, broken down by experimental condition. Aside from a marginally significant 35-ms priming effect for gaze duration (*t* = −1.8), neither gaze nor first-fixation durations showed priming effects (|*t*|s < 0.92). Pretarget gaze duration decreased significantly with prime duration (*b* = −0.18, *SE* = 0.07, *t* = −2.42, for the overall linear trend). First fixations showed no prime-duration effects (|*t*|s < 1.46). Refixation rate was 9.1% and did not differ with respect to the priming and duration conditions (|*z*|s < 0.63).

Table 2.4

Means and Standard Deviations of Pretarget Reading as a Function of Prime Duration and Prime Type (Experiment 2)

	35 ms		80 ms		125 ms	
Prime	M	SD	M	SD	M	SD
Gaze duration [ms]						
related	300	134	298	142	281	120
unrelated	295	148	290	131	283	122
First-fixation duration [ms]						
related	272	115	279	136	269	113
unrelated	275	126	276	129	262	105
Refixation probability						
related	0.118	0.323	0.096	0.294	0.072	0.259
unrelated	0.085	0.280	0.075	0.264	0.098	0.298

Note. Refixation probability ranged from 0 to 1.

2.3.2.2 TARGET WORD

Table 2.5 displays means and standard deviations for skipping probabilities, gaze durations, first-fixation durations, refixation probabilities, and landing positions for target word *n* + 1, broken down for the experimental conditions. As in Experiment 1, the probability of target skipping was low—only 3.2%. Apart from a marginally significant quadratic trend over prime durations (v-shape; *z* = 1.9), none of the priming contrasts or the linear prime duration trend was significant (|*z*|s < 1.0).

Table 2.5

Means and Standard Deviations of Target Reading as a Function of Prime Duration and Prime Type (Experiment 2)

	35 ms		80 ms		125 ms	
Prime	M	SD	M	SD	M	SD
Skipping probability						
related	0.036	0.187	0.027	0.163	0.041	0.198
unrelated	0.046	0.210	0.017	0.128	0.023	0.150
Gaze duration [ms]						
related	244	110	267	116	281	105
unrelated	244	98	279	102	302	144
First-fixation duration [ms]						
related	225	92	249	108	269	104
unrelated	231	86	261	100	286	142
Refixation probability						
related	0.091	0.288	0.102	0.304	0.090	0.287
unrelated	0.072	0.258	0.123	0.329	0.102	0.303
Landing position						
related	0.450	0.238	0.472	0.216	0.479	0.221
unrelated	0.435	0.214	0.468	0.220	0.486	0.214

Note. Refixation probability, skipping probability, and landing position ranged from 0 to 1.

Figure 2.3 shows gaze durations on the target for the six experimental conditions. Contrasts revealed a significant priming effect in the D125 condition (*b* = 24 ms, *SE* = 8.3, ms, *t* = 2.92) but no significant differences in the D35 condition (*b* = −3 ms) and the D80 condition (*b* = 12 ms, *t* = 1.4), respectively. The overall prime effect was also significant (*b* = 11 ms, *SE* = 4.8 ms, *t* = 2.2). As in the other experiments, gaze durations increased significantly across prime durations (*b* = 0.54, *SE* = 0.06, *t* = 8.5, for the overall linear trend). First-fixation durations followed a pattern similar to that observed for gaze durations with a significant overall priming effect (*b* = 12 ms, *SE* = 4.6 ms, *t* = 2.58). Contrasts revealed a significant priming effect in the D125 condition only (*b* = 21 ms, *SE*

= 8.0 ms, *t* = 2.63; D35: *b* = 3 ms and D80: *b* = 13 ms, *t* = 1.6). Again, first-fixation durations increased significantly with prime duration (*b* = 0.55, *SE* = 0.06, *t* = 8.8, for the overall linear trend).

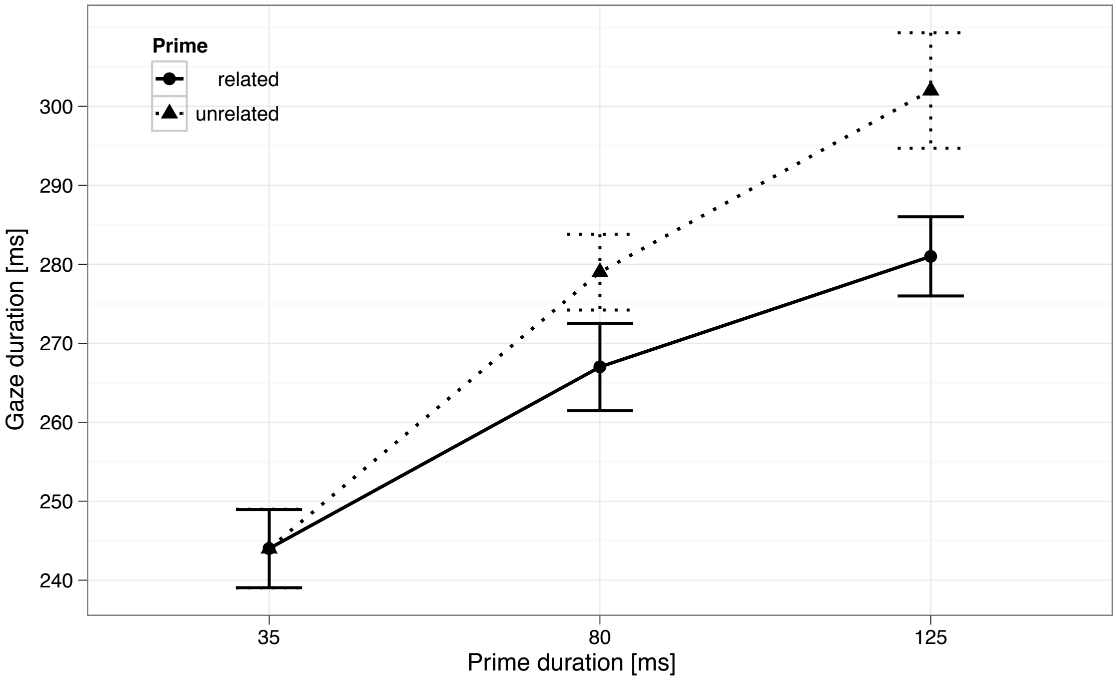

Figure 2.3. Gaze duration on the target word as a function of prime and prime duration (Experiment 2). Error bars denote standard errors, that is, after removal of between-subject and between-item random effects.

Refixation rate of target words was relatively low at 10% and was not influenced by priming (|*t*|s < .79). With respect to prime duration, refixation rate followed an inverted v-shape function, reflected in a marginally significant quadratic trend (*b* = −0.11, *SE* = 0.06, *z* = −1.8).

Mean landing position was .46 and thus slightly left from the target-word center. Along the six experimental conditions there was a narrow range from .44 to .49, and none of the prime contrasts was significant (|*t*|s < 0.9); however, landing position was significantly shifted rightwards with increasing prime duration (*b* = 0.0004, *SE* = 0.0001, *t* = 3.3, for the overall linear trend).

2.3.3 DISCUSSION

In this experiment, the general pattern of results from Experiment 1 could be replicated. A global priming effect and a specific one at the 125-ms condition emerged for both first-fixation and gaze durations. Since we did not replicate the ambiguous 35-ms effect, further research is needed to determine whether the effect obtained in Experiment 1 was a chance effect. Tasks effects on the generally fragile semantic priming effects in the threshold region have been reported in several studies (Dagenbach et al., 1989; Kouider & Dehaene, 2007).

On the other hand, the 125-ms priming effect replicated well, with a size of 24 ms in gaze and 21 ms in first-fixation durations (compared with 23 ms and 18 ms, respectively, in Experiment 1). Furthermore, we observed a trend of increasing differences between related and unrelated primes with increasing prime durations for both gaze and first-fixation durations on the target.

We observed the general linear increase of gaze and first-fixation durations on the target word as a function of prime duration. Gaze duration increased with a slope of 0.54 being virtually identical to the slope obtained in Experiment 1 (0.55).

2.4 EXPERIMENT 3

Experiments 1 and 2 revealed a semantic preview benefit—an effect that has not been found in previous studies. The effect depended on the control of temporal availability of the prime in parafoveal preview. One interesting pattern in the results of Experiment 2 was the relation between prime duration and priming effect size in target fixation durations: As prime duration increased from 35 ms to 80 ms and to 125 ms, the priming effect in gaze duration was −3 ms, 11 ms, and 24 ms, respectively. First fixations showed a similar trend (3 ms, 13 ms, and 21 ms). Since this pattern revealed a nonsignificant but numerical priming effect in the 80-ms condition, we attempted to enhance visual parafoveal recognition to evaluate the potential of a prime presented for 80 ms being sufficient to produce reliable priming.

For this purpose, we designed Experiment 3 to facilitate visual information uptake from the prime word by presenting the primes in bold typeface whereas all other parts of the sentences—targets and sentence frames—were presented in normal typeface. We assumed that a parafoveal word appearing in bold would be more salient than the preceding and succeeding words. Therefore, we expected the parafoveal prime would enhance the semantic preview benefit for succeeding fixation(s) on the target presented in normal typeface.

At present, the influence of a parafoveal word in different typeface has not been studied, but Reingold and Rayner (2006) compared reading of sentences in which a target word was either presented in normal or boldface type and reported only minor disruptions. Single and first fixations did not differ significantly, but gaze duration was slighty higher on boldfaced targets. Compared to other manipulations of stimulus quality in Reingold and Rayner’s study (case alternation; faint typeface), the presentation in a different face had marginal impact on processing the foveal word.

Taken together, we expected that the enhancement of the prime's saliency would enable a faster processing of the prime word but at the same time would not disrupt the reading process itself.

2.4.1 METHOD

2.4.1.1 SUBJECTS

Thirty-six high school and university students (31 women, 5 men) from Potsdam, Germany participated in the experiment. Their age was between 17 and 34 years (*M* = 22, *SD* = 4.4). They were paid €6 or received course credit. All were native speakers of German with normal or corrected-to-normal vision. The experiment lasted between 30 and 40 minutes.

2.4.1.2 MATERIAL

The material of Experiment 1 was used again with a modification of text type: Sentence frames and target words were presented in normal type, but related and unrelated primes were always presented in bold face.

2.4.1.3 PROCEDURE

The experimental procedure was identical to that of Experiment 1. Ninety-five percent of all questions following sentence reading were answered correctly, indicating good comprehension.

2.4.1.4 DATA ANALYSIS

For data analysis, we also followed the procedure described for Experiment 1. After application of all filtering criteria for the target region, approximately 55% valid trials for the left eye and 53% for the right eye remained. Binocular validation resulted in the remaining 48% of all trials. For skipping probabilities for word $n + 1$, 62% of all trials remained after binocular filtering.

2.4.2 RESULTS AND DISCUSSION

2.4.2.1 PRETARGET WORD

Table 2.6 displays means and standard deviations for gaze durations, first-fixation durations, and refixation probabilities for the pretarget word n, broken down by experimental condition. Gaze durations and first-fixation durations did not differ between the experimental conditions; there were no effects of either prime type or prime duration ($|t|$s < 1.39).

Refixation rate on the pretarget word was 6.5% significantly higher for related primes in comparison to unrelated primes in the D80 condition ($b = -0.632$, $SE = 0.277$, $z = -2.28$), but no other priming effects or duration trends were significant ($|z|$s < 1.74).

Table 2.6

Means and Standard Deviations of Pretarget Reading as a Function of Prime Duration and Prime Type (Experiment 3)

	35 ms		80 ms		125 ms	
Prime	M	SD	M	SD	M	SD
Gaze duration [ms]						
related	291	129	293	137	281	118
unrelated	293	156	275	112	283	126
First-fixation duration [ms]						
related	275	119	262	101	261	106
unrelated	276	132	258	101	260	107
Refixation probability						
related	0.100	0.300	0.154	0.302	0.101	0.286
unrelated	0.090	0.361	0.089	0.286	0.136	0.343

Note. Refixation probability ranged from 0 to 1.

2.4.2.2 TARGET WORD

Table 2.7 displays means and standard deviations for skipping probabilities, gaze durations, first-fixation durations, refixation probabilities, and landing positions for target word $n + 1$, broken down by experimental conditions. As in Experiment 1 and 2, the probability of target skipping was low—only 3.3%. None of the contrasts was significant ($|z|$s < 1.21).

Target gaze durations are shown in Figure 2.4. There was a significant priming effect in the D80 condition: Gaze was shorter for related than for unrelated primes (b = 18 ms, SE = 8 ms, t = 2.3). The D125 contrast (9 ms, t = 1.1) was not significant, and the D35-contrast (−8 ms, t = −1.0) was numerically opposite to expectation. As in Experiments 1 and 2, gaze durations increased with prime duration (b = 0.47, SE = 0.06, t = 7.5, for the overall linear trend).

Table 2.7

Means and Standard Deviations of Target Reading as a Function of Prime Duration and Prime Type (Experiment 3)

	35 ms		80 ms		125 ms	
Prime	M	SD	M	SD	M	SD
Skipping probability						
related	0.033	0.179	0.019	0.134	0.042	0.200
unrelated	0.039	0.193	0.029	0.168	0.034	0.182
Gaze duration [ms]						
related	229	98	240	91	267	109
unrelated	223	112	258	105	274	128
First-fixation duration [ms]						
related	212	81	226	86	247	104
unrelated	211	75	242	96	251	95
Refixation probability						
related	0.100	0.300	0.104	0.305	0.122	0.328
unrelated	0.045	0.207	0.096	0.295	0.096	0.296
Landing position						
related	0.451	0.215	0.449	0.221	0.440	0.226
unrelated	0.451	0.208	0.443	0.214	0.469	0.225

Note. Refixation probability, skipping probability, and landing position ranged from 0 to 1.

First-fixation durations generally matched the pattern of gaze durations. A priming effect was present in the D80 condition (*b* = 16 ms, *SE* = 6.7 ms, *t* = 2.35), but not at the D35 condition (−2 ms) or the D125 condition (4 ms). First-fixation durations increased significantly with prime durations (*b* = 0.41, *SE* = 0.05, *t* = 7.65, for the overall linear trend).

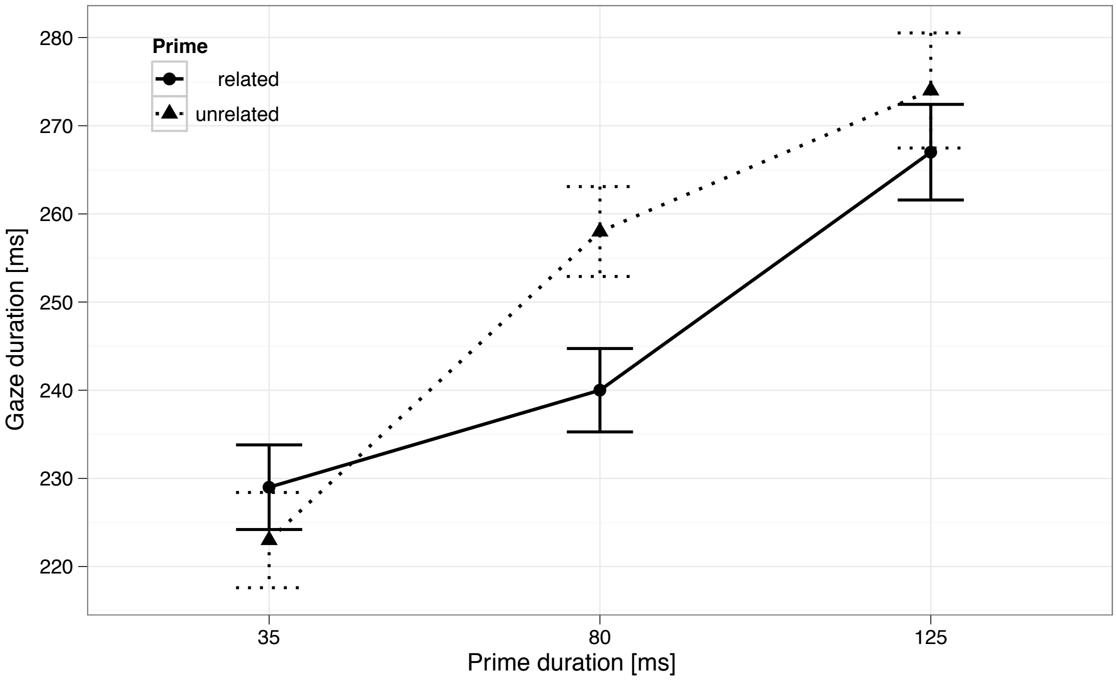

Figure 2.4. Gaze duration on the target word as a function of prime and prime duration (Experiment 3). Error bars denote standard errors, that is, after removal of between-subject and between-item random effects.

The target refixation rate was 9.4%. Over all duration conditions, related primes led to significantly more refixations (3%) than unrelated primes (*b* = −0.37, *SE* = 0.19, *z* = −2.03). Of the three contrasts, the priming effect of 5.5% was significant for the D35 condition (*b* = −0.98, *SE* = 0.38, *z* = −2.58). Refixation rate increased linearly over durations (*b* = 0.006, *SE* = 0.003, *z* = 2.34).

Mean landing position was.45 and thus slightly left from the target-word center. Between the six experimental conditions, there was a narrow range from .44 to .47 and none of the contrasts was significant (|*t*|s < 1.2).

2.4.3 Discussion

A semantic preview benefit effect was found for prime durations of 80 ms, with related parafoveal primes producing shorter gaze (18 ms) and first-fixation durations (16 ms) than unrelated primes. Effects were not significant for prime durations of 35 ms and 125 ms. Numerically, the effect was still in the expected direction in the 125-ms condition, but it turned negative in the 35-ms condition, in which the refixation rate was also significantly higher for related than for unrelated primes. The differences in the profiles between the two experiments suggest a temporal forward shift of processing, presumably induced by the salient prime. In other words, we assume that the D125 condition effect of Experiments 1 and 2 “moved” to the D80 condition in Experiment 3.[5]

We again observed the general increase of gaze and first-fixation durations on target word *n* + 1 as a function of prime duration. As in the other Experiments, the increase was close to linear, again replicating Inhoff et al. (2005). Gaze duration increased with a slope of 0.47, only slightly smaller than the ones obtained in Experiments 1 (0.55) and 2 (0.54). Of special interest was the reliable 23-ms increase in gaze duration from the D35 to the D80 condition because of its relevance for timelines in computational models of eye-movement control. Thus, irrespective of the kind of preview, parafoveal presentation of target words, if only delayed by 35 or by 80 ms, had a strong impact on subsequent reading time.

It is important to note that the increase in the salience of the prime that resulted from its presentation in a different typeface did not disrupt the general reading process by prematurely attracting subjects’ attention to the target region. This is supported by the fact that the rates of regression from the target did not increase from Experiments 1 and 2 (14.6% and 13.6%, repsectively) to Experiment 3 (13.4%).

Finally, given that no priming effect on fixation duration was observed in the D35 condition of Experiment 3, one may wonder whether the ambiguous early semantic-priming effect obtained in Experiment 1 is even real. To put this speculation on solid

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[5] Presumably, the increased saliency of the prime allowed faster processing and thus resulted in a forward shift of the priming effect to the D80 condition. A similar shift mechanism may not hold for the difference in priming effects between the D80 conditions in Experiments 1 and 2 and the D35 condition in Experiment 3. In the latter condition, we observed a nonsignificant negative priming trend (caused by a significantly higher refixation rate for related primes). Obviously, if there is such a shift mechanism, it must be nonlinear.

ground, it seemed advisable to consolidate our knowledge of the early effect in a new experiment.

2.5 EXPERIMENT 4

Experiment 1 revealed a significant parafoveal priming effect in gaze duration with a prime duration of 35 ms. Since this effect was absent for first-fixation duration in Experiment 1 and for both first-fixation and gaze duration in Experiments 2 and 3, we attempted to evaluate the reliability of a very early parafoveal semantic information extraction in this experiment. Moreover, irrespective of the semantic priming effect, we believed it was important to establish the lower boundary for effects of prime duration itself applied during prior fixations on word *n* on the subsequent first-fixation and gaze duration on the primed word *n* + 1. For this purpose, we replicated Experiment 1 with prime durations of 20 ms, 40 ms, and 60 ms. This allowed us to investigate early priming effects under multiple conditions extending the debatable one (35 ms) from Experiment 1.

2.5.1 METHOD

2.5.1.1 SUBJECTS

Thirty-five high school and university students (30 women, 5 men) from Potsdam, Germany participated in the experiment. Their age was between 19 and 37 years (*M* = 22.9, *SD* = 4.3). They were paid €6 or received course credit. All were native speakers of German with normal or corrected-to-normal vision. The experiment lasted between 30 and 40 minutes.

2.5.1.2 MATERIAL

The material of Experiment 1 was used again. Sentence frames, target words, and unrelated primes were always presented in the same typeface.

2.5.1.3 PROCEDURE

The experimental procedure differed from the one in Experiment 1 only with respect to prime durations, which now were 20 ms, 40 ms, or 60 m. Ninety-six percent of all questions following sentence reading were answered correctly, indicating good comprehension.

2.5.1.4 DATA ANALYSIS

For data analysis, we also followed the procedure described for Experiment 1. Since the maximum prime duration in Experiment 3 was 60 ms, the cutoff value for valid pretarget fixations was 60 ms. After application of all filtering criteria for the target region, approximately 54% valid trials for the left eye and 53% for the right eye remained. Binocular validation resulted in the remaining 47% of all trials. For skipping probabilities for word *n* + 1, 58% of all trials remained after binocular filtering.

2.5.2 RESULTS AND DISCUSSION

2.5.2.1 PRETARGET WORD

Table 2.8 displays means and standard deviations for gaze durations, first-fixation durations, and refixation probabilities for the pretarget word *n*, broken down by experimental condition. Neither gaze nor first-fixation durations differed between the experimental conditions; there were neither priming effects nor duration effects ($|t|$s < 0.30). Refixation rate was 9.8% and did not differ with respect to the priming effect and the duration conditions ($|z|$s < 0.61).

2.5.2.2 TARGET WORD

Table 2.9 displays means and standard deviations for skipping probabilities, gaze durations, first-fixation durations, refixation probabilities, and landing positions for target word *n* + 1, broken down by the experimental conditions. As in the other experiments, the probability of target skipping was low—only 3.1%. None of the priming contrasts or prime duration trends was significant ($|z|$s < 1.5).

Table 2.8

Means and Standard Deviations of Pretarget Reading as a Function of Prime Duration and Prime Type (Experiment 4)

	20 ms		40 ms		60 ms	
Prime	M	SD	M	SD	M	SD
Gaze duration [ms]						
related	277	113	277	131	272	107
unrelated	264	116	276	119	271	119
First-fixation duration [ms]						
related	261	105	255	115	250	94
unrelated	242	93	257	107	254	108
Refixation probability						
related	0.090	0.287	0.100	0.301	0.109	0.313
unrelated	0.100	0.301	0.097	0.297	0.093	0.291

Note. Refixation probability ranged from 0 to 1.

Prime type did not have a significant effect on gaze durations ($|t|$s < 1), but gaze durations significantly increased across prime durations (linear: b = 0.61, SE = 0.11, t = 5.32, quadratic: b = −2.7, SE = 1.3, t = −2.1, see Figure 2.5).

First-fixation durations showed a numerical but nonsignificant priming effect in the D60 condition only (b = 9 ms, SE = 5.8, t = 1.55). They changed significantly and only linearly with prime durations between 20 ms and 60 ms (linear trend: b = 0.51, SE = 0.10, t = 5.03; quadratic: t = −0.72).

The target refixation rate was 9% and did not differ between prime types ($|z|$s < 1.8). Refixation rate increased from the D20 to the D60 condition with a significant negative quadratic trend (linear: b = 0.008, SE = 0.006, z = 1.31; quadratic: b = −0.16, SE = 0.06 z = −2.57), reflecting a larger change between 20 an 40 ms than between 40 and 60 ms.

Table 2.9

Means and Standard Deviations of Target Reading as a Function of Prime Duration and Prime Type (Experiment 4)

	20 ms		40 ms		60 ms	
Prime	M	SD	M	SD	M	SD
Skipping probability						
related	0.032	0.176	0.034	0.180	0.032	0.177
unrelated	0.042	0.201	0.015	0.121	0.032	0.175
Gaze duration [ms]						
related	219	85	231	99	238	92
unrelated	211	71	235	91	243	89
First-fixation duration [ms]						
related	207	70	217	85	222	75
unrelated	203	66	216	79	231	86
Refixation probability						
related	0.071	0.258	0.093	0.291	0.088	0.283
unrelated	0.061	0.239	0.133	0.340	0.089	0.286
Landing position						
related	0.434	0.207	0.426	0.219	0.422	0.208
unrelated	0.440	0.213	0.416	0.209	0.428	0.202

Note. Refixation probability, skipping probability, and landing position ranged from 0 to 1.

Mean landing position was .43 and thus slightly left from the target-word center. Along the six experimental conditions, there was a narrow range from .42 to .44 and none of the contrasts was significant ($|t|$s < 1.44).

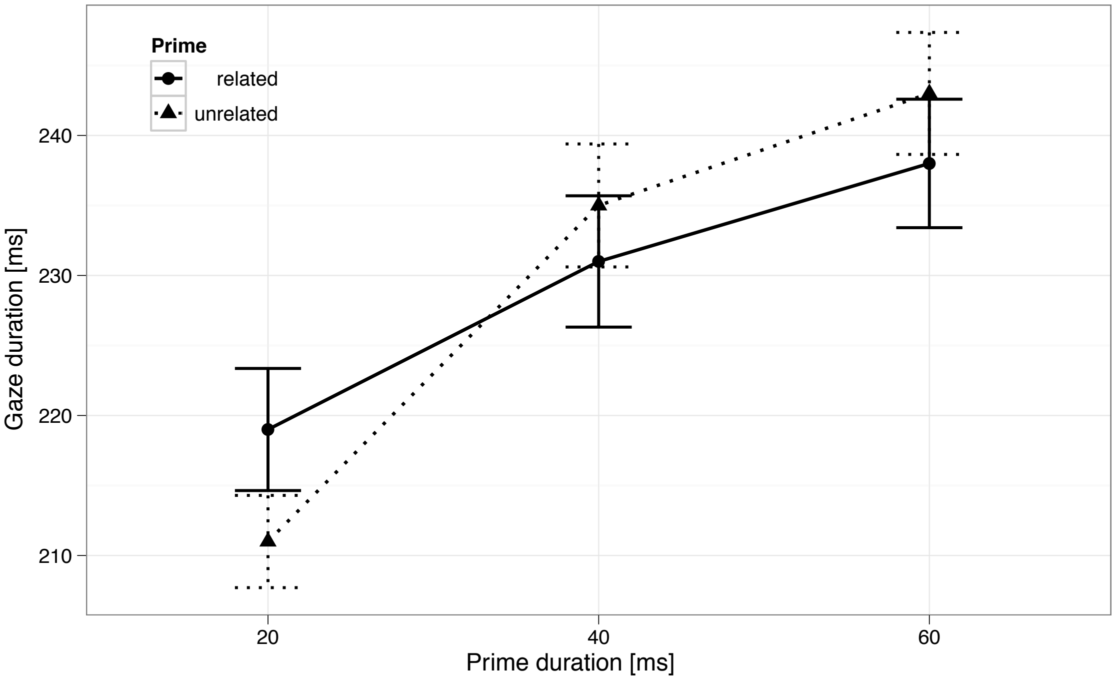

Figure 2.5. Gaze duration on the target word as a function of prime and prime duration (Experiment 4). Error bars denote standard errors, that is, after removal of between-subject and between-item random effects.

2.5.3 DISCUSSION

In this experiment with short prime durations, no semantic preview benefit was present for first-fixation durations or gaze durations. Thus, Experiment 4 did not corroborate the disputable 35-ms effect of Experiment 1. Together with the results from Experiments 2 and 3, this finding suggests that the effect of prime type at this particular duration obtained in Experiment 1 was most likely an outcome of chance.

As in Experiments 1, 2 and 3, we observed a general increase of gaze and first-fixation durations on target word *n* + 1 as a function of prime duration, applied during fixation on pretarget word *n*. The slope of 0.61 in gaze duration was somewhat steeper than the slopes obtained in the other Experiments. Notably, even between rather short target delays (20 ms and 40 ms, respectively), there was a reliable increase of 19 ms in gaze duration serving as an indicator for early parafoveal information processing from fixation onset.

2.6 GENERAL DISCUSSION

2.6.1 FAST PARAFOVEAL PRIMING: A NEW EXPERIMENTAL PARADIGM

In the present study, we tested the time course of parafoveal semantic preprocessing by manipulating the temporal availability of semantic information for a target word. We employed a new display change paradigm entailing two advantages compared to the classical boundary paradigm for the study of parafoveal preprocessing in reading. We highlight these methodological advantages because they are likely to apply to related research questions as well.

First, in classical boundary studies, the parafoveal preview is replaced as soon as the reader’s gaze crosses the boundary preceding the target location. As a result, the visual parafoveal information guiding the saccade program differs from the visual foveal information obtained after the saccade is finished. This might cause disturbance in the visual system since the mismatch between pre- and postsaccade visual information could be interpreted, for example, as the outcome of an erroneous saccade amplitude. In our parafoveal priming paradigm, the change from the preview to the target takes place while the reader fixates the pretarget. Thus, the visual information from the moment the saccade starts to the next word and the moment it reaches its desired goal is the same. The subsequent processing of the target word during the fixation on the target word should be less disrupted than in the case in which the information is changed during the saccade to the target word.

Second, since in classical boundary studies, the duration of preview availability is confounded with pretarget gaze duration, there is no experimental control over temporal aspects of the preview. The duration of the preview presentation is quite long, given that the mean gaze duration in reading is considerably longer than 100 ms and, therefore, may not always allow one to measure fast processes of information extraction in this early time frame. In contrast, the parafoveal fast-priming paradigm employed in the present study affords a detailed analysis of the time course of parafoveal processing.

2.6.2 SEMANTIC PREVIEW BENEFIT IS DEPENDENT ON TIME AND PRIME SALIENCY

In our experiments, we found that semantic information is extracted parafoveally and facilitates the subsequent processing of the target word. Fixation durations on the target word *n* + 1 were shorter after a semantically related preview during the fixation of word *n*. However, this semantic preview benefit depended on the temporal availability of the prime: Semantic priming was effective with a prime duration of 125 ms in Experiments 1 and 2 but was shifted forward to a prime duration of 80 ms in Experiment 3. The only difference among the experiments was the higher salience of the primes relative to the sentence frame in Experiment 3. The highly salient prime presumably allowed for a faster visual and linguistic processing of the word. Therefore, we interpret the results as a forward shift of the priming effect in time.

From this perspective, the effect in the D80 condition of Experiment 3 corresponds to the effect in the D125 condition of Experiments 1 and 2. Further support for this interpretation of results in terms of a forward rather than a backward shift is derived from the observation that the D80 priming effect of Experiment 2 held for both gaze and first-fixation durations, in agreement with the D125 but not with the dubious D35 priming effects in Experiment 1, which mainly resulted from an increase in refixations.

The disappearance of a semantic priming effect with long prime durations in Experiment 3 resembles results of foveal fast-priming experiments. Sereno and Rayner (1992) hypothesized that the mechanism of backward masking depends on prime durations. As the visibility of prime words increases with longer prime durations, the target word (performing as a mask for the prime word) masks less effectively for related primes because of the semantic similarity between both words. As a result, related primes produce greater disruption with longer prime durations. Simultaneously, the influence of unrelated primes given increasing availability of the prime remains constant, and thus the related priming effect is no longer present. H.-W. Lee et al. (1999) argued that an activation-verification model based on the framework by Van Orden (1987) can explain why foveal semantic priming effects are limited to specified prime durations. In the first step of a two-stage process, the semantic code is assessed. Subsequently, a spelling check is initiated, in which the orthographic presentation of the stimulus is compared with all orthographic representations of words semantically related to the prime to select the appropriate stimulus. Since a lasting orthographic representation of the prime takes time to build up, it interferes with the orthographic representation of the target given longer prime durations. To account for the differences between Experiments 1 and 3 with this theoretical approach, one has to assume that saliency accelerates the build-up of the prime-induced orthographic representations. Referring to the backward-masking hypothesis by Sereno & Rayner (1992), the shift of the priming effect from 125 ms in Experiment to 80 ms in Experiment 3 can be attributed to its higher extent of visibility owing to the increase of saliency in Experiment 3.

The D80 priming effect on the target word *n* + 1 in Experiment 3 was foreshadowed in the correspondingly higher refixation rate for related than for unrelated primes on the pretarget word *n*—a priming effect not present at either of the other two prime durations. Related to this effect, pretarget gaze duration in the D80 condition was also numerically—but not significantly—longer (13 ms) for related primes. This pretarget semantic priming effect is mirrored in first-fixation durations on the target word, which are 16 ms shorter for related than unrelated primes without a corresponding difference on the pretarget word (5.7 ms).

Finally, the pretarget refixation rate profile over prime durations in Experiment 3 bears a striking similarity to the corresponding target refixation rate profile in Experiment 1. Indeed, this similarity provides further evidence for the forward-shift interpretation triggered by the salient primes. Specifically, a comparison of refixation rates across the two experiments and how they distribute across the two words is suggestive of a simple tradeoff (Experiment 1: pretarget = 9%, target = 11%; Experiment 3: pretarget = 11%, target = 9%). If the change of font type of the target word had disrupted the reading process, refixation rates should have been considerably higher in Experiment 3 with visually dissimilar primes and targets.

2.6.3 RELATION TO PREVIOUS RESEARCH

The control of the temporal availability of the prime allowed detection of the presence of a parafoveal semantic preview benefit. Several studies in whch the fast-priming paradigm was used (H.-W. Lee et al., 1999; Sereno, 1995; Sereno & Rayner, 1992) showed that *foveal* semantic priming in reading depends on prime duration. Our results suggest that this also holds for *parafoveal* semantic priming.

Theoretically, it is possible that the finding of parafoveal semantic preview benefit in the present study is not due primarily to the controlled presentation time of the preview but to the stimuli (pretargets of very high frequency) and language (German). This is the first study in which both factors are present. First, it is plausible that parafoveal processing is increased with high-frequent pretargets; second, parafoveal semantic processing may differ between languages. Furthermore, some of the studies dealing with the question of semantic preview included confounded variables or methodological problems. Hyönä & Häikiö (2005) did not employ semantically related previews but unrelated emotional ones. In the study of Altarriba et al. (2001), the semantically related and unrelated previews and target words were of a different language and thus possibly produced switch costs (e.g., Meuter & Allport, 1999).

A sizeable fraction of the variance in the influence of different priming durations on the outcome of priming effects is most likely contributed by individual differences in the impact of defined prime durations. For example, Cheesman and Merikle (1985) found that since conscious awareness of primes depends on the subject, the subjective threshold necessary to produce priming effects could vary widely among subjects. To estimate the degree to which the priming effects in our Experiments can be generalized, we analysed individual differences in the effect trends. For this purpose, we performed slightly modified LMM analyses assuming subjects vary reliably in the specified contrasts. Hence, from these random-effect estimations, the sign of the priming effects can be considered for each subject separately. In Experiment 1, positive global priming was present for 97% of the subjects in gaze durations; 83% showed 125-ms priming trends in the expected direction. The outcome for Experiment 2 is very clear: 94% and 100% of the subjects showed positive 125-ms and global priming effect trends, respectively. In Experiment 3, positive trends were present for 92% with a prime duration of 80 ms. Altogether, these values are distinct evidence for the generalizability of the priming effects obtained in the present study.

2.6.4 TIMELINE OF PARAFOVEAL INFORMATION EXTRACTION

On the basis of the priming effects with durations of 80 ms (Experiment 3) and 125 ms (Experiments 1 and 2), we conclude that parafoveal information extraction can take place during an early stage of fixation. Along with these results about semantic parafoveal preprocessing, an additional outcome of the present study is the close to linear relationship between target delay (i.e., prime duration) and gaze duration on the target word.

One interpretation of this increase in processing time draws on the reduced preview time for the target word itself. As the parafoveal presentation of the target word was delayed, subjects could obtain less linguistic information from it while fixating the preceding word. Since a lack of information limits the extent to which the target word could be preprocessed, gaze durations on the target were inflated. Experiments 1, 2, and 3 yielded differences in target gaze durations between the 35-ms and 80-ms delays of the target word. Furthermore, Experiment 4 showed that differences emerge already between delays of 20 ms and 40 ms. This result would suggest an early extraction of parafoveal information, quite a bit earlier than the 70 ms reported by Inhoff et al. (2005), who did not include shorter intervals. A potential alternative explanation of this increase is that the second display change may simply be more noticeable if it occurs later in the fixation. The regression rate analysis of Experiment 1 provides some support for the first explanation.

2.6.5 IMPLICATIONS FOR COMPUTATIONAL MODELS OF EYE GUIDANCE IN READING

Our results are highly relevant for a controversial issue in computational modeling of eye guidance in reading, namely, whether processing of consecutive words is serial with one word being processed at a time or spatially distributed with multiple words at a time (Starr & Rayner, 2001). Cognitive models of eye movement control during reading (for an overview, see Radach, Reilly, & Inhoff, 2007) can analogously be divided into models driven by *sequential attention shifts* (SAS) and *processing gradient* (PG) models.

The currently most advanced SAS model is *E-Z Reader* (Reichle, Pollatsek, Fisher, & Rayner, 1998; Reichle, Pollatsek, & Rayner, 2006; Reichle, Rayner, & Pollatsek, 2003; Reichle, Warren, & McConnell, 2009) in which different consecutive stages are assumed. In the early visual stage, low-level word shape information (e.g., length) is processed preattentively before the first stage of lexical processing (L_1) starts. In this stage, frequency and predictability of a word have an influence. The end of this stage triggers the start of the programming of a saccade from word *n* to word *n* + 1 and simultaneously the start of the second stage of lexical processing (L_2) in which the meaning of a word is extracted. When L_2 is finished, attention is shifted to word *n* + 1 within 50 ms. Since attention shifts are decoupled from saccade programming, it is possible that processing of word *n* + 1 takes place while the eyes are still fixating word *n*.

PG models take an alternative perspective. They assume that attention is distributed continuously as a gradient in the visual field. In the PG model *SWIFT* (Engbert, Longtin, & Kliegl, 2002; Engbert, Nuthmann, Richter, & Kliegl, 2005; Richter, Engbert, & Kliegl, 2006), the gradient is determined by word position and by visual acuity. A dynamic field of lexical activations evolves as a function of the lexical processing difficulty of the words, as several words are processed in parallel. Hence, attention is not limited to a single word.

The results of the present study can hardly be explained by SAS models, as parafoveal semantic priming effects emerged at 125 ms (and 80 ms with a more salient preview), and delaying the target word for 40 ms produced longer gaze durations than delaying it for 20 ms. Even if one assumes very short processing and attention shift stages, serial processing would not be this fast. For example, to account for the 125-ms semantic-priming effect, one has to assume that pretarget word processing and attention shift to the target word and extraction of semantic information from it are done within 125 ms from the onset of the pretarget fixation. This seems to be highly implausible since typical fixation durations in reading are much longer (see the exchange between Inhoff et al., 2005, and Pollatsek, Reichle, and Rayner, 2006).

Of course, at this point, we do not know to what degree such parafoveal semantic priming effects depend on the visual signal generated by related/unrelated primes in the parafovea or on the saliency of the prime for short prime durations. In other words, the effect may be specific to the experimental paradigm. It does, however, represent a proof of principle for a central claim embodied in PG models. These models provide a reasonable base to account for the present results since the assumption of parallel word processing can in principle accommodate parafoveal linguistic influences during early stages of a fixation. Hence, parafoveal information extraction does not depend on completion of foveal word processing, but occurs in parallel to foveal information extraction (and processing). Having said this, we also must recognize that it is highly unlikely that any of the available PG models would correctly reproduce the current pattern of results in their current implementation.

2.6.6 CONCLUSION

In conclusion, the present experiments provided evidence for the existence of semantic parafoveal preview benefit as well as for the possibility of parallel processing of words during reading. On the basis of our results, we believe that further research into the time course of parafoveal information extraction ought to shed more light on the interaction between information type and presentation duration since fast-priming studies showed that the benefit associated with, for example, semantically, orthographically, and phonologically related foveal previews each depends on their presentation duration. It seems reasonable to expect analogous interactions with parafoveal previews as well. Since the present study is the first to show semantic preview benefit from parafoveal words for alphabetic script, future work should specify more precisely the preconditions of this phenomenon. More generally, the application of different prime/delay durations will enhance our understanding of the time course of processing succeeding words in natural reading.

3 SEMANTIC PREVIEW BENEFIT DURING READING

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Running Head: Semantic preview benefit and the boundary paradigm

Hohenstein, S., & Kliegl, R. (2014). Semantic preview benefit during reading. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 40*, 166–190.

doi:10.1037/a0033670

ABSTRACT

Word features in parafoveal vision influence eye movements during reading. The question whether readers extract semantic information from parafoveal words was studied in 3 experiments by using a gaze-contingent display-change technique. Subjects read German sentences containing 1 of several preview words that were replaced by a target word during the saccade to the preview (boundary paradigm). In the 1st experiment the preview word was semantically related or unrelated to the target. Fixation durations on the target were shorter for semantically related than unrelated previews, consistent with a semantic preview benefit. In the 2nd experiment, half the sentences were presented following the rules of German spelling (i.e., previews and targets were printed with an initial capital letter), and the other half was presented completely in lowercase. A semantic preview benefit was obtained under both conditions. In the 3rd experiment, we introduced 2 further preview conditions, an identical word and a pronounceable nonword, while also manipulating the text contrast. Whereas the contrast had negligible effects, fixation durations on the target were reliably different for all 4 types of preview. Semantic preview benefits were greater for pretarget fixations closer to the boundary (large preview space) and, although not as consistently, for long pretarget fixation durations (long preview time). The results constrain theoretical proposals about eye-movement control in reading.

Keywords: eye movements, reading, semantic preview benefit, parafoveal processing, display-change awareness

3.1 INTRODUCTION

During reading, eye movements (saccades) alternate with phases of relative stability (fixations). Properties of the fixated (or foveal) word, the preceding word, and the upcoming (or parafoveal) word all have a significant impact on when and where to move the eyes, but they vary in their degree of influence (see Heister, Würzner, & Kliegl, 2012, for a review). Whereas the parafoveal extraction of orthographic and phonological codes is well documented for various languages, the effect of semantic preprocessing in reading has been elusive at least for languages with alphabetic script (see Schotter et al., 2012, for a review).

Semantic parafoveal processing has been reported for reading of Finnish (White et al., 2008), Chinese (Cui et al., 2013; Tsai et al., 2012; Yan et al., 2009; Yan, Zhou, et al., 2012; Yang, Wang, et al., 2012), Korean (Kim et al., 2012), and German (Hohenstein et al., 2010). None of these demonstrations, however, have been accepted as being conclusive because they depended on nonrepresentative targets (i.e., previews of the second constituent of Finnish compound words), non-Roman script (i.e., Chinese or Korean characters), or a nonstandard experimental paradigm (e.g., parafoveal fast priming in German, reviewed below).

Here we test the hypothesis of parafoveal preprocessing of semantic code in German sentences with the standard boundary paradigm (Rayner, 1975) in three experiments. Recent research also suggests that preview benefit depends on the duration and location of pretarget fixations (see Kliegl, Hohenstein, Yan, & McDonald, 2013, for a review). And there has also been concern about display change awareness in this paradigm (e.g., Slattery et al., 2011; White et al., 2005a). Therefore, we also examine the relevance of these variables for semantic preview benefit in our experiments. Such evidence of a semantic preview benefit is of great interest to the further development of computational models of eye-movement control during reading. We will address this topic in the discussion.

3.1.1 PARAFOVEAL PREVIEW BENEFITS

Parafoveal preprocessing during reading has been extensively tested with the boundary paradigm (Rayner, 1975), in which the position of a critical target is at first occupied by a more or less valid preview word. When the reader's gaze crosses an invisible boundary located directly before the space preceding the preview, the target replaces the preview. Typically, fixation durations on the target are reduced if the preview is identical or related in some aspect to the target, compared to fixation durations with unrelated or nonwords as previews. A significant difference between uninformative and informative preview conditions, *preview benefit*, is interpreted as evidence of parafoveal preprocessing during the fixation on the word preceding the target.

There is considerable evidence of such a benefit arising from orthographic previews (Balota et al., 1985; Inhoff, 1989b). Moreover, phonological and prosodic information can be processed in the parafovea and facilitate the processing of the target (Ashby & Rayner, 2004; Miellet & Sparrow, 2004; Pollatsek et al., 1992). However, with the possible exception of a select set of morphological Hebrew codes (Deutsch et al., 2003, 2005), there have been no reliable findings indicating the effectiveness of morphological previews in alphabetic scripts (Bertram & Hyönä, 2007; Inhoff, 1989a; Kambe, 2004; Lima, 1987).

3.1.2 PAST ATTEMPTS TO ESTABLISH A SEMANTIC PREVIEW BENEFIT

3.1.2.1 INITIAL STUDIES, WHICH FAILED TO DEMONSTRATE SEMANTIC PREVIEW BENEFIT

There has been much debate whether *semantic* codes facilitate parafoveal preprocessing. In the first experiment on this topic, subjects had to fixate a parafoveal word and name it (Rayner, McConkie, et al., 1980). Reaction times were the same for related (*chair*) or unrelated (*chore*) previews to the target (*table*). This experiment did not involve reading sentences, and the preview benefit was not measured in terms of the difference between fixation durations following unrelated and semantically related previews. However, for the standard version of the boundary paradigm, Rayner et al. (1986) subsequently did not find evidence for a semantic preview benefit in sentence reading. The seeming absence of evidence of semantic preview benefit has been supported by three further boundary-paradigm experiments (Altarriba et al., 2001; Dimigen et al., 2012; Hyönä & Häikiö, 2005). In these cases, however, there are other factors that may have worked against finding the effect. Altarriba et al. (2001) used preview words in a second language, possibly entailing disadvantages arising from the switch between two languages (e.g., Meuter & Allport, 1999; Soares & Grosjean, 1984). Hyönä and Häikiö (2005) used unrelated emotional and unrelated neutral previews rather than related ones. Therefore, in this case, it is not clear whether this qualifies as a semantic preview. Finally, Dimigen et al. (2012) used semantically related and unrelated previews, but relied on a word list reading task in which subjects were asked to report whether an animal was included. Hence, one should note that strictly speaking, this list of experiments includes only one that used the standard boundary paradigm for reading sentences and an explicit manipulation of semantic relatedness (Rayner et al., 1986).

3.1.2.2 FINNISH COMPOUNDS

White et al. (2008) used the boundary paradigm *within* words and found parafoveal semantic information extraction. The preview for the second constituent of a Finnish compound noun (*vaniljakastike*; translation: vanilla sauce) was either semantically related (*sinappi*; mustard) or unrelated (*rovasti*; priest) to the second constituent (*kastike*; sauce). When the reader’s gaze crossed the boundary between the two constituents, the target replaced the preview. Fixation times on the target indicated that related previews facilitated the extraction of semantic information from the parafoveal part of the fixated word.

3.1.2.3 CHINESE

Two differences between Chinese and alphabetic script facilitate the detection of a semantic preview benefit in Chinese. Firstly, Chinese characters are more directly connected to meaning (Hoosain, 1991) than alphabetic characters. Secondly, and more importantly, most Chinese words are only one or two characters long (Yu et al., 1985). Therefore, the mean distance between the current fixation position and the next word is smaller than in alphabetic script, and the next word occupies less space within the parafoveal field. Relying on the boundary paradigm with noncompound (i.e., very simple) characters, Yan et al. (2009) established significant semantic preview benefit with simplified Chinese, the orthography used in mainland China. Recently, Tsai et al. (2012) replicated these results with traditional Chinese characters used in Taiwan. Furthermore, semantic preview benefit in Chinese also exists when using compound characters (Cui et al., 2013; Yan, Zhou, et al., 2012; Yang, Wang, et al., 2012).

3.1.2.4 KOREAN

Korean combines features of both alphabetic and syllabic writing. The orthography is based on phonology and represented in syllable blocks. Case markers are used to indicate syntactic functions of words and thereby provide semantic information about thematic roles. Kim et al. (2012) used correct and incorrect syntactic case markers as parafoveal previews. Incorrect previews led to a syntactic and semantic mismatch between the initially visible case marker and the one following the display change. Target fixation durations were longer in the incorrect preview condition, indicating that processing of parafoveal syntactic and semantic information does occur while a person is reading Korean.

3.1.2.5 PARAFOVEAL FAST PRIMING

For alphabetic scripts, there is evidence of a semantic preview benefit from a nonstandard boundary paradigm. Hohenstein et al. (2010) used German sentences and a *parafoveal fast-priming* technique, in which the temporal availability of the preview was determined by a timer (for foveal fast-priming, see Sereno & Rayner, 1992). For a critical target *n* + 1 (*Knochen*; bones), a nonword string (*Nzwrfgt*) initially occupied the target location. It was then replaced by a semantically related (*Schädel*; skulls) or an unrelated preview (*Stiefel*; boots) as soon as the reader fixated the pretarget *n*. This preview was available for a variable prime duration (i.e., 35, 80, or 125 ms) before being replaced by the target. Thus, information extraction from the preview was limited to an experimentally determined duration, and the target became available while the reader was still fixating the preceding word. Semantic preview benefit was present for prime durations of 125 ms. When the saliency of the preview was increased with bold font in another experiment, the effect was found for prime durations of 80 ms (but no longer for 125 ms). So, in addition to providing first evidence of semantic preview benefit from the upcoming word in an alphabetic script, the results also suggested a relationship between semantic preview benefit and preview time.

In summary, the question whether semantic relatedness of preview and target affects processing of the target appears to depend on several factors pertaining to script (alphabetic vs. character script), task (natural reading vs. reading of word lists), and methodology (boundary paradigm vs. parafoveal fast priming). In addition, as we will review in the following two sections, semantic preview benefit may also depend on factors that are intrinsic to the boundary paradigm.

3.1.3 PREVIEW SPACE AND PREVIEW TIME

3.1.3.1 PREVIEW SPACE

If the fixation on the pretarget is close to the boundary, there is much preview space, because more of the preview falls into the perceptual span (McConkie & Rayner, 1975; Rayner & Bertera, 1979) than for a far-away fixation position. Indeed, McDonald (2006) reported evidence of a greater identity preview benefit if the launch site distance (the distance between the position of the pretarget fixation and the beginning of the target) is small. Preview benefit was highly significant for launch sites of four characters or less, but despite increasing constraints on visual acuity, it was still significant for saccades launched 9 or 10 letters before the target. In their reanalysis of McDonald’s data, Kliegl et al. (2013) analysed saccade amplitude not as a categorical but continuous variable. Their results also corroborate a positive relationship between preview space and preview benefit, thereby replicating results from studies in which the distance to the preview word was used as categorical covariate (e.g., Pollatsek, Rayner, & Balota, 1986; Rayner, 1975).

3.1.3.2 PREVIEW TIME

In the standard boundary paradigm, preview time is identical with the pretarget fixation duration. Preview time is not fixed but terminated by the reader's eye movement. Therefore, semantic preview benefit may depend on the pretarget fixation duration. Indeed, for a reanalysis of Yan et al.'s (2009) data on semantic preview benefit during reading Chinese, Yan, Risse, Zhou, and Kliegl (2012) reported time-dependent parafoveal facilitation effects: Semantic preview benefit was smaller for long pretarget fixation durations than for short ones. In another study (Yan, Zhou, et al., 2012), the effect was different: The preview benefit was significantly greater when the subjects were given a longer preview duration. These opposite effects need to be followed up, but they may be related to differences in processing demand of the targets in two studies (i.e., noncompound vs. compound characters)

3.1.4 THE PRESENT STUDY

Here we report three experiments that establish parafoveal semantic preprocessing for subjects reading German sentences with the classic boundary paradigm. In the first experiment, we used nouns as previews and targets. In regular German spelling, nouns are capitalized. The capitalization of nouns in German, combined with the use of highly frequent pretargets, may facilitate parafoveal processing. To test this hypothesis, we presented sentences with either capitalized or lowercase target nouns in the second experiment. In the third experiment, we used four preview conditions, that is, an identical and a nonword preview in addition to the semantically related and unrelated conditions. This extension of the design allowed us to compute semantic preview benefit relative to alternative baselines. In this experiment, we also presented sentences at two levels of text contrast. For each of the three experiments, we also tested whether semantic preview benefit depends on preview space and preview time and carried out detailed analyses of correlations between self-reported awareness of the fact that words were exchanged during reading and semantic preview benefit.

3.2 EXPERIMENT 1

3.2.1 METHOD

3.2.1.1 SUBJECTS

Thirty students (19 women, 11 men) from Potsdam, Germany, participated in the experiment. They were between 19 and 30 years of age (*M* = 22, *SD* = 3.1). They were paid €7 or received course credit. All were native speakers of German with normal or corrected-to-normal vision.

3.2.1.2 APPARATUS

Subjects were seated 60 cm [24 in.] in front of an Iiyama Vision Master Pro 514 monitor (Iiyama Seiki Co., Nagano, Japan; 1024 × 768 pixels; 53 cm [21 in.]; vertical refresh rate 150 Hz; 20-pt Courier New bold font). One character covered 12 pixels horizontally (0.45° of visual angle). All sentences were presented in black on a white background. We measured the luminance with a PR-650 SpectraScan Colorimeter (Photo Research, Inc., Chatsworth, CA) at the center of the screen: The luminance of the background was 92.3 cd/m^2; the luminance of the text was below 3.4 cd/m^2. The text luminance was too dark to be measured, and the reported value is an upper limit based on manufacturer's data on the sensitivity of the instrument.

The experiment was run in MATLAB (The MathWorks, Natick, MA) with the Psychophysics Toolbox (Brainard, 1997; Pelli, 1997) and the Eyelink Toolbox (Cornelissen, Peters, & Palmer, 2002). The eyes were monitored with an EyeLink II system (SR Research Ltd., Osgoode, ON, Canada) with a sampling rate of 500 Hz, an instrumental spatial resolution of 0.01°, and an average accuracy better than 0.5°. The recording was binocular, and the heuristic filter was set to level 1. Heads were positioned on a chin rest to minimize head movements.

3.2.1.3 MATERIAL

We used Hohenstein et al.'s (2010) sentences, including semantically related and unrelated previews for targets. The 102 experimental sentences were constructed around the target region of the foveal pretarget *n* and the parafoveal target *n* + 1 and ranged from six to 13 words. All frequency variables were extracted from the lexical database dlexDB (version 0.2.5; Heister et al., 2011) based on the DWDS corpus (Geyken, 2007).

The pretargets were unique, between four and eight characters long (*M* = 5.4), and of high frequency (range: 8−6718 per million).[6] Words were selected to increase the possibility for a broad perceptual span and facilitate the pickup of information from the parafoveal target or to induce faster attention shifts, respectively (e.g., J. M. Henderson & Ferreira, 1990). The mean of the base-10 logarithmic frequency was 2.5. Pretargets covered different word classes (e.g., verbs, adjectives), but no nouns (which were used as targets), and were at positions 3−7 in the sentences.

The targets were unique, between four and eight characters long (*M* = 5.3), and their frequency ranged from 0.13 to 212 per million; the related previews were of the same length, and their frequency ranged from 0.28 to 248 per million. Table 3.1 provides details on the lemma frequencies of targets as well as related and unrelated previews. All the targets and previews were nouns and thus—according to German spelling—capitalized. One major constraint in generating the stimuli, given the display changes in the study, was that the previews had to be of the same length as the targets.

The unrelated previews were constructed to have the same length as the target, an overlap of characters with the target identical to the related preview (at the same spatial position), and minimal frequency differences between the related and the unrelated preview. The unrelated previews ranged in frequency from 0.06 to 177 per million. The two lists of preview types were matched in terms of their lemma frequency. The unrelated previews had been constructed with regard to orthography (i.e., character overlap with the target), frequency, and length, but 47% of them did not fit into the sentence syntactically. Finally, the targets, related previews, and unrelated previews

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[6] Note that some measures differ from the ones reported in Hohenstein et al. (2010), which were based on the November 2007 (prerelease) version of the lexical database.

were used only once, with the exception of one unrelated preview that was used twice, leading to a total of 305 words. See Table 3.2 for sample sentences with translations.

Table 3.1

Means and Standard Deviations of the Untransformed and the Log$_{10}$ Lemma Frequencies of Targets, Related Previews, and Unrelated Previews Together With the Absolute Differences Between Both Preview Types

	Target		Related preview		Unrelated preview		Difference[a]	
Frequency	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Untransformed	44.2	77.6	38.3	64.7	38.4	62.2	5.9	15.1
Log$_{10}$	1.2	0.6	1.2	0.6	1.2	0.6	0.11	0.22

Note. Frequency values are scaled to counts per million.

[a] Absolute difference between related and unrelated preview on sentence level.

We measured the cloze task predictability for the target position in a study with 23 native speakers of German (14 women, nine men, mean age = 21 years), who did not participate in Experiments 1–3. Participants were given a sentence up to, but not including, the target and were asked to generate the next word. The mean predictability of targets, related previews, and unrelated previews was .03, .02, and 0, respectively. Up to the 8th decile, the predictability values are 0 for all three word groups. Hence, the target was not constrained by sentence context.

In addition to the experimental sentences, there were 12 training and 24 filler sentences with targets as well as related and unrelated previews. In the filler sentences, targets were selected from different word classes (adjectives, adverbs, verbs, but not nouns). Training sentences also contained targets of different word classes. See Hohenstein et al. (2010) for further details.

Table 3.2

Example Sentences With Related and Unrelated Previews

Sentence	Preview: Related	Preview: Unrelated
Beim Ausgraben waren *Knochen* zum Vorschein gekommen. (With the excavation *bones* came to light.)	Schädel (skulls)	Stiefel (boots)
Für manche Zwecke war die kleine *Trage* viel praktischer. (For some purposes the small *stretcher* was much more useful.)	Bahre (bier)	Roste (gratings)
Am späten Abend konnte kein *Riese* im Land gesehen werden. (Late in the evening no *giant* could be seen in the country.)	Zwerg (dwarf)	Trend (trend)
Diese Frauen brauchen noch *Wolle* zum Fertigstellen der Kleidung. (These women need more *wool* to finish the clothes.)	Seide (silk)	Seife (soap)

Note. The target is in italics; translations are in parentheses.

3.2.1.4 DESIGN

The experimental design implemented two conditions (related vs. unrelated preview) with 102 trials per subject. There were 51 experimental sentences per condition and subject. Each sentence occurred the same number of times in each of the two conditions. As 30 subjects were tested, each sentence was read 15 times in each condition. The mapping of the experimental condition to sentences was counterbalanced; the order of presentation of sentences, and hence of experimental conditions, was randomized.

3.2.1.5 PROCEDURE

Subjects were naive concerning the purpose of the experiment. They were instructed to read single sentences for comprehension. Their field of vision was calibrated with a standard 9-point grid. If the eye tracker identified a fixation, the fixation point disappeared and a sentence was presented such that the centre of the first word replaced the initial fixation point. Participants ended presentation of a sentence by looking into the lower right corner of the screen. A three-alternative multiple-choice question followed a random sample of one third of the sentences. It was answered by clicking on one of the response alternatives. Ninety-six percent of all questions were answered correctly, indicating no serious problems of comprehension.

Subjects read six practice sentences (a random subset of all 12 training sentences), followed by the experimental and filler sentences. When a sentence was presented initially, the preview (related or unrelated) occupied the target location. An invisible boundary located directly after the last letter of pretarget *n* was present in each sentence. When either eye crossed the boundary, the preview word on position *n* + 1 was replaced by the target. The sentence remained in this final form until the end of the trial. In total, each person read 132 sentences including 102 experimental ones.

We measured the delay between eye movement and display change with the Black Box ToolKit (Plant, Hammond, & Turner, 2004). After either eye crossed the boundary, display changes were accomplished within approximately 10 ms. This delay does not only include the time required to technically make the display change after the information of boundary crossing has been transferred to the system, but rather comprises the entire delay measured from an actual eye movement (physically, not in the eye tracker software) to the moment the changed display appears on the screen. Since saccades in reading typically last about 30 ms (Rayner, 1998, 2009), the display change should occur during the saccade to the target.

Following the last sentence of the experiment, subjects were asked to answer a paper-and-pencil questionnaire consisting of three questions: Did you notice anything unusual concerning the presentation? (yes/no); were words exchanged during reading? (yes/no); in how many sentences were words exchanged during reading (%)? Twenty-nine out of thirty subjects completed the questionnaire.

3.2.1.6 EYE-MOVEMENT MEASURES AND SELECTION CRITERIA

Data from sentences with a blink or loss of measurement were only used until the point in time preceding the first loss and only if the loss occurred after the target region. Saccades were detected with a binocular velocity-based algorithm (Engbert & Kliegl, 2003; Engbert & Mergenthaler, 2006). Small saccades were considered part of a fixation if they covered a distance less than the width of two characters. Analyses are based on right-eye fixations.

We applied the following criteria to filter trials: Trials were included only if pretarget and targets were fixated in sequence on first pass. This filter left us with 79% of all trials. In addition, the change from the preview to the target had to occur during the saccade from the pretarget to the target (trials remaining: 70% from related and 72% from unrelated previews). Finally, we excluded all trials in which data loss occurred during target gaze.

For these 71% of all trials, gaze durations (the sum of all first-pass fixations), first-fixation durations and single-fixation durations were computed for words *n* and *n* + 1 (for a definition of these measures, see Inhoff & Radach, 1998; Rayner, 1998). In addition, we computed the relative landing positions in the target (i.e., the position of the first fixation) and the target refixation probability. To determine the skipping probability of the target, we used trials in which word *n* was fixated before boundary crossing and was left with a right-directed saccade triggering the display change. Seventy-seven percent of all trials remained for this measure.

3.2.1.7 STATISTICAL ANALYSIS

Inferential statistics for fixation durations are based on linear mixed models (LMMs), specifying subjects and sentences as crossed random factors (for a discussion of advantages of LMMs over F_1/F_2 analyses of variance, see Baayen et al., 2008; Bates, 2010; Kliegl et al., 2010; Kliegl, Wei, Dambacher, Yan, & Zhou, 2011). Effects in models with continuous dependent variables were estimated with the lme4 package (Bates, Maechler, & Bolker, 2011) in the R environment for statistical computing (version 2.14.2, 64-bit build; R Development Core Team, 2012). LMMs were fitted with the restricted maximum likelihood statistic.

Binary dependent variables were analysed with the Automatic Differentiation Model Builder (ADMB; Fournier et al., 2012), with the R interface provided by the glmmADMB package (Skaug, Fournier, Nielsen, Magnusson, & Bolker, 2012). In a simulation study of generalized LMMs, ADMB-based confidence intervals were more accurate in terms of coverage probability than lme4-based ones (Bolker, Kliegl, & Fournier, 2011; Zhang et al., 2011).

To select the random-effects structure used for the analyses, we used a drop-one procedure starting with the full model including all varying intercepts and varying slopes of the main effects of the experimental design. Varying slopes not contributing significantly to the goodness of fit (as assessed through likelihood ratio tests) were removed from the model. This procedure was separately applied to each dependent variable.

Theoretically, the full model including variance components for all terms of the experimental design is the preferred model for statistical analyses (Schielzeth & Forstmeier, 2009; see also van de Pol & Wright, 2009). In our data, the variances between subjects and between sentences related to fixed effects (“varying slopes”) is often very small. Therefore, corresponding variance components are estimated as close to 0 and the model is likely to be overparameterized; there simply is not enough information in the data to support a model of such complexity. On the other hand, coverage probability of confidence intervals associated with fixed effects is better for LMMs including random slopes than for models including intercepts only (Schielzeth & Forstmeier, 2009). It is our approach to include variance components if they contribute significantly to the model. It serves as a compromise between a full model and a model without any random slopes.

Continuous predictors were centered at their mean; factors (such as preview type) entered the analyses as sum contrasts (−0.5 vs. 0.5). Therefore, the intercept estimates the grand mean of the dependent variable; regression coefficients estimate the difference between factor levels. The base model for all dependent variables includes the fixed effect for preview type. For additional analyses, quasi-experimental and material-related covariates as well as their interactions with preview type were separately added to the base model’s fixed-effects structure.

We report regression coefficients with t and z statistics. Degrees of freedom are not known for t statistics of LMMs, but for large numbers of subjects, sentences, and observartions, as in this experiment, the *t* statistic converges to the *z* statistic of the normal distribution. For all tests we apply the two-tailed criterion ($|t| \geq 1.96$; $|z| \geq 1.96$), corresponding to a 5% error criterion for significance. On the basis of the analyses of model residuals, we decided to use the (natural) logarithm of all fixation-duration measures. All graphics were created with ggplot2 (Wickham, 2009).

3.2.2 RESULTS

3.2.2.1 TARGET: SEMANTIC PREVIEW BENEFIT

Table 3.3 summarizes means and standard deviations for fixation durations, refixation probabilities, skipping probabilities, and landing positions by experimental condition for target *n* + 1. The analyses are based on 2,170 observations for gaze and first-fixation durations and 1,887 observations for single-fixation durations.

Table 3.3

Means and Standard Deviations of Target Reading (Experiment 1)

	Gaze duration [ms]		First-fixation duration [ms]		Single fixation duration [ms]		Refixation probability		Skipping probability		Landing position	
Preview	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Related	306	182	280	163	283	166	.13	.34	.08	.27	.49	.25
Unrelated	337	185	309	173	319	177	.13	.34	.06	.24	.48	.24

Note. Refixation probability, skipping probability, and landing position ranged from 0 to 1.

Fixation times on the target were significantly longer for unrelated than for semantically related previews (*b* = 0.11, *t* = 5.5, for gaze durations; *b* = 0.10, *t* = 4.8, for first-fixation durations; *b* = 0.13, *t* = 5.8, for single-fixation durations). The regression coefficient *b* estimates the log fixation duration difference for unrelated compared to related previews. With respect to measures in milliseconds, the regression coefficients of the preview benefit correspond to differences of about 31 ms, 27 ms, and 35 ms for gaze duration, first-fixation duration, and single-fixation duration, respectively. Skipping rate, landing position, and refixation probability were not significantly influenced by the type of preview (t = 1.60, both |z|s = 1.67).

3.2.2.2 PRETARGET

Table 3.4 summarizes results for the pretarget. There were no significant effects of type of preview present for the succeeding word on fixation durations (all |t|s < 1.24). Thus, there were no significant parafoveal-on-foveal effects.

Table 3.4

Means and Standard Deviations of Pretarget Reading (Experiment 1)

	Gaze duration [ms]		First-fixation duration [ms]		Single fixation duration [ms]	
Preview	*M*	*SD*	*M*	*SD*	*M*	*SD*
Related	274	114	247	99	255	101
Unrelated	277	117	251	98	257	99

3.2.2.3 MODULATION BY PRETARGET FIXATION DURATION

Gaze duration, first-fixation duration, and single-fixation duration can be included in nine combinations in LMMs as dependent variable “log target viewing time” and covariate “log pretarget viewing time”, along with preview type and the interaction between preview type and the covariate. None of the three pretarget viewing times had a reliable main effect on the three target viewing times. The magnitude of the preview benefit, however, was significantly modulated by pretarget gaze duration for target gaze duration (t = 2.0) and target single-fixation duration (t = 1.96). In the remaining combinations, the interaction did not reach significance (all |t|s < 1.20). The positive regression coefficients for the interactions indicated an increase of preview benefit with longer pretarget fixation duration.

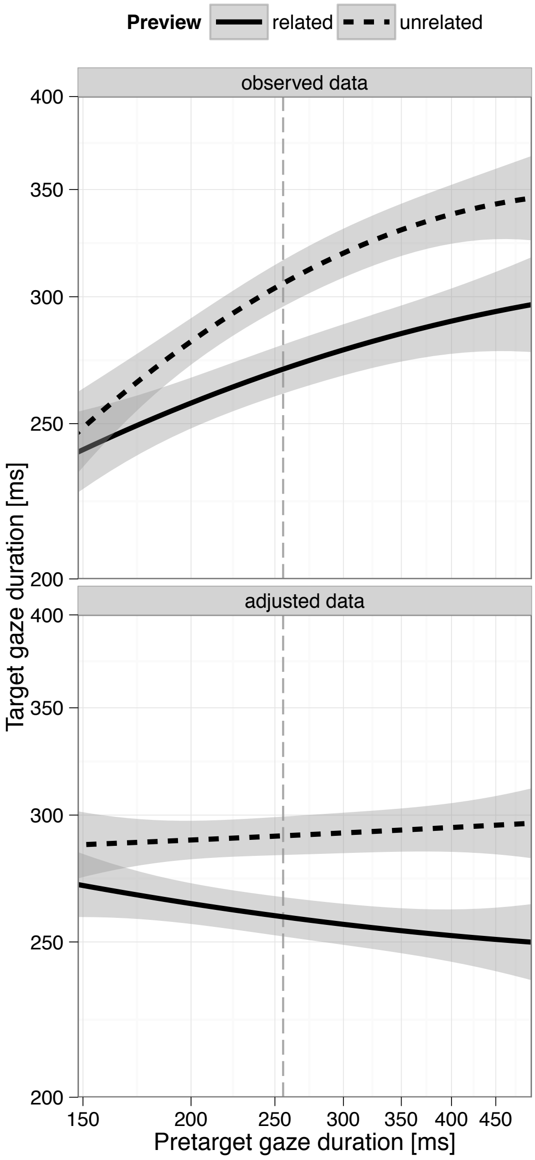

Figure 3.1. Top panel: Second-order polynomial trend of the regression of target gaze duration (on a log scale) on pretarget gaze duration (on a log scale) for related and unrelated previews (Experiment 1). Bottom panel: The same plot after removal of between-subject and between-sentence variance of the dependent variable. Shaded error bands represent 95% confidence interval. The horizontal axis covers roughly 90% of the data; minor differences are due to choosing the same *x*-axes limits for both panels; the mean is denoted by the vertical line.

To analyse the source of this modulation, we separately plotted pretarget and target fixation durations for observations (Figure 3.1, top panel) and for LMM estimates (i.e., after removing between-subject and between-sentence variance in the dependent variable;[7] Figure 3.1, bottom panel). Clearly, the overall increase in target fixation duration with pretarget gaze duration in the top panel of Figure 3.1 was mainly due to differences in the reading speed of subjects. With statistical control of individual differences in gaze durations, the semantic preview benefit (the difference between the two lines) emerged as a decrease in target gaze duration for related previews relative to fairly constant fixation durations for unrelated previews (bottom panel).

Modulation of preview benefit by pretarget gaze duration was independent of the frequency of the pretarget: Whereas the frequency of the pretarget had an impact on pretarget gaze ($b = -0.05$, $t = -2.2$; but not on first- and single-fixation duration, both $|t|$s < 1.24) and—as a spillover—on target viewing times (all ts < −2.5), a model including pretarget frequency and preview did not reveal an interaction between both variables for the prediction of target viewing times (all $|t|$s < 0.16). Thus, there was no evidence of a link between the preview benefit modulation by pretarget gaze and lexical difficulties in pretarget processing, but preview benefit increased with preview time.

3.2.2.4 MODULATION BY LAUNCH SITE DISTANCE AND LANDING POSITION

Figure 3.2 displays target gaze duration as a function of preview and launch site distance. Increasing distance from the last pretarget fixation to the target significantly reduced preview benefit in gaze duration ($b = -0.031$, $t = -2.4$) and marginally significantly in single-fixation duration ($t = -1.66$) and first-fixation duration ($t = -1.64$).

Preview benefit also increased with the relative landing position on the target ($b = 0.19$, $t = 2.7$, for gaze durations; $b = 0.21$, $t = 3.0$, for first-fixation durations); the effect was marginally significant for single fixations ($t = 1.68$). Launch site distance and target landing position correlated negatively ($r = -.49$, $p < .001$), but they accounted for unique amounts of variance in fixation durations.

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[7] The adjustment of the dependent variable (target gaze duration) was achieved by subtracting random effects estimated in an LMM for subjects and sentences from the log raw data. For this analysis the predictor pretarget gaze duration was centered (indicated by the vertical line in Figure 3.1).

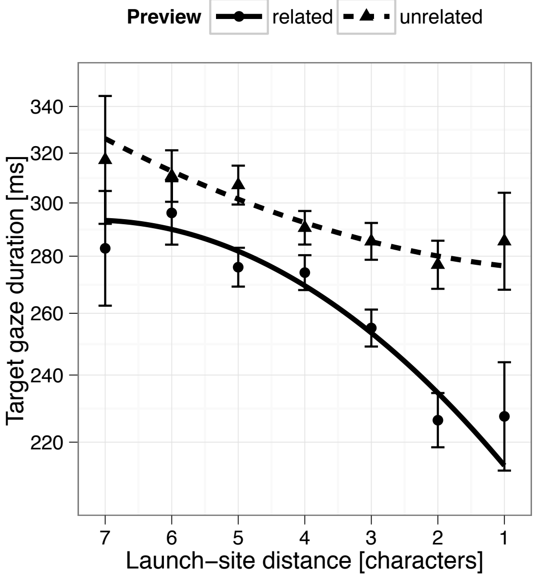

Figure 3.2. Second-order polynomial trend of the regression of target gaze duration (on a log scale) on launch site distance for related and unrelated previews (Experiment 1). Between-subject and between-sentence variance have been removed from the dependent variable. Error bars represent standard errors. The very infrequent trials with a launch site distance of eight characters were omitted (0.3%).

In addition, we analysed whether semantic preview benefit was related to length and frequency of pretargets and targets, and to the predictability of targets. The only notable result was a marginally greater preview benefit for predictable targets, in agreement with Balota et al. (1985). Thus, there was no evidence indicating that preview benefit depended on word characteristics, but it did depend on launch site and landing position. Finally, we tested whether high-level influences could explain the semantic preview benefit: Preview benefit remained significant for trials in which previews syntactically fit into the sentence and when we statistically controlled for preview predictability.

3.2.2.5 AWARENESS OF DISPLAY CHANGE

Twenty-six of 29 subjects (90%) who completed the questionnaire after the experiment noticed that display changes had taken place. Answers to the question concerning the amount of display change had a broad range (0%−95%). Display changes were used in all trials of the experiment. Mean of the self-reported detection rate was 40% (*SD* = 41%); the median was 33%. Though almost all subjects reported that they had noticed display changes, they clearly were not aware that this had occurred in every trial.

The central question, of course, does not concern the relation of overall fixation duration to awareness of display change, but whether semantic preview benefit correlates with the awareness of display changes. A model including preview type and the continuous predictor display-change recognition rate (%) revealed a significant main effect of recognition rate ($b = 0.005$, $t = 4.0$, for gaze durations; $b = 0.005$, $t = 4.2$, for first-fixation durations; $b = 0.005$, $t = 4.0$, for single-fixation durations), but—most importantly—no interaction between preview benefit and display change recognition rate ($t = -0.18$, for gaze durations; $t = 0.10$, for first-fixation durations; $t = 0.06$, for single-fixation durations). Thus, subjects with longer fixation durations on targets reported a higher percentage of display changes, but there was no statistically reliable evidence that this measure relates differentially to related and unrelated previews.

Is the positive correlation between the self-reported detection rate of display change and target fixation duration due to individual differences in overall reading speed? With first-fixation duration as dependent variable and display-change detection rate as predictor, regression coefficients were positive for each word position relative to the target position (excluding first and last words); they were significant within a broad range of four words before the target to two words behind it (all *t*s > 2.2), indicating that subjects who were susceptible to display changes read slower in general. In an alternative analysis, we specified the position of the fixated word as 10 treatment contrasts (relative to the target; up to five positions before and five after the target), together with the self-reported display-change detection rate. All interactions were significantly negative (all *t*s < −2.6). Hence, the relationship between fixation duration and display-change awareness was strongest at the target.

3.2.3 DISCUSSION

In the present study, we obtained shorter target fixation durations if the parafoveal preview was semantically related to the target, compared to unrelated previews.

Moreover, we show that parafoveal semantic facilitation is (a) significantly moderated by launch site distance, (b) significantly moderated by pretarget gaze duration, and (c) not significantly related to the subjects’ self-reported ability to detect display changes.

3.2.3.1 SEMANTIC PREVIEW BENEFIT

The interpretation of the general effect of preview is a straightforward matter: Readers were able to pick up semantic information. This result provides evidence that a semantic preview benefit can be obtained with the standard boundary paradigm for a language using alphabetic script, adding to evidence already available for Chinese and Korean. The magnitude of the semantic preview benefit, however, depends on several other factors.

3.2.3.2 PREVIEW SPACE

Semantic preview benefit was stronger when the eyes were close to the target. Several models for eye movements during reading predict this dependence (see General Discussion). Furthermore, our results are in agreement with a study on identity preview benefit by Kliegl et al. (2013; see also McDonald, 2006), who reported a decrease of the preview benefit with an increase in launch distance.

3.2.3.3 PREVIEW TIME

The effects of preview time and display-change awareness are new, or not clearly predictable from the available literature. The magnitude of the semantic preview benefit covaried with gaze duration on the pretarget. When the pretarget was fixated longer, entailing longer availability of preview, the semantic preview benefit on the target was greater. This finding resembles results in Kliegl et al. (2013), who reported a positive relationship between pretarget fixation duration and identity preview benefit. However, in that study, the preview benefit depended on gaze duration; it did not vary with first- and single-fixation duration on the pretarget. Most likely, the effect is quite fragile and may depend on specific experimental conditions, or simply not be very reliable (e.g., White et al., 2005a). At this point, evidence is simply not sufficient to draw definite conclusions on the influence of preview time on parafoveal preprocessing, but these issues should be resolved eventually because condition-specific timelines are important constraints for theoretical proposals about the time course of information integration during word recognition.

The positive relationship between pretarget gaze duration (and thus the temporal availability of the parafoveal preview) and the magnitude of the semantic preview benefit differs from results of an earlier study on semantic preprocessing using the parafoveal fast-priming paradigm (Hohenstein et al., 2010). Semantic preprocessing was demonstrated with a preview duration of 125 ms (Experiments 1 and 2). However, in Experiment 3, with increased preview saliency, the effect disappeared at 125 ms but was present at 80 ms of preview duration. This result was interpreted as a forward shift in visual processing of the highly salient parafoveal stimulus associated with larger interference between the semantic representations of preview and target. In the present study, a semantic preview benefit was present for much longer preview durations (i.e., pretarget fixation duration; see Figure 3.1). Obviously, then, different mechanisms are at work during parafoveal fast priming and the classical boundary paradigm: Preview and target are presented consecutively in fast priming, whereas the saccade from the pretarget to the target is in between the presentations of preview and target. Thus, interference should be less likely in the boundary paradigm. We submit that the two paradigms are likely to be useful for different questions and that more experimental work with parafoveal fast priming is needed to understand the underlying mechanisms.

3.2.3.4 DISPLAY CHANGE AWARENESS

Most subjects reported awareness of display changes. Importantly, on average they thought that a change occurred in 40% of the trials, when in reality a change occurred on every trial. Thus, they did not notice display changes in 60% of the trials. In White et al.'s (2005a) study, one third of all subjects reported having noticed display changes (the proportion was even lower in Rayner et al., 1986). What are the reasons for this discrepancy? There are three differences: First, we used an EyeLink II system, whereas White et al. and Rayner et al. used a Dual Purkinje eye tracker, which has a very high spatial accuracy leading to fewer incorrect display changes caused by a mismatch between actual and measured gaze position. Second, since in the present study pretargets were highly frequent, subjects' attention may have spread faster to the location of the preview word. After the boundary was crossed, differences between target and preview may have been more noticeable. Third, since White et al. ran an identity preview benefit condition, inherently, in half of the trials no display change occurred. This is to say there were cases in which the preview was identical with the target. Thus, the probability of noticing a display change was potentially half as high than in the present study in which words were exchanged in every trial. We also found a positive correlation between reading time and display-change awareness. Slow reading increased the chance of perceiving the difference between preview and target, presumably because of the longer preview time. White et al. (2005a) did not report an effect of display-change awareness on reading speed, but fixation durations on pretarget and target were numerically longer for aware subjects.

In summary, the main result of Experiment 1 is a significant benefit of semantically related, as opposed to unrelated, parafoveal previews. This is the first demonstration of such an effect in the boundary paradigm for a language using alphabetic script. Most notably, such an effect has not been found in a boundary experiment for reading English sentences (Rayner et al., 1986). Besides methodological differences between studies, differences between English and German script may be responsible for the divergence of results. We followed up this possibility in Experiment 2.

3.3 EXPERIMENT 2

In Experiment 1 we obtained a semantic preview benefit for subjects reading German sentences. German script has the unusual characteristic that all nouns, not only proper names and first words of sentences, are spelled with an initial capital letter (capitalization). Since all targets in experimental sentences were nouns, it is plausible that capitalization had an impact on parafoveal preprocessing. A capitalized character of a preview in parafoveal vision may be salient and attract attention to the preview word. Furthermore, German capitalization possibly reduces the cost of lexical processing. From the first letter alone, readers of German script obtain the word class information (whether the next word is a noun or a nonnoun). Deeper lexical (semantic) processing of the word may start faster than in other languages because of the early availability of word class information. Therefore, we hypothesized that more remaining resources or faster processing triggers a deeper processing of semantic code in the parafovea and hence enhances semantic preview benefit.

There is research demonstrating the positive influence of capitalization on reading rate in German (Bock, 1989, 1990; Bock, Augst, & Wegner, 1985; Bock, Hagenschneider, & Schweer, 1989; Gfroerer, Günther, & Bock, 1989). Reading rate was lower if uppercase and lowercase letters were used improperly, compared to texts where the German capitalization rules were observed. On the basis of several experiments, Bock (1989) argued that the function of German capitalization rules for reading is independent of word shape and allows a reader to differentiate between nouns and nonnouns without analysing a word’s meaning. Furthermore, there is more recent evidence of an influence of German capitalization rules on the missing-letter effect (Müsseler, Nisslein, & Koriat, 2005) and on the identification of briefly presented nouns (Jacobs, Nuerk, Graf, Braun, & Nazir, 2008).

In conlcusion, these studies clearly demonstrate a beneficial effect of German noun capitalization on the recognition processes. Most likely, the use of German nouns as targets in Experiment 1 enhanced lexical processing of the parafoveal preview and therefore contributed to the semantic preview benefit. To date, there has been no study on the effect of capitalization for parafoveal processing. In the studies reviewed above, targets were always fixated directly. In Experiment 2, words were presented according to spelling rules of German; that is, nouns were capitalized or written completely in lowercase. If German noun capitalization was a major reason for the outcome in Experiment 1, we expect a reduced semantic preview benefit for noncapitalized sentences and previews.

3.3.1 METHOD

3.3.1.1 SUBJECTS

Thirty-two students (20 women, 12 men) participated in the experiment. They were between 16 and 39 years of age (*M* = 23, *SD* = 4.8).

3.3.1.2 MATERIAL

We used 100 of the 102 experimental sentences of Experiment 1, since four within-subject conditions were present (see below). In the capitalized condition, capitalization followed the spelling rules of German. In the noncapitalized condition, all characters were presented in lower case.

3.3.1.3 DESIGN

The experimental design implemented the two within-subject factors preview (related vs. unrelated) and capitalization (capitalized vs. noncapitalized). Capitalization was manipulated in a block design as a between-subject factor (capitalized first vs. noncapitalized first); it was applied not only to previews and targets, but to all nouns of the sentences in the block. Each experimental condition was presented the same number of times, rendering 25 experimental sentences per condition and subject. Since 32 subjects were tested, each sentence was read four times in each condition.

3.3.1.4 PROCEDURE

At the beginning of the experiment, subjects were told that the experiment consisted of two parts. One part of the sentences was presented following German rules of capitalization, and the other was presented completely in lowercase. Each part started with six training sentences, followed by 62 experimental and filler sentences. Subjects were informed when the second part started. Each person read 136 sentences, including 100 experimental ones. Accuracy of comprehension was 95%. Thirty-one out of 32 subjects completed the questionnaire concerning the detection of display changes.

3.3.1.5 MEASURES, SELECTION CRITERIA, AND CONTRAST SPECIFICATION

Data selection followed the procedure described for Experiment 1. After applying all filtering criteria for the target region, approximately 72% valid trials remained. For skipping probabilities for the target, 76% of all trials remained. The experimental factors preview and capitalization were specified as two sum contrasts and were of primary interest in almost all analyses.

3.3.2 RESULTS

3.3.2.1 TARGET: SEMANTIC PREVIEW BENEFIT

Table 3.5 summarizes results for the target $n + 1$. The analyses are based on 2,296 gaze durations, 2,296 first-fixation durations, and 2,062 single-fixation durations. Again, fixation times on the target were significantly longer for unrelated than for semantically related previews ($b = 0.08$, $t = 5.4$, for gaze durations; $b = 0.07$, $t = 4.8$, for first-fixation durations; $b = 0.08$, $t = 5.3$, for single-fixation durations). When sentences were presented in lowercase, targets were fixated longer compared to sentences following the German rules of capitalization. This main effect of capitalization was reliable for gaze durations ($b = 0.06$, $t = 2.9$), first-fixation durations ($b = 0.07$, $t = 3.9$), and single-fixation durations ($b = 0.07$, $t = 3.9$). The interaction of preview and capitalization—a tendency of lesser preview benefit from noncapitalized previews—did not reach significance (all $|t|$s < 1.4).[8]

Furthermore, the relative landing position on the target was not significantly influenced by preview type ($t = -0.6$), capitalization ($t = -1.0$), or the interaction ($t = -1.4$). The probability of a target refixation also was not reliably modulated by preview type ($z = 1.05$), capitalization ($z = -0.66$), or the interaction ($z = 0.35$).

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[8] Post hoc comparisons revealed reliable preview benefit for both capitalized ($t = 4.6$, for gaze durations; $t = 4.2$, for first-fixation durations; $t = 4.6$, for single-fixation durations) and noncapitalized presentation ($t = 2.9$, for gaze durations; $t = 2.4$, for first-fixation durations; $t = 2.7$, for single-fixation durations).

Table 3.5

Means and Standard Deviations of Target Reading (Experiment 2)

		Gaze duration [ms]		First-fixation duration [ms]		Single fixation duration [ms]		Refixation probability		Skipping probability		Landing position	
Capitalization	Preview	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Regular	Related	258	130	241	112	243	112	.10	.30	.11	.31	.46	.25
	Unrelated	280	121	257	102	262	100	.11	.31	.06	.23	.47	.25
Lowercase	Related	279	118	263	108	267	109	.09	.29	.03	.16	.46	.24
	Unrelated	292	116	274	111	279	111	.11	.31	.03	.16	.45	.23

Note. Refixation probability, skipping probability, and landing position ranged from 0 to 1.

Target skipping rate was significantly reduced in the noncapitalized condition, compared to the capitalized condition (b = −1.32, z = −5.74). The type of parafoveal preview had no reliable influence (b = −0.36, z = −1.60) on skipping probability, but the interaction was marginally significant (b = −0.85, z = −1.90).

3.3.2.2 PRETARGET

Table 3.6 summarizes results for the pretarget. Fixation durations were not influenced by the type of preview present for the succeeding word (all $|t|$s < 0.9); that is, there were no significant parafoveal-on-foveal effects. Surprisingly, pretargets were fixated for shorter durations when the sentence was presented completely in lowercase (b = −0.10, t = −5.6, for gaze durations; b = −0.06, t = −4.3, for first-fixation durations; b = −0.09, t = −5.4, for single-fixation durations). The interaction terms were not reliable (all $|t|$s < 1.4).

The analyses of the effect of capitalization on fixation durations measured on pretarget and targets revealed rather peculiar results: Violation of German rules of capitalization led to longer target fixations, but pretargets were fixated for shorter time spans in this condition. We analysed this trade-off for all data and found an interplay between capitalization and word class, indicating different reading strategies in capitalized and noncapitalized texts (Hohenstein & Kliegl, 2013).

Table 3.6

Means and Standard Deviations of Pretarget Reading (Experiment 2)

		Gaze duration [ms]		First-fixation duration [ms]		Single fixation duration [ms]	
Contrast	Preview	*M*	*SD*	*M*	*SD*	*M*	*SD*
Regular	Related	260	101	238	90	244	92
	Unrelated	270	119	241	90	246	91
Lowercase	Related	241	114	223	90	223	84
	Unrelated	237	97	224	85	225	82

3.3.2.3 MODULATION BY PRETARGET FIXATION DURATION

Figure 3.3 displays target gaze duration as a function of preview type, pretarget gaze duration, and capitalization; the corresponding three-factor interaction was significant ($b = -0.2$, $t = -2.6$). The figure shows that the semantic preview benefit (i.e., the difference between unrelated and related previews) was observed in capitalized (left panel) and noncapitalized (right panel) conditions, but was stronger in the capitalized than in the noncapitalized condition. Moreover, the effect of pretarget gaze duration was different for the two conditions. A strong semantic preview benefit was observed in the capitalized condition for long pretarget gaze durations. Post hoc analyses yielded a significant interaction between preview type and pretarget gaze duration for the capitalized condition ($b = 0.14$, $t = 2.4$), but not for the noncapitalized condition ($t = -1.19$). The same significant pattern of results (i.e., a reliable three-factor interaction) was also obtained for the combinations including pretarget gaze or single-fixation duration as predictor. Finally, the numerical trends were similar for the three remaining combinations with pretarget first-fixation duration as predictor.

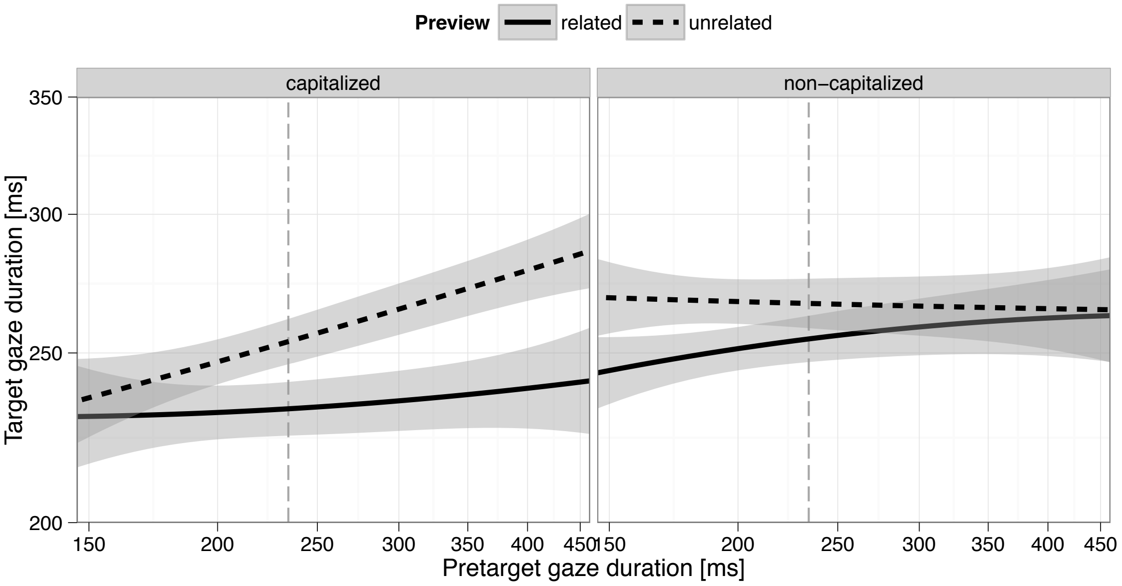

Figure 3.3. Second-order polynomial trend of the regression of target gaze duration (on a log scale) on pretarget gaze duration (on a log scale) for related and unrelated previews as a function of capitalization (Experiment 2). Between-subject and between-sentence variance have been removed from the dependent variable. Shaded error bands represent 95% confidence interval. The horizontal axis covers roughly 90% of the data; minor differences are due to choosing the same *x*-axis limits for both panels; the mean is denoted by the vertical line.

3.3.2.4 MODULATION BY LAUNCH SITE DISTANCE

Figure 3.4 displays target gaze duration as a function of preview type, launch site distance, and capitalization; the corresponding three-factor interaction was significant (*b* = 0.07, *t* = 3.2). The figure shows that the effect of launch site distance on semantic preview benefit differed for the two capitalization conditions: The semantic preview benefit increased with decreasing launch site distance for capitalized nouns, but not when nouns were presented completely in lowercase. Post hoc analyses revealed a significant interaction between preview type and launch site distance for the capitalized condition (*b* = −0.05, *t* = −3.5), but not for the noncapitalized condition (*b* = 0.007, *t* = 0.48). The same significant pattern of results (a reliable three-factor interaction) was also obtained for single-fixation duration (*b* = 0.05, *t* = 2.2); the effect was similar for first-fixation duration (*b* = 0.03, *t* = 1.55).[9]

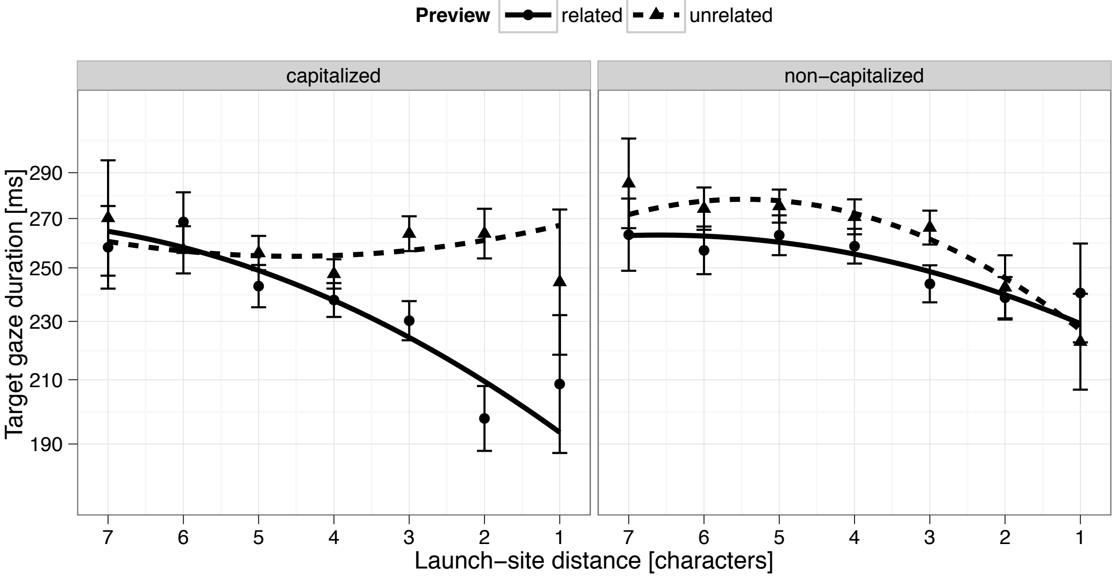

Figure 3.4. Second-order polynomial trend of the regression of target gaze duration (on a log scale) on launch site distance for related and unrelated previews as a function of capitalization (Experiment 2). Between-subject and between-sentence variance have been removed from the dependent variable. Error bars represent standard errors. The very infrequent trials with a launch site distance of eight or nine characters were omitted (0.7%).

3.3.2.5 AWARENESS OF DISPLAY CHANGE

Twenty-five out of 31 subjects (81%) noticed that display changes took place. The self-reported frequency of display changes ranged from 0% to 98%. Mean of the self-reported detection rate was 26% (*SD* = 31%); the median was 10%.

The main question is whether semantic preview benefits correlate with the perception of display changes. A model including preview type, capitalization, display-change recognition rate, and all interactions between these variables revealed a significant main effect of recognition rate (*b* = 0.002, *t* = 2.4, for gaze durations; *b* =

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[9] Although the three-factor interaction was not reliable for first-fixation durations, the numerical pattern of effects in the post hoc analyses matches the results of gaze and single-fixation durations.

0.002, $t = 2.7$, for first-fixation durations; $b = 0.002$, $t = 2.6$, for single-fixation durations), but no reliable two- or three-factor interactions including display-change recognition rate (all $|t|$s < 1.63). Thus, as in Experiment 1, subjects with longer fixation durations on targets reported a higher percentage of display changes, but again there was no evidence of this measure relating differentially to related and unrelated previews.

3.3.3 DISCUSSION

In Experiment 2, subjects read sentences in which a parafoveal preview for a critical target was either semantically related or unrelated to the target. In addition, sentences were presented as capitalized nouns, as required by spelling rules of German, or completely in lowercase. Manipulation of capitalization was used to test whether significant semantic preview benefits in Experiment 1 were exclusively due to the capitalization of all nouns in German.

The results were clear. Fixation durations were shorter for related than for unrelated previews, irrespective of capitalization. German subjects were able to process previews presented parafoveally, even when the whole sentence was presented in lowercase letters. Therefore, we conclude that semantic preview benefits did not depend exclusively on this German rule of capitalization.

Along with semantic preview benefit, we also replicated significant interactions between preview type and launch site distance, as well as preview type and pretarget fixation durations, but only if the presentation followed the German rules of capitalization. With increasing distance between the pretarget fixation position and the preview word, the preview benefit decreased. Furthermore, if the pretarget was fixated longer, the difference between related and unrelated previews for target fixation duration was more pronounced. The interaction between preview type and pretarget fixation duration was present only in a subset of combinations of the various durations, similar to results of Experiment 1 and to Kliegl et al. (2013).

Most subjects were aware of display changes; the average self-reported detection rate was 26%. As in Experiment 1, there was no evidence that semantic preview benefit was significantly influcenced by the subjects' awareness (or vice versa).

Thus, again, we have no evidence that our finding of a benefit from semantically related previews in parafoveal vision was an artifact of the noticeable display changes. This finding contrasts with those of White et al. (2005a) and Slattery et al. (2011), who reported a larger difference between nonword and identical previews for aware subjects, compared to unaware subjects.

Comparison between our first two experiments and earlier studies is limited because we used two nonidentical previews, whereas in earlier research one of the previews (namely the identical condition) was not accompanied by a detectable display change. Possibly, these methodological differences were responsible for some of the differences in the results. Therefore, we conducted a third experiment in which we used not only related and unrelated previews, but also identical and neutral nonword previews.

3.4 EXPERIMENT 3

The main goals of Experiment 3 were to evaluate benefits and, possibly, costs of related and unrelated parafoveal previews and compare them to conditions with identical (no display change) and neutral (nonword) previews.

3.4.1 IDENTICAL PREVIEW CONDITION

In the identical preview condition, the target was constantly available for parafoveal processing without any detectable change in the display (the preview was replaced by itself). This condition allows us to assess the preview cost associated with the semantically related preview. It also reduces the probability of a trial containing a display change from 100% to 75% for experimental sentences (which we reduced further to 69% with additional fillers). Thus, display-change awareness was now evaluated under conditions that resembled earlier research more than our first two experiments (White et al., 2005a).

This condition also allows us to follow up on several reports of modulation of identical preview benefit (relative to unrelated words) by pretarget fixation duration. The influence of pretarget fixation duration has also been examined in several boundary experiments with alphabetic scripts for *identical* preview benefit (i.e., identical vs. unrelated previews). Schroyens, Vitu, Brysbaert, and D'Ydewalle (1999) used a word triad task in which a sequence of three words, rather than a complete sentence, was presented. Results showed a (marginally significant) trend for smaller preview benefit if the single fixation on the pretarget was short. With the classical boundary paradigm and using identical vs. unrelated previews in natural reading, White et al. (2005a) did not obtain a significant modulation of preview benefit by pretarget fixation duration. However, Kliegl et al. (2013; reanalysis of McDonald, 2006) reported evidence of a positive relationship between the preboundary fixation duration and preview benefit for English sentences. In other words, the difference between identical and unrelated previews increased with preview time.

Evidence is also mixed in the case of Chinese script. Yan, Risse, et al. (2012) found a significant interaction between unrelated vs. identical preview and pretarget single-fixation duration for target gaze duration, but not for first- and single-fixation duration. In Yan, Zhou, et al.'s (2012) study, the interaction was only marginal significant for first-fixation duration. Tsai et al. (2012) used pretarget gaze duration as predictor and reported an increase in identity preview benefit measured in single-fixation duration. Thus, at this point, there are various reports according to which pretarget fixation duration contributes to (identity) preview benefit during reading of alphabetic and Chinese scripts, but the conditions required for these effects to occur are not clear.

3.4.2 NEUTRAL PREVIEW CONDITION

A neutral condition was included to test interference triggered by semantically unrelated previews. A difference between unrelated and related preview may materialize due to lexical difficulties induced by unrelated previews, rather than semantic facilitation by related previews. In this scenario, fixation durations should not be shorter after a related preview than after a neutral preview, but unrelated previews should lead to longer target fixations than neutral previews. In short, in this hypothetical case, results are more compatible with a notion of preview cost than preview benefit.

Which condition qualifies as a *neutral preview*? In their classic review of the implications of cost-benefit analyses in the field of reaction time studies, Jonides and Mack (1984) demonstrated that, in general, a neutral condition is not neutral with respect to performance. Furthermore, changes in reaction times induced by experimental covariates are not limited to valid and invalid items, but also occur for neutral ones. Jonides and Mack recommended foregoing usage of a neutral condition and focusing on examining performance under valid and invalid cues relative to other variables. Our approach of analysing preview benefit modulation by covariates such as preview time and preview space implements this perspective (Kliegl et al., 2013; Yan, Risse, et al., 2012). If neutral conditions are necessary when it comes to addressing theoretical questions, Jonides and Mack suggested that constructing neutral stimuli required great effort and that neutral and nonneutral items needed to match as closely as possible.

McNamara (2005) reviewed the question as to what to choose as a neutral condition in the context of semantic priming, an issue closely related to semantic preview benefit. He concluded that “orthographically regular, pronounceable nonwords may be the best choice for neutral primes” (p. 52). Furthermore, nonword primes should not be repeated to avoid repetition priming. Also, from the perspective of eye-movement control during reading, first letters should be a primary concern when generating nonwords. Saccade amplitudes to a parafoveal word or nonword appear to increase with the frequency of first letters and thereby influence landing positions in the targets (Hyönä, 1995; Plummer & Rayner, 2012; Radach et al., 2004; Vonk et al., 2000; White & Liversedge, 2004, 2006a, 2006b). Furthermore, even the duration of the pretarget fixation seems to be affected by a familiar beginning-letter sequence of the parafoveal stimulus (Inhoff, Starr, et al., 2000; Plummer & Rayner, 2012; Pynte et al., 2004; Rayner, 1975; Starr & Inhoff, 2004; G. Underwood et al., 2000; White, 2008). To avoid preview-related differences in these early measures, beginnings of neutral nonwords should match real words as closely as possible.

3.4.3 TEXT CONTRAST

Furthermore, we manipulated text contrast in this experiment to evaluate the influence of low-level visual properties on preview benefit and display-change recognition. Contrast has an impact on a subject's ability to recognize characters and other patterns in peripheral vision (see Strasburger, Rentschler, & Jüttner, 2011, for a review). The levels of contrast in experimental reading studies conducted in different laboratories may differ slightly, and there is not much research to date on whether such differences matter for preview benefits. Our subjects' self-reported display-change awareness was comparable to the hit rates in the no-delay condition reported by Slattery et al. (2011). On the other hand, the majority of White et al.'s (2005a) subjects were unaware of words being exchanged. We suspect that the main reason for the difference in display-change awareness is the difference in the overall probability of display changes, but a difference in display contrast may be another source.

We used the *Michelson contrast* definition (Michelson, 1927), $C = \frac{I_{max} - I_{min}}{I_{max} + I_{min}}$, where I_{max} and I_{min} denote the maximum and minimum luminance, respectively, yielding a contrast value between 0 and 1. For text, I_{min} refers to the dark letters and I_{max} to the background. The minimum text contrast for reading at maximum speed is about 10% (Legge, Parish, Luebker, & Wurm, 1990; Legge, Rubin, & Luebker, 1987). Reading rate suffers from reductions of contrast below this value. Legge, Ahn, Klitz, and Luebker (1997) demonstrated that when reading speed slows down due to low contrast, this is linked to a reduced visual span, that is, the number of letters that may be recognized reliably without moving the eyes. Under these conditions, text is read with more and longer fixations (see also White and Staub, 2012). Note that text contrast seems to have a major influence on reading, but visual quality does not generally have strong effects on fixation durations (Jordan, McGowan, & Paterson, 2013).

Several recent eye-movement studies used contrast manipulation for a single target. Reingold and Rayner (2006) presented sentences with a contrast of 85% with the critical target presented at the same or reduced contrast (10%). Fixation durations on the target were increased in the low-contrast condition. This finding was replicated in similar studies with different text contrast levels (99% vs. 6%, Drieghe, 2008; 95% vs. 21%, Wang & Inhoff, 2010; 84% vs. 10%, White & Staub, 2012). Wang and Inhoff (2010) also manipulated parafoveal preview of the posttarget word (identical vs. nonword). Although they found a reliable preview benefit, its magnitude was not influenced by stimulus quality.

In the present experiment, in addition to the four preview types, we manipulated the contrast of the whole sentences, following the work of Legge et al. (1997, 1990, 1987), and White and Staub (2012). We did not want to disrupt normal reading by setting contrast below the critical level and, therefore, chose levels of 93% and 21%, closely matching those used by Wang and Inhoff (2010). We specified text contrast as a between-subject factor because we also wanted to evaluate its effect on display-change awareness with a questionnaire following the experiment.

3.4.4 METHOD

3.4.4.1 SUBJECTS

Forty-eight students (38 women, 10 men) participated in the experiment. They were between 19 and 34 years of age (*M* = 22, *SD* = 3.9).

3.4.4.2 APPARATUS

Sentences in the high-contrast condition were presented in black on a white background (just as in Experiments 1 and 2). Luminance of the background was 92.3 cd/m^2; luminance of the text was below 3.4 cd/m^2. In the low-contrast condition, sentences were presented in dark gray (14.5 cd/m^2) on a light gray background (22.2 cd/m^2). Michelson contrast for the low-contrast conditions was .21. In the high-contrast condition, the Michelson contrast was higher than .93.

3.4.4.3 MATERIAL

We used the material of Experiment 2, including 100 experimental sentences. In addition to the semantically related and unrelated previews, we introduced two further conditions: identical preview and neutral preview. In the identical condition, the target was present as a parafoveal preview and replaced by itself. The neutral previews were pronounceable nonwords constructed by changing one to five letters in existing German nouns, which were not used as preview or target. All neutral previews were unique. All previews—this includes the pronounceable nonword as well—were matched on a number of relevant lexical variables (see Table 3.7). We took great care to insure that the information provided by the initial letters and their frequency did not differ between the parafoveal previews. Furthermore, we controlled orthographic overlap between previews and target.

Table 3.7

Means and Standard Deviations of Lexical Properties for the Four Preview Conditions in Experiment 3

	Identical preview		Related preview		Unrelated preview		Nonword preview	
Stimulus characteristic	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Length [characters]	5.3	1.0	5.3	1.0	5.3	1.0	5.3	1.0
Initial unigram frequency[a]	4.1	0.2	4.1	0.3	4.1	0.2	4.1	0.3
Initial bigram frequency[a]	3.1	0.4	3.2	0.5	3.2	0.5	3.2	0.5
Initial trigram frequency[a]	2.2	0.6	2.2	0.7	2.2	0.6	2.2	0.8
Regularity[b]	1.0	0.5	1.0	0.5	1.0	0.6	1.0	0.5
Relative character overlap with target[c]	1	0	.10	.13	.10	.13	.10	.11

Note. Frequency values are case-sensitive and scaled to $\log_{10}$ counts per million. Relative character overlap with target ranged from 0 to 1.

[a] The cumulated frequency of all words (types) sharing the same initial *n*-gram. [b] Regularity is defined as the number of different words (types) of the same length sharing the same initial trigram. [c] The number of characters the preview shares with the target (at the same position), relative to word length.

For the training and filler sentences, we also had an identical condition, but not a neutral one. Instead, in 50% of the nonexperimental trials, we presented an identical preview. The idea behind this approach was to lower the overall rate of display changes. Throughout the whole experiment words were exchanged in 69% of all trials.

3.4.4.4 DESIGN

The experimental design implemented the within-subject factor preview (identical vs. related vs. unrelated vs. neutral) and the between-subject factor contrast (high vs. low). Each experimental condition was presented equally often, rendering 25 experimental sentences per preview condition and subject and 24 subjects per contrast condition and experimental sentence. As 48 subjects were tested, each sentence was read 6 times in each condition.

3.4.4.5 PROCEDURE

Subjects read eight training sentences, followed by the experimental and filler sentences. The contrast of the sentences was constant throughout the experiment. The background of the sentences was also used for instruction screens and calibrations. In the identical preview condition, the target was present as parafoveal preview and replaced itself as soon as the subjects' gaze crossed the invisible boundary.

In total, each person read 132 sentences including 100 experimental ones. Accuracy of comprehension was 97%. Forty-seven out of 48 subjects completed the questionnaire concerning the detection of display changes.

3.4.4.6 MEASURES AND SELECTION CRITERIA

Data selection followed the procedure described for Experiment 1. After applying all filtering criteria for the target region, approximately 75% of all trials remained valid. For skipping probabilities for the target, 80% of all trials remained.

3.4.4.7 STATISTICAL ANALYSIS

We manipulated two experimental factors: text contrast and preview. In the analyses, the binary predictor text contrast was coded with the (statistical) sum contrast. As to the effects of the different types of parafoveal preview, we specified three planned nonorthogonal contrasts: (a) unrelated vs. related preview, (b) related vs. identical preview, and (c) nonword vs. unrelated preview. The first contrast replicates the semantic preview benefits of Experiments 1 and 2. The second contrast represents the benefit related to the availability of the target for parafoveal preprocessing as opposed to a semantically related preview. This contrast is of major interest because it also represents the effects of display change vs. constant display. The third contrast was specified to evaluate potential preview cost associated with unrelated words relative to a nonword baseline (McNamara, 2005), with control for relevant properties of initial letters.

3.4.5 RESULTS

Table 3.8 summarizes results for the target *n* + 1. The analyses are based on 3,600 observations for gaze and first-fixation duration and 3,250 for single-fixation duration, respectively.

Table 3.8

Means and Standard Deviations of Target Reading (Experiment 3)

		Gaze duration [ms]		First-fixation duration [ms]		Single fixation duration [ms]		Refixation probability		Skipping probability		Landing position	
Contrast	Preview	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
High	Identical	235	84	221	70	222	71	.08	.27	.06	.23	.47	.24
	Related	255	110	239	100	242	102	.09	.29	.06	.23	.48	.24
	Unrelated	281	104	260	99	268	100	.12	.32	.05	.21	.48	.25
	Nonword	292	103	271	99	278	99	.13	.34	.03	.17	.47	.24
Low	Identical	237	93	221	73	224	73	.07	.26	.10	.30	.51	.27
	Related	246	88	235	82	238	83	.06	.24	.09	.29	.51	.27
	Unrelated	273	107	251	94	256	93	.12	.32	.05	.23	.49	.27
	Nonword	284	94	263	89	272	87	.10	.30	.05	.21	.50	.26

Note. Refixation probability, skipping probability, and landing position ranged from 0 to 1.

In the following, we report results sorted according to the three planned comparisons, (a) semantic preview benefit, (b) display-change effect, and (c) differences between neutral and unrelated previews, and their associated interactions for fixation durations, refixations, and skippings—we obtained no significant effects on the relative target landing position (all $|t|$s < 1.4). The sections about (a) main effects of text contrast and covariates, (b) the pretarget, and (c) the influence of display-change awareness will follow. Omission of dependent variables or effects within one of the sections implies that there was no significant result.

3.4.5.1 CONTRAST 1: SEMANTIC PREVIEW BENEFIT (UNRELATED VS. RELATED PREVIEW)

Fixation durations

The semantic preview benefit of the first two experiments was replicated for all types of fixation durations and at both levels of contrast. Fixation times on the target again were significantly longer for unrelated than for semantically related previews (b = 0.11, t = 6.0, for gaze durations; b = 0.10, t = 5.4, for first-fixation durations; b = 0.08, t = 4.3, for single-fixation durations). The new text contrast did not interact with related vs. unrelated preview (all $|t|$s < 1.66).

Figure 3.5 shows target gaze duration as a function of preview type and launch site distance. The difference between unrelated and related previews significantly decreased with launch site distance (b = −0.03, t = −3.3, for gaze durations; b = −0.03, t = −3.0, for first-fixation durations; b = −0.03, t = −2.8, for single-fixation durations). These results replicate Experiments 1 and 2, but we failed to replicate the influence of pretarget fixation durations on preview benefit reported for the first two experiments (all $|t|$s < 1.08); the trend was in the expected direction for six out of nine combinations.

Refixation probability

The probability of a target refixation was reliably higher for unrelated than related previews (b = 0.56, z = 3.2), indicating more efficient processing of targets for which a semantically related preview was presented.

Skipping probability

The probability of target skipping was lower in the unrelated preview, when compared to the related preview condition (5% vs. 7%; b = −0.54, z = −2.4). There was no evidence indicating that preview condition influences skipping in Experiments 1 and 2, but this result is in agreement with findings from the first study on semantic preview benefit: Rayner et al. (1986) reported a significantly higher probability of target skipping if the preview was identical, or a semantically related word (7%), compared to an unrelated word (1%).

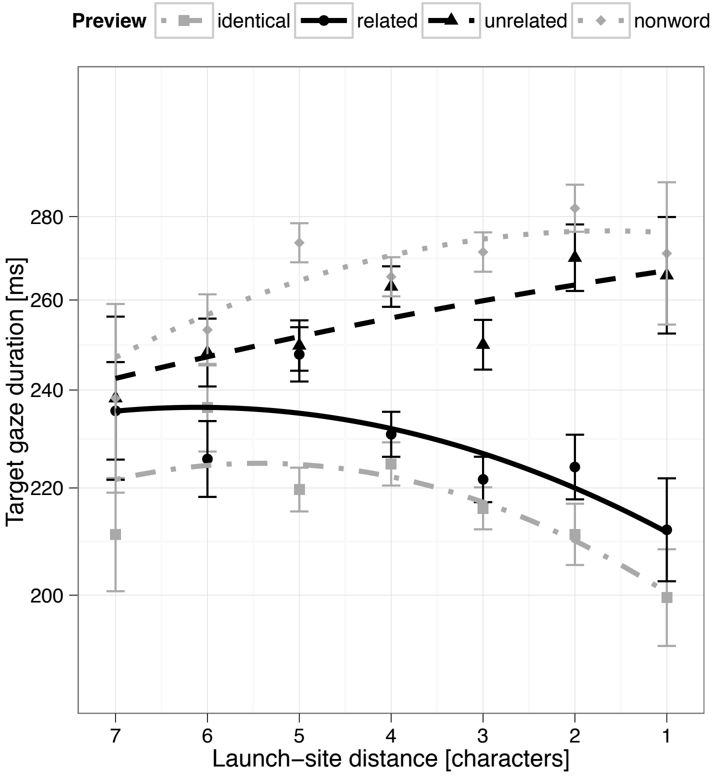

Figure 3.5. Second-order polynomial trend of the regression of target gaze duration (on a log scale) on launch site distance for identical, related, unrelated, and nonword previews (Experiment 3). Data from both contrast conditions were combined. Between-subject and between-sentence variance and fixed effects associated with text contrast have been removed from the dependent variable. Error bars represent standard errors. The very infrequent trials with a launch site distance of eight characters were omitted (0.8%).

3.4.5.2 CONTRAST 2: DISPLAY-CHANGE EFFECT (RELATED VS. IDENTICAL PREVIEW)

We may interpret the second contrast as the influence associated with the display change. In the identical condition, the target was constantly visible during the reading process.

Fixation durations

First-fixation durations (b = 0.05, t = 2.2) and single-fixation durations (b = 0.05, t = 2.3) were significantly shorter for identical rather than related previews; the contrast is marginally significant for gaze durations (t = 1.89). This difference between preview conditions was not significantly modulated by text contrast (all $|t|$s < 0.65), launch site distance (all $|t|$s < 0.6; see Figure 3.5), or pretarget fixation duration (all $|t|$s < 1.66).

3.4.5.3 CONTRAST 3: PREVIEW COST DUE TO UNRELATED WORD (NONWORD VS. UNRELATED PREVIEW)

Fixation durations

Furthermore, compared to neutral nonword previews, target fixations were shorter for unrelated ones (b = 0.05, t = 3.6, for gaze durations; b = 0.06, t = 4.2, for first-fixation durations; b = 0.05, t = 3.8, for single-fixation durations). Thus, we have no evidence in fixation durations of preview cost from “wrong” words interfering. Rather, the parafoveal presence of an unrelated word resulted in shorter target fixations, if compared to a pronounceable nonword preview. This difference between preview conditions was not significantly modulated by text contrast (all $|t|$s < 1.24) or launch site distance (all $|t|$s < 1.07; see Figure 3.5).

This contrast depends on pretarget fixation duration: The interaction between neutral vs. unrelated preview and pretarget first-fixation duration was reliable for target first-fixation duration (b = 0.09, t = 2.1) and single-fixation duration (b = 0.11, t = 2.4); for target gaze duration the effect was marginally significant (t = 1.80). Longer pretarget fixations were connected to larger differences of target fixation durations between neutral and unrelated previews.

Finally, analyses revealed a three-factor interaction between neutral vs. unrelated preview, pretarget fixation duration, and text contrast, indicating that the influence of preview time on the processing of neutral and unrelated previews depended on contrast. This effect was only significant with single-fixation duration as predictor and gaze duration as dependent variable (b = 0.21, t = 2.1). Post hoc analyses of gaze durations revealed that also a reliable interaction between nonword vs. unrelated preview and pretarget single-fixation duration was present for the low-contrast condition ($b = 0.17$, $t = 2.3$), this interaction was not significant for the high-contrast condition ($b = -0.04$, $t = -0.60$).

3.4.5.4 MAIN EFFECTS OF TEXT CONTRAST, PRETARGET FIXATION DURATION, AND LAUNCH SITE DISTANCE

The design includes main effects of text contrast, pretarget fixation duration, and launch site. As main effects, by implication, they are of potential interest if they are accentuated in interactions with preview contrasts.

Text contrast

The main effect of text contrast was not significant for fixation durations (all $|t|$s < 0.7). However, target skipping rate was significantly reduced in the high-contrast condition, compared to the low-contrast condition (5% vs. 7%; $b = 1.01$, $z = 2.0$). At first glance, this result appears counterintuitive, but most likely it is due to the pretarget fixation duration being significantly longer at low text contrast (see below), entailing a longer availability of the parafoveal preview.

Pretarget fixation duration

The combination of gaze duration, first-fixation duration, and single-fixation duration as pretarget (predictor) and target (dependent variable) resulted in nine analyses. First-fixation and single-fixation durations on targets increased significantly with increasing pretarget gaze (both ts > 2.3) and single-fixation (both ts > 2.1) durations; the effect was not significant in the remaining analyses (all $|t|$s < 1.5).

Launch site distance

The main effect of launch site distance was significant for gaze duration ($b = 0.01$, $t = 3.5$), but not for first- and single-fixation duration (both $|t|$s < 1.43).

3.4.5.5 PRETARGET

Table 3.9 summarizes results for effects on pretarget fixation durations. They were significantly shorter when the text was presented with high rather than low contrast (*b* = 0.08, *t* = 1.97, for gaze durations; *b* = 0.08, t = 1.96, for first-fixation durations; *b* = 0.08, *t* = 2.0, for single-fixation durations). We obtained no reliable effects of preview and therefore no parafoveal-on-foveal effects.

Table 3.9

Means and Standard Deviations of Pretarget Reading (Experiment 3)

		Gaze duration [ms]		First-fixation duration [ms]		Single fixation duration [ms]	
Contrast	Preview	*M*	*SD*	*M*	*SD*	*M*	*SD*
High	Identical	242	86	225	72	228	71
	Related	236	88	217	68	219	69
	Unrelated	240	91	223	83	228	84
	Nonword	247	103	221	77	224	79
Low	Identical	270	115	239	75	244	73
	Related	263	95	239	82	246	83
	Unrelated	260	93	241	82	245	81
	Nonword	256	88	235	75	241	74

3.4.5.6 AWARENESS OF DISPLAY CHANGE

Display changes occurred on 69% of the trials in this experiment; in the first two experiments, they occurred on every trial. Thirty-four out of 47 subjects (72%) noticed that display changes took place. The self-reported frequency of display change ranged from 0% to 80%; two answers indicated estimates (70% and 80%) higher than the actual frequency. Mean was 17% (*SD* = 21%); median was 10%. Relative to the actual number of display changes, mean detection rate was 25% (in accord with the hit rate reported by Slattery et al., 2011). The values reported by subjects did not reliably differ between the text contrast conditions, when using a Wilcoxon rank sum test to correct for skewness

(*W* = 299, *p* = .62); numerically, however, the mean in the low-contrast condition was lower than in the high-contrast condition (15% vs. 19%). Figure 3.6 displays target gaze duration as a function of preview type and the proportion of trials in which a display change was detected (self-report). One main question is whether the semantic preview benefit correlates with the perception of display changes. In an LMM for gaze durations with effects of preview types, text contrast, display-change recognition rate, and all interactions only recognition rate was significant (*b* = 0.002, *t* = 2.1); this effect was marginally significant for single-fixation durations (*t* = 1.75), but not for first-fixation durations (*t* = 1.56). Text contrast was never significant (all |*t*|s < 0.86).

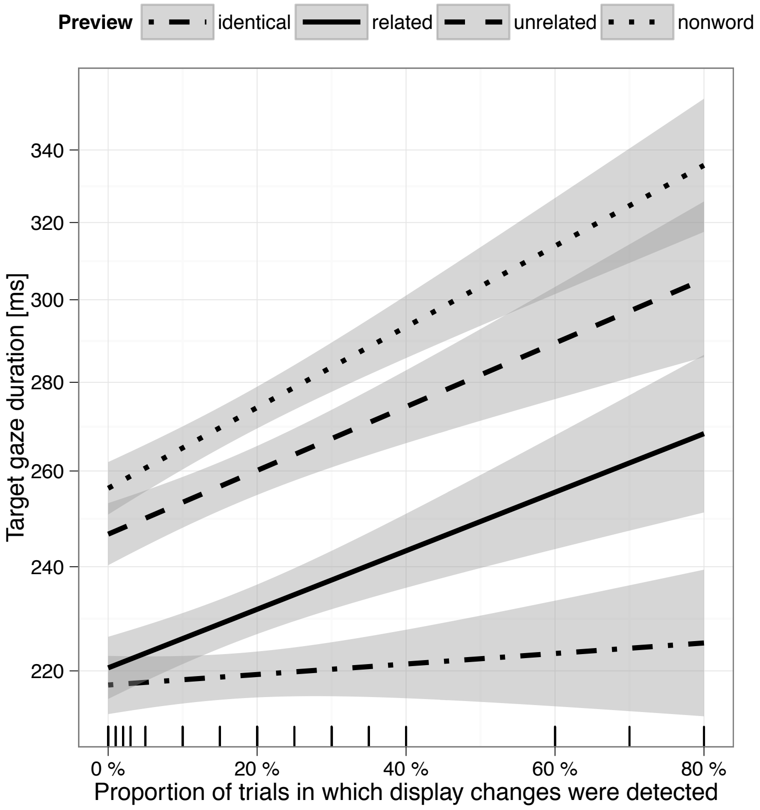

Figure 3.6. Linear trend of the regression of target gaze duration (on a log scale) on the proportion of trials in which display changes were detected (self-report) for identical, related, unrelated, and nonword previews (Experiment 3). Data from both contrast conditions were combined. Between-subject and between-item variance and fixed effects associated with text contrast have been removed from the dependent variable. Tick marks on the horizontal axis indicate observed values. Shaded error bands represent 95% confidence interval.

Interestingly, we obtained a reliable interaction between the self-reported display-change awareness and the display-change contrast (b = 0.002, t = 2.6, for gaze durations; b = 0.002, t = 2.2, for first-fixation durations; b = 0.002, t = 2.3, for single-fixation durations). The difference between related and identical previews increased with increasing display-change awareness. Just as in Experiments 1 and 2, there was no reliable interaction between display-change awareness and the semantic preview benefit (all $|t|$s < 0.62). Hence, there is no evidence that a subject's ability to detect display changes affects the magnitude of the semantic preview benefit. Similarly, display-change awareness does not relate differentially to neutral and unrelated previews (all $|t|$s < 1.53). In Figure 3.6, the slope of the regression line for identical previews is not significantly different from zero (b = 0.0004, t = 0.39, for gaze durations; b = 0.00004, t = 0.04, for first-fixation durations; b = −0.00001, t = −0.01, for single-fixation durations).

3.4.6 DISCUSSION

Subjects read sentences in which a critical target was initially occupied by an identical, a semantically related, an unrelated, or a neutral pronounceable nonword preview, which subsequently was replaced by the target. Sentences were presented with a high or a low contrast. As opposed to unrelated previews, target fixations were shorter if a semantically related preview was presented parafoveally, replicating the critical results of Experiments 1 and 2.

As expected, fixation times were further reduced when the preview was identical to the target and therefore allowed for parafoveal processing of the target. When compared to nonidentical previews, the major advantage of identical previews has been demonstrated in many studies (see Schotter et al., 2012, for a review). Importantly, although we took great care in constructing neutral nonwords, target fixation times were shorter in the unrelated, compared to the nonword preview condition. All nonword stimuli were unique and pronounceable. In addition, identical, related, unrelated, and nonword previews were matched on several orthographic and lexical variables. We agree with other researchers who state that a "neutral" preview is difficult to define for reading, but the use of nonwords as reference condition for the computation of preview benefit leaves open an interpretation of preview benefit in terms of preview cost if nonwords induce inhibitory processes during lexical access. Nonwords may take longer to encode than real words. As a consequence, the processing of a parafoveal nonword may spill over into processing of the target (see McNamara, 2005, for a discussion). Since unrelated previews did not result in longer fixations than nonwords, we have no evidence that the semantic preview benefit obtained was due to inhibition from unrelated previews. However, it is also possible that all types of nonidentical preview cause interference, but related words do so less than unrelated ones. In White et al.'s (2008) study on semantic preview benefit within Finnish compounds, the order of gaze durations across preview types was identical < semantically related < unrelated < pronounceable nonword. Most importantly, gaze duration on the compound (measured from when the target constituent was fixated first) was significantly longer for nonword than unrelated previews.

Experiments 1 and 2 produced reliable evidence indicating that launch site distance has an impact on semantic preview benefit. Experiment 3 produced this evidence as well. The interaction was statistically the same for both levels of contrast. Interestingly, neither related vs. identical nor nonword vs. unrelated preview benefits were significantly influenced by the distance between pretarget fixation location and the preview word. As is shown in Figure 3.5, the regression lines of nonword and unrelated previews are quite similar. Also, the regression lines of related and identical previews are almost parallel.

As opposed to the robust effect of an impact of launch site distance on preview benefit, the evidence of an influence of pretarget fixation duration is very elusive. The difference between unrelated and related previews was never significantly modulated by pretarget fixation duration or the interplay between pretarget fixation duration and text contrast. In Experiments 1 and 2, this effect was tenuous at best and present only in a few analyses. However, there was some evidence indicating a modulation of the difference between nonword and unrelated previews by pretarget fixation duration and contrast. Surprisingly, this preview benefit modulation by pretarget fixation time was limited to the low-contrast condition. Possibly, inhibition processes arising from prolonged presence of the parafoveal nonword were responsible for this outcome. Reduced contrast may delay parafoveal information extraction and therefore inhibition. In general, modulation of preview benefit effects by pretarget viewing time was weak, but follow-ups on these results may greatly contribute to an understanding of parafoveal information extraction during reading.

The impact of the text contrast manipulation on reading was—aside from main effects on target skipping and pretarget fixation duration—negligible. Increased fixation durations at low contrast were in accord with previous studies in which contrast was reduced for the whole sentence (Legge et al., 1987; 1990; 1997; White & Staub, 2012) and for critical targets (Drieghe, 2008; Reingold & Rayner, 2006; Wang & Inhoff, 2010; White & Staub, 2012). In our data, the effect was reliable for the pretarget, but not for the target. Possibly, the contrast reduction we implemented was not strong enough to dramatically change reading performance. We had deliberately chosen the lowest level of contrast that still allowed for normal reading speed (cf. Legge et al., 1987); we did not want to induce a qualitatively different reading behavior. Manipulating contrast did not significantly affect semantic preview benefit or display-change awareness. Of course, our results may not hold for more severe reductions of visual contrast, but they establish the reliability of the semantic preview benefit for a considerable range of text contrast.

Finally, we found no evidence of a relation between a subject’s self-reported display-change awareness and the magnitude of the semantic preview benefit in any of the experiments. Similarly, there was also no evidence of a relation with the benefit arising from unrelated previews (compared to nonword previews). At first glance, these results look different from those of White et al. (2005a) and Slattery et al. (2011), who reported a larger difference between nonword and identical previews for aware, as opposed to unaware subjects. However, as shown in Figure 3.6, the difference between related and identical previews also increased with increasing display-change awareness in our experiment. Regression lines of the three nonidentical conditions were close to parallel, whereas the regression line of identical previews was stastistically unaffected by display-change awareness.

3.5 META-ANALYSIS OF SEMANTIC PREVIEW BENEFIT IN EXPERIMENTS 1−3

We conducted three experiments in which related and unrelated previews were used. An analysis integrating all the data affords a test of whether interactions involving semantic preview benefit, launch site, and display-change awareness were missed due to limited statistical power of individual experiments. Interactions involving continuous covariates are known for their poor reliability (G. H. McClelland & Judd, 1993). In addition, we used the aggregated data to test whether mislocated fixations could be the main source of the semantic preview benefit. This argument has served as an alternative explanation for parafoveal-on-foveal effects (Drieghe, Rayner, & Pollatsek, 2008; Rayner, Pollatsek, et al., 2007) and might also apply to semantic preview benefits.

3.5.1 SEMANTIC PREVIEW BENEFIT AND DISPLAY-CHANGE AWARENESS

Figure 3.7 displays the distribution of the proportion of reported display changes, along with the mean target gaze duration of all subjects, separately for related and unrelated previews. Even for most of the subjects who were aware of display changes, the probability of detecting a display change was lower than the opposite outcome; that is, most of the points in Figure 3.7 are below 50% on the horizontal axis (see also shape of density curve). In none of the three experiments did we obtain a reliable interaction between unrelated and related preview. These results are reflected in the virtually parallel lines in Figure 3.7.

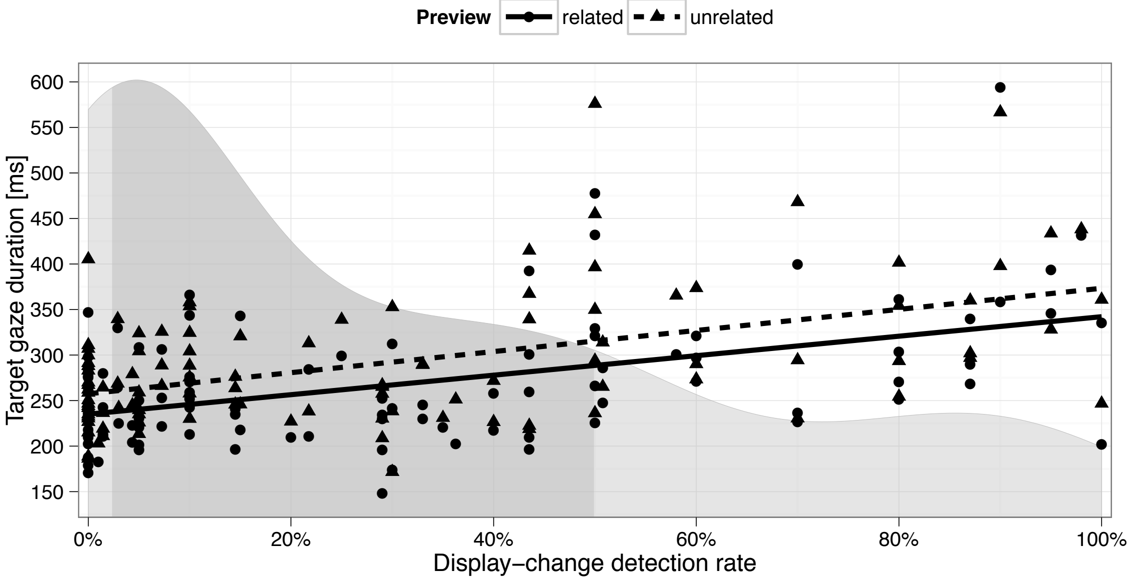

Figure 3.7. Linear trend of the regression of average target gaze duration on display-change detection rate (self-report; relative to the actual proportion of display changes) for related and unrelated previews (Experiments 1–3). Data from both capitalization and both contrast conditions were combined. Black symbols indicate subjects' average gaze durations for related (circles) and unrelated previews (triangles), respectively. The shaded area in the background represents the density of the detection rate (without relationship to the vertical scale; zero density is represented by the position of the horizontal axis); the darker area indicates the interquartile range of the distribution.

To evaluate this issue with better statistical power, we analysed data of related and unrelated trials of all three experiments.[10] This analysis encompasses observations from 107 subjects. There still was no significant modulation of semantic preview benefit by self-reported display-change detection rate (b = −0.000008, t = −0.03, for gaze durations; b = −0.0001, t = −0.36, for first-fixation durations; b = 0.00006, t = 0.21, for single-fixation durations). To assess the reliability of these null results, we generated

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[10] For this analysis, the proportion of detected display changes reported by subjects of Experiment 3 was linearly scaled to the actual proportion of display changes; according to this transformation, two subjects reported a relative detection rate of more than 100%. Since it logically is not possible to detect more display changes than trials, these two values were set to 100%.

95% confidence intervals for the regression coefficients of the interaction effect, based on 10,000 posterior simulations (Gelman et al., 2012). Intervals for gaze durations ([−0.0007; 0.0005]), first-fixation durations ([−0.0007; 0.0005]), and single-fixation durations ([−0.0006; 0.0006]) roughly correspond to fixation duration changes ([−0.17 ms; 0.13 ms], [−0.17 ms; 0.11 ms], and [−0.15 ms; 0.16 ms], respectively), associated with a 1% increase in detection rate. Effects outside these ranges could reliably be rejected, given the data and analyses. Even if we compared detection rates of 0% and 100%—the latter not representative of the distribution of reported values—the interaction effects were considerably below the main preview effects.

Traditionally, subjects who reported display-change awareness in boundary experiments were excluded from the analyses; usually this number was very small. In contrast, in each of our three experiments, there were only a few participants who reported no detection of display changes. Therefore, we did not limit our analyses to unaware subjects. When aggregated across the three experiments, the number of subjects unaware of display change adds up to 22 (21%), warranting a separate analysis. These subjects showed longer fixation duration when the preview was unrelated, compared to semantically related previews (b = 0.09, t = 4.9, for gaze durations; b = 0.09, t = 5.2, for first-fixation durations; b = 0.10, t = 5.4, for single-fixation durations). Thus, the extraction of semantic code from the parafovea remained significant even for subjects meeting the traditional criterion of being unaware of display changes.

3.5.2 SEMANTIC PREVIEW BENEFIT AND MISLOCATED FIXATIONS

We interpret our finding of a semantic preview benefit on the target as evidence of parafoveal processing of semantic information, but targeting of saccades is not perfect. Therefore, due to oculomotor error, saccades sometimes are too short and hence undershoot their goal (McConkie et al., 1988). As a result, the fixation can be on the pretarget, but attention may still be on the intended preview word. If, despite the oculomotor error, attention were in fact on the intended saccade target, the semantic preview benefit would be a parafoveal effect with respect to the location of the eye, but not with the respect to the location of attention. We will refer to such fixations as “mislocated” fixations. Mislocated fixations are more likely to be on the edges of words (Nuthmann, Engbert, & Kliegl, 2005). Therefore, the closer a fixation is to the boundary preceding the target location, the higher the probability of it being a mislocated fixation.

Using the aggregated data, we can check the significance of the semantic preview benefit as a function of launch site. Since pretargets had a length of four to eight characters, launch site distance could range from one to nine characters. A fixation on the last character of the pretarget has a launch site distance of 1; a fixation on the space preceding an eight-character pretarget is indicated by a launch site of 9. Fixations on the space between pretarget and target are considered as target fixations.

Results from these analyses are listed in Table 3.10. Semantic preview benefit was significant for gaze durations, first-fixation durations, and single-fixation duration in a subset of data with pretarget fixations located five to nine characters before the target. In this region, there is a very low probability that the intended fixation location was on the target. Nevertheless, the negative relationship between launch site distance and the regression coefficient associated with the semantic preview effect could hint at an additional influence from mislocated fixations for fixations close to the boundary. We conclude that our finding of semantic processing of parafoveal words cannot be explained by mislocated fixations alone.

Drieghe et al. (2008) found effects from properties of a critical target on the fixation of the preceding word (parafoveal-on-foveal effects) to be limited to near-target fixations and argued that mislocated fixations, rather than parallel processing, can explain this phenomenon. In contrast, Kennedy (2008) obtained parafoveal-on-foveal effects up to seven characters before the parafoveal target. In the present study, we did not find parafoveal-on-foveal effects but semantic preview benefit was greater for short rather than long launch site distances, but this effect was still significant for launch sites that are unlikely to be classified as mislocated fixations by any algorithm we are aware of.

Table 3.10

Linear Mixed-Model Analyses of Semantic Preview Benefit on the Target with the Dependent Variables Gaze Duration, First-Fixation Duration, and Single-Fixation Duration Subsets of Data Defined by Different Ranges of Launch Sites

	Gaze duration				First-fixation duration				Single-fixation duration			
Launch site distances	Obs (%)	*b*	*SE*	*t*	Obs (%)	*b*	*SE*	*t*	Obs (%)	*b*	*SE*	*t*
1–9	100.0	0.10	0.01	9.04	100.0	0.08	0.01	6.45	88.9	0.10	0.01	8.32
2–9	96.1	0.10	0.01	9.08	96.1	0.08	0.01	6.38	85.2	0.10	0.01	8.42
3–9	81.2	0.08	0.01	7.48	81.2	0.07	0.01	5.32	71.3	0.09	0.01	7.24
4–9	56.2	0.06	0.01	5.01	56.2	0.05	0.01	3.10	48.4	0.07	0.01	4.84
5–9	29.4	0.06	0.02	3.58	29.4	0.06	0.02	3.03	24.6	0.08	0.02	4.30
6–9	11.3	0.06	0.02	2.57	11.3	0.05	0.03	1.70	9.5	0.07	0.03	2.33
7–9	3.4	0.07	0.05	1.41	3.4	0.05	0.05	0.98	2.9	0.08	0.06	1.37

Note. Analyses are based on log data from 110 subjects of Experiments 1−3 and were performed on subsets of observations (obs). Launch site distances are given in characters. A launch site distance of 1 indicates a fixation on the pretarget's last letter. The proportion of observations is relative to all observations including related or unrelated preview (N = 6,251). Analyses based on the very infrequent trials with a launch site distance of eight or nine characters were omitted (0.6%).

3.6 GENERAL DISCUSSION

We report a semantic preview benefit from the upcoming word next to the currently fixated one during reading of an alphabetic script, using the boundary paradigm as the experimental venue. So far, reports of semantically related parafoveal previews facilitating the reading process were limited to within-word processing (White et al., 2008), reading of character-based Chinese script (Cui et al., 2013; Yan et al., 2009; Yan, Zhou et al., 2012; Yang, Wang, et al., 2012), and Korean script (Kim et al., 2012), and delimitating the duration of preview presentation (parafoveal fast priming; Hohenstein et al., 2010). In the present study, we used the German language and highly frequent foveal pretargets and demonstrated a semantic preview benefit for fixation times on the target. We also showed that parafoveal semantic facilitation is potentially moderated by pretarget gaze duration and moderated by launch site distance; we did not find a significant relation between semantic preview benefit and subjects' self-reported ability to detect display changes. Furthermore, we found no evidence that the effect depended on capitalization of targets or contrast of text against background. The effect is also not an artifact of mislocated fixations. We conclude that extraction of semantic codes during reading can be demonstrated for the (right-directed) parafoveal region and does not depend on whether the parafoveal region is made up of a part of the fixated word or another word. Given this positive evidence, we can move on to determine the conditions required for its occurrence.

3.6.1 WHAT ABETS PARAFOVEAL SEMANTIC PREVIEW BENEFIT?

How does the present study differ from previous ones in which no semantic preview benefit has been reported? As described in the Introduction, with the exception of Rayner et al. (1986), earlier studies did not use the standard boundary paradigm. The positive findings for a semantic preview benefit in the present study could be due to the use of high-frequency pretargets. High-frequency words are easier to process and hence allow for more extensive preprocessing of parafoveal words, yielding a greater (identity) preview benefit than low-frequency words (J. M. Henderson & Ferreira, 1990; Kennison & Clifton, 1995; White et al. 2005). Such a dynamic modulation of the perceptual span, reflected in parafoveal-on-foveal effects of the frequency of word *n* + 1 on fixations on word *n*, has also been reported in analyses of large corpora of eye movements (Kennedy et al., 2013; Kennedy & Pynte, 2005; Kliegl et al., 2006). For the present study, we explicitly selected pretargets to this end. The semantic facilitation effect obtained from parafoveal preview may, to some extent, be due to this characteristic of the foveal word.

Although there are invariant aspects of reading, across orthographies (see Frost, 2012, for a discussion), differences between languages are highly important. The orthographic consistency in German script is relatively high. As a consequence, immediate on-line assembly of syllables is much more likely in German than in English (Frith, Wimmer, & Landerl, 1998). Resulting differences in phonological encoding probably are relevant when it comes to extracting lexical information during reading (see Laubrock & Hohenstein, 2012).

3.6.2 PREVIEW SPACE AND PREVIEW TIME

The impact of both preview space and preview time on parafoveal preprocessing fits predictions of different computational models of eye-movement control during reading (see below). If the distance between pretarget fixation location and preview location is small, more information from the parafoveal preview falls into the perceptual span. This has implications for the parafoveal preprocessing of the upcoming word. In all three experiments, semantic preview benefit was reliably modulated by launch site distance. The difference in target fixation durations for semantically related and unrelated previews increased with decreasing space between pretarget fixation and preview word. We interpret this interaction as evidence of more efficient lexical processing of proximal previews. Since visual acuity is highest for the fovea and quickly drops in the parafoveal region, the low-level visual representation of the preview does benefit from a short launch site distance. This advance in the visual representation most likely abets processing speed of orthographic and lexical information.

Consistent with Kliegl et al. (2013), benefit associated with identical previews is higher, compared to nonword previews, if the distance between pretarget and target fixation location is short. Furthermore, the distance to a parafoveal preview influences the performance of subjects who are asked to detect display changes while reading sentences for comprehension (Slattery et al., 2011). Accuracy is higher if the eyes land closer to the target region. This more efficient detection of stimuli changes for closer launch sites can be explained with limitations of visual acuity. The influence of spatial distance also for semantic preview processing is evidence indicating that a low-level visual advantage of the preview location is not limited to parafoveal preprocessing of basic features, but applies also to the encoding of word meaning. The larger effect for small, rather than larger, distances may in part be due to mislocated fixations undershooting the intended target, but the effect was still significant for distances at which explanations exclusively in terms of mislocated fixations are highly unlikely.

The effects of pretarget fixation duration on semantic preview benefit are less clear. The fixation duration on the pretarget limits parafoveal preview time. We obtained a reliable positive relationship between preview time and semantic preview benefit, but this effect was present only in a subset of analyses of Experiments 1 and 2. In Experiment 3, we found no reliable evidence of this interaction. In previous studies with alphabetic script, the impact of pretarget fixation duration on identity preview benefit was in the focus of attention. Schroyens et al. (1999) found an only marginally significant positive relationship; the effect was not reliable in White et al.'s (2005a) data. As in the present study, Kliegl et al. (2013) found reliable positive effects in a subset of their analyses. In Chinese, the effect appears to be quite labile as well (Yan, Risse, et al., 2012; Yan, Zhou, et al., 2012). Thus, concerning the influence of preview time on preview benefit, our results are mixed and reflect the overall picture arising from findings in previous studies.

Preview time influencing parafoveal processing is also consistent with other recent findings showing that the perceptual span dynamically changes during a fixation (Ghahghaei, Linnell, Fischer, Davis, & Dubey, 2013). During the first half of a fixation, the perceptual span expands, entailing more processing of parafoveal stimuli. Such an influence of preview time on parafoveal processing during reading delivers important constraints for computational models of eye-movement control during reading. More research is necessary to determine the timelines of preview on semantic and other types of preview benefit (Dambacher et al., 2012).

3.6.3 DISPLAY-CHANGE AWARENESS

The study of parafoveal preview benefit requires an exchange of words during reading. White et al. (2005a) and Slattery et al. (2011) reported greater identity preview benefit (nonword vs. identical preview) when display changes were detected and therefore argued that subjects' awareness of these changes is critical to the results. Although we found a positive relationship between subjects' fixation durations and their ability to detect display changes, there was no evidence of a subject's self-reported display-change awareness having an impact on the magnitude of the semantic preview benefit. The result was very different when we compared nonidentical and identical previews: Increasing awareness of display changes increased the difference between related and identical previews. Comparing nonidentical and identical previews has one drawback. It confounds a comparison of relatedness and a physical change on the display; nonidentical previews require a display change, whereas identical previews do not. Our finding of an awareness-determined increase in preview benefit when including an identical condition is consistent with that of White et al. (2005a) and Slattery et al. (2011), but for comparisons between nonidentical preview conditions, there was no evidence indicating that the magnitude of the preview benefit is affected by the detection of display changes.

Independence of semantic facilitation and degree of awareness is an important result concerning boundary studies in general and also concerning the reliability of the outcome of experiments using the parafoveal fast-priming technique (Hohenstein et al., 2010). The finding is reminiscent of research on the relation between action priming by metacontrast-masked primes and awareness of the prime (Vorberg, Mattler, Heinecke, Schmidt, & Schwarzbach, 2003). They showed that the time course of priming was identical for reportable and invisible prime stimuli and concluded that “experimental variations that modify the subjective visual experience of masked stimuli have no effect on motor effects of those stimuli in early processing“ (p. 6275).

3.6.4 IMPLICATIONS FOR COMPUTATIONAL MODELS OF EYE-MOVEMENT CONTROL IN READING

Our results are relevant to a controversial issue in computational modeling of eye-movement control in reading, namely, whether processing of consecutive words is serial, with one word being processed at a time, or spatially distributed with multiple words at a time (Starr & Rayner, 2001). Cognitive models of eye-movement control during reading (see Radach et al., 2007, for an overview) can analogously be divided into *sequential attention shift* (SAS) models (see Reichle, 2011, for an overview) and *processing gradient* (PG) models (see Engbert & Kliegl, 2011, for an overview).

The best known SAS model is E-Z Reader (Reichle et al., 1998, 2003, 2009), which postulates consecutive stages of processing. In the early visual stage, low-level word shape information (e.g., length) is processed preattentively before the first stage of lexical processing (L_1) starts. This stage is influenced by word frequency and word predictability. Completing this stage triggers a saccade program from word *n* to word *n* + 1 and simultaneously the second stage of lexical processing (L_2), lexical access. When L_2 is completed, attention shifts to word *n* + 1 within 50 ms. If L_1 of word *n* + 1 is completed while the saccade program to the target *n* + 1 is still in the labile phase M_1, this old saccade program is cancelled and a new one starts toward word *n + 2*. If the saccade program is already in the nonlabile phase M_2, the saccade will arrive at the target and start the critical fixation duration.

How can an SAS model like E-Z Reader explain the present results? In general, preview benefit is greater with highly frequent pretargets, such as those used in the present experiments, since stages of lexical processing in E-Z Reader are shorter as frequency increases and attention shifts earlier from pretarget to target. Several findings coincide very well with these basic model assumptions. L_1 is longer if the word is farther removed from the center of vision. Thus, our result of a negative relationship between launch site distance and preview benefit can be explained by the slower lexical processing of a distant parafoveal preview word. In the E-Z Reader framework, greater preview benefit for long pretarget fixation durations is a consequence of the increased timespan during which the parafoveal preview could be processed. There are two potential sources of variation in the pretarget gaze duration: First, the M_1 and M_2 stages of saccade programming are random deviates from gamma distributions; second, if a word is refixated, the amount of lexical processing from the preceding fixations on the same word will reduce the time needed to finish lexical processing. Thus, attention will shift to the next word earlier, generating a longer period for parafoveal processing before the saccade to the next word is executed.

There are two conditions under which the model can account for semantic preview benefit, but the constraints for this to happen are quite formidable. First, the pretarget fixation could be a mislocated fixation resulting from an erroneous undershoot of the target. Our analyses suggest that this explanation is unlikely to account for all of the semantic preview benefit we observed. Second, the first stage of lexical processing of the parafoveal preview L_1 of word $n + 1$ must be completed during the remainder of the non-labile phase M_2 of the saccade program from word n to word $n + 1$; otherwise, the reader will skip the target, which will then not contribute to analyses of preview benefit. Thus, the time the preview is in stage L_2 must be shorter than the duration of M_2.

PG models provide an alternative perspective. According to these models, attention is distributed continuously as a gradient in the visual field. In the PG model SWIFT (Engbert et al., 2002, 2005; Schad & Engbert, 2012), the gradient is determined by word position and foveal processing. A dynamic field of lexical activations evolves as a function of the lexical processing difficulty of the words, as several words are processed in parallel. Hence, attention is not limited to a single word. Like E-Z Reader, word processing comprises two phases. The first phase represents low-level preprocessing. Activation of a word increases until it reaches a difficulty-determined maximum. In the second phase, lexical access takes place and activation decreases until the word is completely processed. In the most recent version of the model (Schad & Engbert, 2012), the processing span is also influenced by foveal word processing. During the increasing phase, the processing span is at a fixed minimum. After preprocessing is completed, the processing span dynamically increases with decreasing activation of the foveal word. This zoom lens behavior allows for more parafoveal processing if the fixated word is easier to process. The assumption of parallel lexical processing of words enables PG models to explain the present results.

Applying the theoretical framework of SWIFT to the current experiment includes the following: Lexical processing of the preview in parafoveal position occurs during fixation of the pretarget *n*. When processing of target $n + 1$ is in the decreasing (lexical) phase, semantic information is extracted. An increased preview benefit with short launch site distances is due to a higher processing gradient near the fixation location. There are two sources for a positive relationship between preview benefit and pretarget fixation duration in the SWIFT framework: The longer the preview duration, the longer lexical processing of the preview will be, and the larger the processing span, with an increase of processing rate for the preview word.

Saccade target selection is not a deterministic process, but a stochastic process, assuming a word's target selection probability is proportional to its relative activation. The start of saccade programs is a stochastic process modulated by foveal activity. Therefore, although the amount of semantic parafoveal processing is positively correlated conceptually with the probability of skipping the next word, skipping probability depends on temporal, spatial, and lexical properties. Fixating a word implies lexical preprocessing, and thereby preview benefit is expected in SWIFT. The results of the present study are clearly in the theoretical spirit of PG models. Nevertheless, we must recognize that it is unlikely that any of the implemented model variants correctly reproduce the pattern of results.

3.6.5 CONCLUSION

The results of three experiments are in support of semantic parafoveal preprocessing for readers of an alphabetic script: Targets are read faster with a related-word preview than with an unrelated-word preview. The semantic preview benefit was greater when fixation position was close to the upcoming word. We also observed several positive effects of pretarget fixation durations (preview time) on semantic preview benefit. The degree of awareness of display change was positively related to average mean fixation duration and the magnitude of identity preview benefit, but subjects' degree of awareness of display changes was not significantly related to semantic preview benefit. The results are in support of theoretical and computational proposals allowing for complete parafoveal processing of words during reading.

4 GENERAL DISCUSSION

Parafoveal processing of words has been studied in a series of seven experiments. Most importantly, targets were fixated shorter if they were previewed by a semantically related compared to an unrelated word. This is the first demonstration of semantic preview benefit in a language based on the Roman writing system. Secondly, a new paradigm for the study of parafoveal processing during reading, parafoveal fast priming, was introduced. This technique offers new possibilities for the research of preview benefit. Thirdly, time-dependent effects of semantic parafoveal processing were obtained by both experimental and statistical control of preview duration. The corresponding results constitute a reference of the complexity of the reading process. Fourthly, the influence of display-change awareness on preview benefit has been evaluated. This is the first study in which a modulation by awareness was tested with a comparison of nonidentical previews. Finally, technical details like variable transformation, random effects, and the assessment of display-change delays are going to be discussed in the appendices.

The findings of the experiments reported in Chapters 2 and 3 and their implications have been extensively discussed in the corresponding sections. Therefore, this General discussion is situated on a metalevel. I will address the results and general considerations in a broader context of three relevant topics.

Firstly, gaze-contingent display-change paradigms will be reviewed and discussed in section 4.1. Their usage has clearly increased over the last years due to technical improvements and new research interests. Technical issues concerning display changes have different implications for the boundary paradigm and parafoveal fast priming.

The present results are relevant to the time course of reading. Since important issues have already been discussed in Chapters 2 and 3, I will add thoughts on implications for computational models of eye movement control and the time-dependency of semantic processing in section 4.2.

Finally, the finding of reliable semantic preview benefit is in agreement with the results of studies with Chinese material, but is in contrast with a seminal study in English. In section 4.3, I will discuss how differences in experimental results might be due to differences between languages.

4.1 THE BOUNDARY TECHNIQUE AND RELATED GAZE-CONTINGENT PARADIGMS

Two gaze-contingent display-change paradigms were used in this thesis. I will review the evolution of these techniques and discuss why their use is on the rise. Gaze-contingent paradigms have been very helpful for understanding the process of reading. Furthermore, critical points, particularly concerning the classical boundary paradigm and the parafoveal fast-priming paradigm, will be discussed. Comparisons to other studies are of interest for interpreting the current results on display-change awareness, but with the following review I have mainly attempted to offer a general insight into the growing field of gaze-contingent reading experiments.

4.1.1 THE FIRST YEARS

Rayner (1975) introduced the gaze-contingent boundary paradigm, in which a preview occupies a critical target and is replaced with the target when the gaze crosses the boundary. There is one target and one display change per sentence. In contrast to today’s studies, Rayner used five different boundary locations, ranging from nine character spaces to the left of the first letter of the target to the fourth letter of the target.

McConkie, Zola, Wolverton, and Burns (1978) discussed the possibilities and technical requirements associated with gaze-contingent display changes. Furthermore, they argued that it is important to develop appropriate dependent variables. In today’s studies with the boundary paradigm, it appears usual to report different types of reading measures (at least first-fixation duration and gaze duration) on pretarget and target location. In the first study with the boundary paradigm, Rayner (1975) reported the durations of fixations prior to and after the display change. The duration of the fixation before the display change was not constrained by the pretarget location, but the region prior to the target was divided into sections of three character spaces. These sections ranged from 16−18 character spaces prior to the target up to the three initial characters of the target. Notably, some of these fixations were on words before the pretarget. Furthermore, the duration of the fixation preceding the display change could be the final fixation of multiple fixations on a single word. Fixations were considered as target fixations when the fixation was located in a range of three letters before to eight letters after the initial letter of the target, although the length of the target ranged from five to seven characters. Also, target fixations were grouped by the fixation location of the fixation preceding the display change. Interestingly, a target-location based measure of preview benefit was not present in Rayner's (1975) groundbreaking work.

Despite the potential of the boundary paradigm for reading research, different gaze-contingent paradigms were created and used in the following years. Besides several experiments with the moving-window technique (McConkie & Rayner, 1975; see Introduction), in which a certain number of characters around the fixation location is visible and the display changes during each saccade, researchers developed the following experimental techniques: Rayner (1978) asked subjects to fixate and name a single parafoveally presented word. The preview was replaced with the target when the gaze moved to the parafoveal stimulus. Rayner and Bertera (1979) masked text at the fixation location during reading. McConkie and Zola (1979) presented text in alternating case (lIkE tHiS) and changed the case during each saccade (LiKe ThIs). Rayner et al. (1981) employed a variant of the moving-window paradigm in which text was masked after a delay relative to fixation onset. In a further moving-window variant, Rayner et al. (1982) used word-based windows (only the fixated word or the fixated word and one to three words to the right) and compared the valid presentation of the next word with a condition in which only the initial letter was preserved. Lima and Inhoff (1985) also used word-based windows, but the text left of the fixated word was always available. Furthermore, Lima and Inhoff focused on critical targets. Apart from the moving-window technique, these gaze-contingent paradigms are not widely used today.

It was to take ten years until the second study with the classic boundary paradigm was published. Balota et al.'s (1985) approach is prototypical for today’s studies on preview benefit: They presented different types of preview and analysed target measures like first-fixation duration, gaze duration, and skipping probability. As opposed to Rayner (1975), Balota et al. used only one boundary location: the next to the last letter in the pretarget. Due to the boundary location in Balota et al.’s study, they had to exclude sentences in which the fixation landed on the last two letters of the pretarget. In a reanalysis of Balota et al.’s (1985) data, Pollatsek et al. (1986) reported target landing position and refixation probability, variables frequently taken into account in present studies.

4.1.2 DIFFERENTIATION OF GAZE-CONTINGENT TECHNIQUES

Further extensions and modifications of the boundary paradigm have been developed. Morris et al. (1990) delayed the availability of parafoveal information to the right of the fixation in a word-based moving-window paradigm. Pollatsek et al. (1992) were the first to place the boundary between pretarget and target. This location is now most common in studies with the boundary paradigm. Sereno and Rayner (1992) demonstrated an extension of the boundary technique for the study of foveal processing: the fast-priming paradigm. Parafoveal preview of the target was denied until the gaze crossed the boundary, which triggered presentation of a foveal preview at fixation location (first display change). After a specified delay, the actual target replaced the preview while the eyes still fixated the target location (second display change). Schroyens et al. (1999) used the boundary technique in word lists rather than sentences. Hyönä, Bertram, and Pollatsek (2004) demonstrated parafoveal preview benefit within words. They placed the boundary within words (two-constituent compound nouns) and manipulated the preview for the second constituent. Starr and Inhoff (2004) manipulated information to the right and the left (against reading direction) of a fixated target. While the target was fixated, either the word to its right, to its left, or both to its right and left were masked. This technique includes (at least) two display changes since all words are available before and after target fixation. White, Rayner, and Liversedge (2005b) manipulated parafoveal preview of a space which was either available or occupied with a character. Inhoff et al. (2005) delayed the parafoveal presentation of a critical target by a specified duration relative to the onset of pretarget fixation. In Rayner et al.'s (2006) study, a critical target and/or the word to its right were masked or disappeared with the onset of target fixation. Words reappeared when another word was fixated. McDonald (2006) placed the boundary in the middle of the pretarget and analysed target fixations in trials in which the pretarget was fixated after the eyes crossed the boundary. Rayner, Juhasz, et al. (2007) used the classic boundary paradigm and manipulated preview of a critical target at position *n* + 2. In an extension, Angele et al. (2008) orthogonally manipulated the preview of word *n* + 1 and word *n* + 2. Wang, Tsai, Inhoff, and Tzeng (2009) manipulated text to the left of the fixation: The first character of a two-character Chinese word was changed when the gaze crossed the boundary located between both characters. When the gaze left a critical area, the actual character reappeared. Wang, Inhoff, and Radach (2009) used critical three-word sequences and manipulated the preview of the first and the third word. Two boundaries were used, and therefore the display changed two times. Miellet, O'Donnell, and Sereno (2009) introduced the parafoveal magnification technique, in which the size of the parafoveal text is a function of fixation location: The character size compensates the drop in visual acuity as a function of eccentricity. Wang and Inhoff (2010) used the classic boundary paradigm and presented the target in regular or low visual contrast. Hohenstein et al. (2010; Chapter 2) presented parafoveal preview for a specified duration in a parafoveal fast-priming technique. Slattery et al. (2011) used the classic boundary paradigm, but delayed the display change and asked subjects to detect display changes. Yen, Radach, Tzeng, and Tsai (2012) presented Chinese sentences with a parafoveal two-character target and single-character posttarget. They manipulated preview of the posttarget character such that the combination of the second character of the target and the preview character was a legal word. Wang and Inhoff (2013) masked both target and posttarget and delayed the unmasking of the posttarget if the target was skipped. Dambacher, Slattery, Yang, Kliegl, and Rayner (2013) used the one-word moving-window paradigm and delayed the unmasking of the fixated word by a specified duration. Finally, Bicknell, Higgins, Levy, and Rayner (2013) did not change the characters of the text, but the entire sentence was shifted to the left or the right when the boundary was crossed. In the retrospective, especially the $n + 2$ boundary paradigm has been very influential and served as a basis for the conduction of numerous studies in different languages.

4.1.3 STUDIES WITH THE BOUNDARY PARADIGM

In the following, I will focus on studies in which the classic boundary paradigm was used. Studies are included if they fulfill the following criteria: (a) Subjects read *sentences* for comprehension, (b) there are a *single boundary* and a single display change per sentence, (c) the parafoveal preview of an *upcoming word* or upcoming part of a word is manipulated, and (d) the display change is *not artificially delayed*. Figure 4.1 displays an overview of the number of these boundary-paradigm studies and the studies with citations of Rayner (1975) published between 1975 and 2012.[11] While there has continuously been interest in the boundary paradigm, the turn of the millennium marks the begin of a period of increased attention. In 2004, the frequency of both the citations of Rayner (1975) and the published studies with the boundary paradigm reached a new peak. Twelve studies were published in 2012. In view of the most recent (2013) studies and the studies in press, the number will most likely be even higher in 2013. There are three main reasons for the increased interest in parafoveal preview benefit: eye-tracking devices, models of eye-movement control, and language differences.

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[11] The information on the citations of Rayner (1975) is based on the Web of Knowledge database (Thomson Reuters Corp., New York, NY, USA). Information on the number of boundary studies is based on my own research.

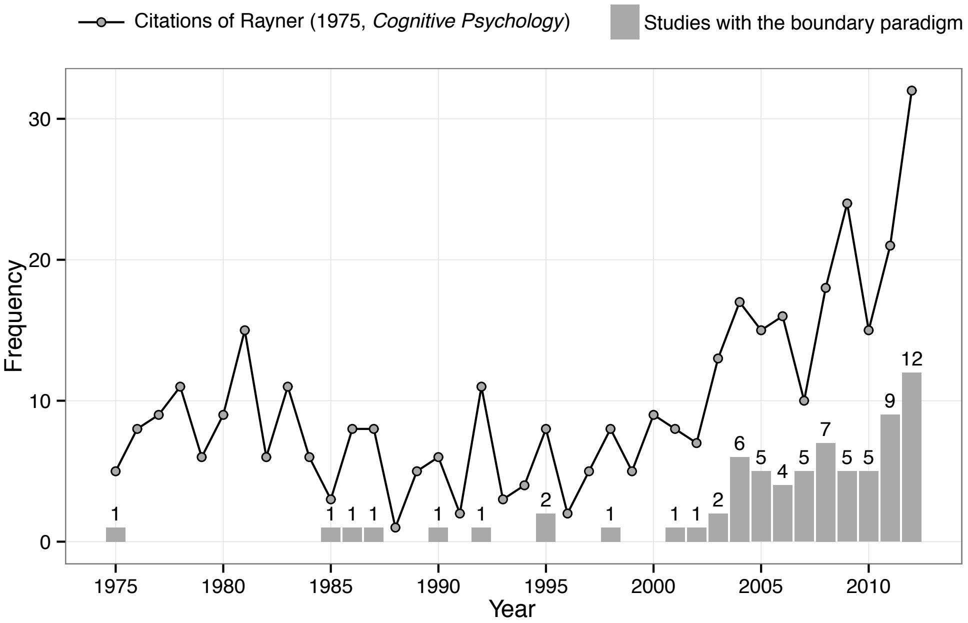

Figure 4.1. The number of studies with the boundary paradigm (represented as bars) and the number of studies in which Rayner (1975) was cited (represented as circles connected by lines).

4.1.3.1 EYE-TRACKING DEVICES

Studies with the boundary paradigm afford eye-tracking devices of high spatial and temporal accuracy for both accurate tracking of the gaze position and immediate implementation of display changes. The dominant device in the earlier studies was the dual-Purkinje-image eyetracker (Crane & Steele, 1985). This device uses the first and the fourth Purkinje reflections for measuring gaze position (see Duchowski, 2007, for a discussion of eye-tracking techniques). Dual-Purkinje-image eyetrackers had very high precision and accuracy and were very fast because of a sampling rate of 1 kHz. However, the device was very expensive and difficult to maintain; head stabilization was required and the visual field of recording was relatively small (see Holmqvist et al., 2011). Though this eye-tracking device allowed reliable recordings, its high prize and the necessity of technical skills generally limited the number of eye-movement laboratories and studies. A less expensive and easy-to-handle alternative was released in 1994: The EyeLink system by SR Research used the position of the pupil center (and the cornea reflection) to calculate gaze position. This head-mounted device had a sampling rate of 250 Hz. Its successors had higher temporal resolutions: The EyeLink II, released in 2001, operates at 500 Hz and the EyeLink 1000, a tower system released in 2005, at 1000 Hz for binocular recording and 2000 Hz in monocular mode. The EyeLink systems expanded quickly in reading research. In 40% of the studies with the boundary paradigm published in the first five years of the current century, 2001−2005, an EyeLink system was used. The usage has risen continually over the last years. In the year 2012, the proportion of studies in which the EyeLink was used was as high as 91%. Holmqvist et al. (2011) consider this eye-tracking device as the most dominant on the market for the academic user group.

4.1.3.2 MODELS OF EYE-MOVEMENT CONTROL

There has been a debate on whether words are processed serially or in parallel (Murray et al., 2013; Starr & Rayner, 2001). The E-Z Reader model (Reichle et al., 1998) and the SWIFT model (Engbert et al., 2002) provide advanced computational frameworks of eye-movement control during reading. In the last years, a large number of studies on empirical evaluation of predictions derived from these models have been published. Moreover, these models have been referred to in articles on parafoveal processing. In 64% of the studies with the boundary paradigm published in 2012, results have been discussed with respect to E-Z Reader and SWIFT.

4.1.3.3 LANGUAGES

In most studies with the boundary paradigm, English material was used. Nevertheless, the focus on other writing systems and on language differences has become increasingly important (see Frost, 2012, for a recent discussion). Additional evidence of parafoveal preview benefit in sentence reading has been accumulated for a large number of different languages including Spanish (Altarriba et al., 2001), Chinese (Liu, Inhoff, Ye, & Wu, 2002), Hebrew (Deutsch et al., 2003), Finnish (Hyönä et al., 2004), French (Miellet & Sparrow, 2004), German (Kliegl et al., 2007), Japanese (Perea, Nakatani, & Van Leeuwen, 2011), Thai (Winskel, 2011), and Korean (Kim et al., 2012). Notably, it was to take more than one quarter of a century until the first study with the boundary paradigm and non-

English material was conducted. The higher interest in reading in other languages, foremost Chinese, is one major source for the increase of preview-benefit studies over the last years. The interest in different languages is also reflected in a general increase of international scientific collaboration in the field of psychology (Kliegl & Bates, 2011). In the year 2012, only 42% of the published studies, in which the boundary paradigm was used, were conducted with English material. Interestingly, another 42% of the 2012 studies included Chinese texts.

4.1.3.4 CONCLUSIONS

The importance of the boundary paradigm (and other gaze-contingent techniques) has increased over the last years. Importantly, the rise in both citations of Rayner (1975) and the studies with the boundary paradigm is not an artifact of a general increase in scientific publications. The SCImago SJRproject (Grupo Scimago, 2007) provides publication statistics for several research fields including psychology.[12] Currently, the database is limited to the period 1996–2011. I extracted the numbers of psychology articles in this period. The average relative per-year increase in the number of publications in psychology was 4.7%, while the increase of citations of Rayner (1975) was 6.4%, and the number of studies with the boundary paradigm has risen by 11.3%. Thus, the increase rate of the studies with the boundary paradigm was more than twice the one of all publications in psychology. The reasons for this phenomenon have been discussed. In summary, there are several open questions concerning reading for which gaze-contingent experiments offer a viable assessment. Knowledge of technical issues and the saccade timing is helpful to conduct and interpret this kind of studies.

4.1.4 THE BOUNDARY PARADIGM AND THE PARAFOVEAL FAST-PRIMING PARADIGM

For the present thesis, the classic boundary technique (Chapter 3) and the new parafoveal fast-priming paradigm (Chapter 2) have been used. Technical issues, the

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[12] SCImago SJR is based on the Scopus database (Elsevier B.V., Amsterdam, the Netherlands).

influence of display-change awareness, and applications will be discussed in the following.

4.1.4.1 TECHNICAL CHARACTERISTICS

The boundary paradigm has been criticized for technical imperfection of display changes (O'Regan, 1990). O'Regan argued that gaze-contingent display changes entail problems related to (a) the persistence of displays on the screen and (b) apparatus delays. Due to the persistence of the phosphor in the monitor, luminance remains—at low levels—for the duration of multiple refresh cycles after the display has been changed. Furthermore, visible flicker after a saccade might affect saccadic latency and thereby fixation time, even if the reader is not aware of the display change.

Both delay and display persistence depends on the type of screen. Elze (2010) discussed characteristics of cathode ray tube (CRT) and liquid crystal display (LCD) monitors in the context of experiments which involve brief presentation of stimuli. The CRT technology is based on an electron beam scanning the raster of pixels line-wise from left top right, beginning with the uppermost line. The beam stimulates phosphor that reaches its maximum luminance almost instantaneously. After this, energy decays very fast. When the beam has passed the last pixel in the last line, it jumps to the first pixel of the first line. The period of the jump causes a blank for about 5% of the frame time. Hence, presentations of stimuli on a CRT monitor are not constant, but a series of pulses. In contrast, the signal stays at a constant level at LCD monitors, which are based on passive backlight. Luminance is controlled by the alignment of the liquid crystals. The rise and fall times of the luminance of LCD monitors are much longer, compared to CRT monitors. Due to the imperfections of both technologies, stimuli presentation times often do not match the specified durations. In the research with gaze-contingent display change paradigms, CRT monitors are usually preferred due to their shorter reaction times (Plant & Turner, 2009).

The influence of display persistence in paradigms with gaze-contingent display changes was addressed by Inhoff, Starr, Liu, and Wang (1998), who compared two types of screens, a phosphor-based tube and an electroluminescent panel. In contrast to phosphor-based tubes, electroluminescent panels are not subject to display persistence. Target fixation times did not significantly differ between both conditions, indicating preview benefit is not an artifact due to the slow decay of phosphor energy.

Inhoff et al. (1998) also addressed O'Regan's (1990) critique concerning delays and demonstrated that briefly visible flickers at fixation onset are not important for the outcome of gaze-contingent paradigms. In contrast, Reingold and Stampe (2000) employed later flickers (110 ms or 158 ms after fixation onset) in texts and showed time-dependent saccadic inhibition and thereby an impact on fixation durations. Saccadic inhibition is the phenomenon that sudden visual onsets can disrupt saccade programs. This results in a dip in saccadic frequency roughly 100 ms after the onset of the display change. Furthermore, the frequency of late saccades increases, compared to a baseline with constant display. The influence of saccadic inhibition during reading has been demonstrated in several studies by Reingold and Stampe (2000, 2003, 2004; see also Luke, Nuthmann, & Henderson, 2013). These results indicate that the visibility of display changes is more critical for the parafoveal fast-priming paradigm than for the classic boundary paradigm.

4.1.4.2 AWARENESS OF DISPLAY CHANGES

In contrast to natural reading, the displayed text in boundary paradigms depends on which word a subject is fixating. In the parafoveal fast-priming technique (Chapter 2), the display change occurs during the fixation and is noticeable. Awareness of display changes is also relevant to boundary studies in which display changes occur during saccades.

The actual delay of display changes—the time from an eye movement to a new display—was technically assessed in this thesis (see Appendix C). However, delays have been reported in previous studies, too. These values were mainly based on the sampling rate of the eye-tracking device and refresh rate of the monitor. Though additional sources of delay can never be ruled out, I will refer to these values.

The speed of the implementation of display changes varies. Indeed, in the first study including the boundary paradigm (Rayner, 1975), a filter in the eye-tracking device was activated and therefore many display changes occurred delayed, particularly during the initial 20 ms of the fixation at the target location. Nevertheless, subjects generally did not notice the display changes. This result is quite interesting since it is in contrast to the current finding: In the boundary experiments, most subjects were aware although words were exchanged considerably faster than in Rayner (1975). Of course, delays were shorter in later studies. For example, in Balota et al.'s (1985) experiment, the position of the eye was determined every 4 ms and the display was changed in 5 ms. Again, awareness was generally very low: In only 1% of trials, subjects reported having noticed a display change. The reported values in more recent studies are similar (e.g., 10 ms delay in Yang, Rayner, Li, & Wang, 2012). However, in most studies display-change awareness is not addressed.

Even though visual input is suppressed during saccades (Matin, 1974), subjects may become aware of stimulus changes while the eye crosses the invisible boundary. In the experiments reported in Chapter 3, the vast majority of subjects were aware of display changes. Importantly, semantic preview benefit was not modulated by awareness and was also significant for the subset of participants who did not recognize display changes at all. Accordingly, White et al. (2005a) classified their subjects into aware and unaware groups, depending on whether they reported noticing something strange about the appearance of the text when they were asked after the experiment. The preview benefits were larger for subjects who were aware of display changes, which points to the relevance of accounting for differences between individual subjects in such reading experiments. As a direct assessment of this effect, Slattery et al. (2011) manipulated the parafoveal preview and the delay of the display change (0 ms vs. 25 ms) and asked subjects after each sentence whether a word had been replaced in the sentence they had just read. As expected, subjects were more likely to detect a display change if it was delayed. The size of the preview benefit increased with display-change detection, but was also significant in trials in which subjects failed to detect a change.

Mean detection rate in all three experiments with the boundary paradigm (Chapter 3) was 29%. For the no-delay condition, Slattery et al. reported a hit rate of

25% for nonword previews; the hit rate increased significantly with fixation duration on the target. This result is in agreement with the present finding of a positive relationship between self-reported detection rate and target fixation duration. Furthermore, as in the experiments reported in Chapter 3, the preview benefit in Slattery et al.'s study was significant for all trials and the subset of trials in which display-changes were not detected. In the latter condition, the size of the benefit due to an identical preview was numerically smaller. The direction of this effect is the same as in the study of White et al. (2005a).

The results of White et al. (2005a) and Slattery et al. (2011) are in agreement with the present findings concerning the positive relationship between display change awareness and the size of identity preview benefit (nonidentical preview vs. identical preview). Hence, subjects' awareness of display changes should be taken into account when a static condition is compared with a nonidentical preview. In the boundary paradigm, display changes are usually too fast to produce saccadic inhibition. The increased fixation duration following display changes might be due to a perceived mismatch between the parafoveal preview and the fixated target.

In comparison to other studies with the classic boundary paradigm, the self-reported values of display-change awareness were relatively high in the present experiments. In the light of the results, neither the actual delay of display changes nor German noun capitalization or the used text contrast can serve as sources for this outcome.[13] Furthermore, phosphor persistence cannot account for the outcome since display-change awareness was not reliably reduced in the low-contrast condition which inherently entails reduced persistence times (cf. Demeyer, De Graef, Wagemans, & Verfaillie, 2010). Results of linguistic studies on sentence parsing are an indicator of a major role of expectation for German readers (see section 4.3.2). Attention may to a

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[13] German spelling was varied within subjects. Hence, there was no direct assessment of its influence on display-change awareness. However, mean detection rate in Experiment 2 (Chapter 3) was similar to the values in Experiments 1 and 3 (Chapter 3).

higher degree be allocated to upcoming parts of the text, and therefore a representation of word *n* + 1—at least at a low level—might be built up faster. As a direct result, readers may recognize a mismatch between the representation of the parafoveal preview and the fixated target. Hence, they might not have become aware of the visual display change itself but the exchange of words. This reasoning is supported by reliable preview effects of word *n* + 2 in German texts (e.g., Kliegl et al. 2007) and a recent study on preview benefit of word *n* + 1 in German, in which subjects reported relatively high rates of awareness of display changes (Risse & Kliegl, 2014). Having said that, however, direct cross-linguistic studies are needed to evaluate differences in parafoveal processing between languages.

4.1.4.3 Display changes in parafoveal fast priming

Though display changes during saccades and at fixation onset are not disruptive and therefore negligible (Inhoff et al., 1998), later display changes can cause saccadic inhibition (Reingold & Stampe, 2000). Results from the double-step paradigm (Becker & Jürgens, 1979) indicate that programing of saccades is a process involving two stages. During the early (labile) stage, a saccade program can be modified or canceled. In this case, a new saccade program is initiated. In the late (nonlabile) stage, the saccade program cannot be disrupted and the original saccade will be executed. Two-stage saccade programing with labile and nonlabile stages is important for gaze-contingent paradigms and has been integrated in models of eye-movement control (Engbert et al., 2002; Reichle et al., 1998). Since the probability of a saccade program being disrupted decreases with the time from fixation onset, saccadic inhibition is more likely with early display changes. This is supported by the current finding of shorter pretarget fixation durations at longer prime durations (see Chapter 2), in agreement with Inhoff et al. (2005). If a display change occurs 125 ms after fixation onset, a larger proportion of saccades are already in their nonlabile stages, compared to display changes at 80 ms and 35 ms. If a saccade program is canceled and a new saccade program is started, fixation duration will be inherently longer.

Due to saccadic inhibition, conditions with display changes during fixations and no-delay conditions involving immediate display changes during saccades cannot be directly compared. Saccade programs in a no-delay condition are not subject to disruption. Obviously different mechanisms take place at no-delay and delay conditions. Indeed, no-delay conditions revealed strange results in gaze-contingent studies. Inhoff et al. (2005) compared different delays (0, 70, 140, and 210 ms) of the appearance of parafoveal targets. Pretarget fixation duration decreased from the 70-ms to the 210-ms condition, but fixation times were shorter in the no-delay condition compared to the 70-ms condition. This pattern of results can be easily explained by saccadic inhibition: When the target was unmasked during a saccade in the no-delay condition, the display change was invisible and the saccade program could not be canceled. In contrast, in the delayed conditions (70–210 ms), the proportion of labile saccade programs decreased with increasing delay. Inhoff et al. (2005) showed an increase of fixation durations from the 70-ms to the 210-ms condition on the target word. Interestingly, fixation duration in the no-delay condition was not significantly different from the 70-ms condition. The observed target fixation durations might be a combination of a trade-off of decreasing pretarget fixation times and the delay of parafoveal information (this conclusion also holds for the present results). Dambacher et al. (2013) delayed unmasking of the fixated word by 0, 33, 66, and 99 ms. Fixation durations increased from the 33-ms to the 99-ms condition, but the no-delay condition yielded longer fixation durations than the 33-ms condition. In summary, there might be qualitative differences between visible and invisible display changes, and observed differences in eye movements between immediate and delayed display changes cannot be explained by the time course of word processing alone.

In summary, the parafoveal fast-priming paradigm is a practical tool for the evaluation of the time course of parafoveal information extraction. However, the technique should be used with nonidentical previews only, e.g., an orthographically or semantically related preview versus an unrelated preview. Identical previews do not involve display changes.[14] Hence, observed differences between identical and nonidentical previews would be hard to interpret. In the present experiments, display changes associated with both semantically related and unrelated previews could have disrupted saccades. In agreement with this perspective, nested contrasts (preview type within the different levels of prime duration) were used for statistical analyses. Differences in fixation durations between preview conditions are due to the relatedness of the preview. Since display changes caused the disappearance of the parafoveal preview, semantic information extraction was independent of possible disruption due to saccadic inhibition. In contrast to the classic boundary paradigm, which provides a more natural reading situation and therefore higher ecological validity, the parafoveal fast-priming paradigm allows evaluating how early after the onset of pretarget fixation parafoveal information can be extracted. This is important for analysing the time course of word processing during reading.

4.2 TIME COURSE OF THE EXTRACTION OF MEANING FROM PARAFOVEAL WORDS

The present results are valuable for understanding the time course of reading. Implications have been discussed above. In summary, the results are more compatible with a theory of parallel processing of words than of serial processing. Moreover, semantic preview benefit increased with pretarget fixation duration and prime duration with one exception in the experiment with salient primes.

4.2.1 IMPLICATIONS FOR MODELS OF EYE-MOVEMENT CONTROL

Details of the architecture of computational models have been provided in Chapters 2 and 3. Furthermore, it has been discussed how these models can explain the present results. I will not repeat these discussions but add some general points.

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[14] It is however possible to present text in aLtErNaTiNg CaSe and change both preview and case. Under these circumstances, identical and nonidentical previews could be compared.

The finding of parafoveal semantic preview benefit is compatible with the SWIFT model in which words are processed in parallel (Engbert et al., 2005). This does not hold for the E-Z Reader model in which serial word processing is assumed (Reichle et al., 1998). The debate on serial versus parallel processing of words has attracted a great deal of attention in reading research (Murray et al., 2013; Starr & Rayner, 2001). It is important to note, however, that semantic preview benefit does not appear to be the ideal test to distinguish between these concepts. In contrast to parafoveal-on-foveal effects, which constitute an indicator of parallel processing, semantic effects of a parafoveal preview on a subsequent target fixation can also be explained by serial processing of words. Firstly, in E-Z Reader, the extraction of semantic code is limited to the second stage of lexical processing and therefore inherently triggers a saccade program to the posttarget. In contrast, if a proportion of the extraction of semantic code were assumed to take place before the next saccade goal is chosen, semantic preview benefit would be a reasonable phenomenon given serial processing. This hypothetical architecture would necessitate an earlier beginning of semantic processing such that the time course of saccade programing remained the same. Hence, the extraction of semantic code could start during the first stage of lexical processing, therefore allowing both semantic processing of the preview and fixating word *n* + 1.

Secondly, computational models of eye-movement control do not only differ with respect to serial and parallel processing, but also in how ongoing cognitive processes affect when to move the eyes. In E-Z Reader, the first (labile) stage of a new saccade program starts when the first stage of lexical processing is finished. Therefore, cognitive processes have a direct effect on eye-movement control in this model. Due to direct control, fixation durations are immediately influenced by the fixated word. Direct control of eye movements can be contrasted with indirect control. Indirect control refers to the assumption that saccades are initiated at a certain rate (see Reingold et al., 2012, for a discussion). SWIFT incorporates indirect control of eye movements by an autonomous random timer. Additionally, the generation of saccades is modulated by time-delayed foveal inhibition. Hence, both indirect (random timer) and direct control (foveal inhibition) are part of the SWIFT model. Dambacher et al. (2013) provided evidence for direct control of eye movements during reading (see also Reingold et al. 2012) and, moreover, demonstrated an influence of indirect control on a subset of saccades. In a recent non-reading study, Trukenbrod and Engbert (2014) used a visual-search paradigm and showed that fixation durations on the stimuli cannot be explained with purely direct control of eye movements.

Engbert and Kliegl (2001) evaluated the influence of autonomously triggered saccades in an eye-movement model with serial processing of words. They compared models with purely direct control and with a combination of direct and indirect control. In any case, attention was confined to one word at a time. The durations of the simulated fixations matched the experimental data more closely if indirect control of the eye movements was added to the model framework. The assumption of indirect control has implications for the explanation of semantic preview benefit: Decoupling of the extraction of semantic code from parafoveal vision and saccade timing could facilitate subsequent processing of a semantically related target. Even if only a subset of saccades to the target location were generated by a random timer after the onset of semantic processing, semantic preview benefit would be a reasonable outcome. In conclusion, semantic preview benefit can hypothetically be explained by serial and parallel processing of words. Nevertheless, the present results are more compatible with the assumption of parallel processing. This is particularly true for the early effects obtained at 80 ms and 125 ms with parafoveal fast priming (Chapter 2). Having said that, however, the present findings—especially *how* a semantic representation of the preview influences processing of a related target—can most likely not be derived from any implemented model of eye-movement control.

4.2.2 TIME-DEPENDENCY OF PARAFOVEAL SEMANTIC PROCESSING

Whereas there was a robust effect of preview space (quantified as launch site distance) on preview benefit in the experiments with the classic boundary paradigm (Chapter 3), the influence of preview time (quantified as pretarget fixation duration) was only reliable in a subset of analyses. Semantic preview benefit was larger with long pretarget fixations than with short ones. Time-dependent effects of semantic preview benefit have also been reported for Chinese. With respect to previous work on semantic processing, our findings are in agreement with the Chinese reading study by Yan, Zhou, et al. (2012), in which increased pretarget fixation duration was accompanied by larger semantic preview benefit (from opaque previews), but differ from Yan, Risse, et al. (2012)—a reanalysis of Yan et al.'s (2009) data—in which a reverse relationship was found. The default explanation is the large difference between reading Chinese and alphabetic script as well as the use of characters of different frequency in the Chinese reading studies. Specifically, in German, semantic information is acquired relatively late. As a consequence, with increasing fixation durations, the semantic representation builds up slowly. In Chinese, early activation of semantic code may lead to inhibition caused by longer preview availability. Most likely, the use of highly frequent preview characters in Yan, Risse, et al.'s (2012) study resulted in a negative relationship between pretarget fixation duration and preview benefit. With less frequent characters (Yan, Zhou, et al., 2012), parafoveal processing and the build-up of a semantic representation were slower. In this case and in the present study, pretarget fixation durations may not have been long enough to cause inhibition between representations of the preview and the target. In a reanalysis of Yan et al.'s (2009) data and Yan, Zhou, et al.'s (2012) data, W. Zhou, Kliegl, and Yan (2013) studied the combined influence of preview space and preview time on semantic preview benefit. Whereas there was no reliable effect in the first dataset, a significant three-factor interaction was found in the latter one. Interestingly, the largest semantic preview benefit (from transparent previews) was obtained if the pretarget fixation was short and the launch site distance was large. Differences in the time-dependence of preview effects associated with transparent (negative relationship) and opaque previews (positive relationship) might also be due to inhibition. Since transparent previews are not only conceptually but also visually related to the concept of the target, inhibitory effects presumably emerge earlier than with opaque previews. A negative effect of preview space on lexical processing has also been reported by Yen, Tsai, Tzeng, and Hung (2008), who showed that a Chinese target is fixated shorter if it is previewed with a word than with a pseudoword. Preview benefit was larger after short than long pretarget fixations.

Further evidence for time-dependent facilitation and inhibition due to semantic representations has been demonstrated in a lexical-decision task with isolated two-character Chinese compounds (X. Zhou, Marslen-Wilson, Taft, & Shu, 1999). They used character primes which shared the first character with the target but had a different second character. Due to the different second character, the meaning of the first character in the prime was not identical to the meaning of the first character in the target. Compared to an unrelated prime, the character prime produced positive priming effects at short prime durations. At longer prime durations, negative priming effects were observed. The authors argued that the initial morpheme of the character prime preactivates the representation of the corresponding target morpheme. This semantic activation leads to facilitation at short prime durations. When the prime is presented for a longer time, there is interference between semantic representations, leading to inhibitory effects.

It is however important to note that in the studies with Chinese sentences—in agreement with the present results—the modulation of preview benefit by preview time was significant in a subset of the analyses only. Furthermore, though Tsai et al. (2012) used the material of Yan et al. (2009), but presented sentences in Traditional Chinese, the relationship between semantic preview benefit and pretarget fixation duration (Yan, Risse, et al., 2012) could not be replicated. In summary, these effects appear to be quite fragile.

Although a positive effect of preview time on parafoveal processing is theoretically plausible and the present results constitute evidence of this relation, its obviously elusive nature most likely reflects the manifold interactions in the highly complex process of reading. When the duration of a salient parafoveal preview was experimentally manipulated with the parafoveal fast-priming technique, semantic preview benefit initially increased with preview time, but decreased again if preview time was too long. These phenomena are most likely due to inhibition processes neutralizing benefit from related preview words in the parafoveal region (see General discussion in Chapter 2). It must, however, be noted that a decrease in preview benefit was found in one experiment only. Furthermore, clearly visible display changes during fixations (in fast priming) presumably affect how attention is distributed in the text and therefore might lead to differences in processing of words. More research is necessary to understand the implications of the parafoveal fast-priming technique and its relation to the classic boundary paradigm. Furthermore, the present results highlight the importance of preview time (and preview space) for parafoveal processing. These issues have been addressed in a subset of past studies only. Over the last years, software for the convenient use of (generalized) linear (mixed) models has become available. These models allow specifying categorical and continuous predictors at the same time, making them a great tool for analyzing interactions of preview type and preview time at high statistical power. To further develop our knowledge concerning the time course of reading, studies with different languages and paradigms as well as different types of preview would be very helpful.

4.3 LANGUAGE CONTRASTS

Semantic preview benefit has been consistently shown in this thesis. This finding is in contrast to earlier results by Rayner at al. (1986). Importantly, Rayner et al. used English material, whereas German sentences were used in the present experiments. What could be reasons for this difference between the results obtained in these Germanic languages? In the following, I will argue that the answer lies in critical differences concerning (a) processing at the word level and (b) sentence parsing.

4.3.1 WORD PROCESSING

The degree of orthographic consistency is different between both languages: In German, the correspondence between graphemes and phonemes is relatively high, whereas the relation is rather opaque in English due to its very complex phonological space. As a consequence, the immediate on-line assembly of syllables is much more likely in German than in English (Frith et al., 1998). It seems plausible that orthographic consistency affects both the strategies and mechanisms of word processing. Given that orthography codes for both semantic and phonological information, more cognitive resources are occupied by phonological decoding and fewer resources are available for semantic decoding in English. Differences in orthographic consistency are one likely reason for the behavioral differences concerning semantic preview benefit. This reasoning is quite compatible with developmental differences in the acquisition of phonological recoding in English and German (Aro & Wimmer, 2003; Frith et al., 1998; Goswami, Ziegler, Dalton, & Schneider, 2001, 2003; Goswami, Ziegler, & Richardson, 2005; Landerl, Wimmer, & Frith, 1997; Lange-Küttner, 2005; Seymour et al., 2003; Wimmer & Goswami, 1994). Children learning to read languages with low transparency have to acquire a much larger set of ambiguous orthographic-phonological relations (cf. Sprenger-Charolles, 2004). In a large cross-language study with children, Seymour et al. (2003) compared letter knowledge, familiar word reading, and nonword reading in English and twelve other European orthographies and concluded that the rate of development of basic decoding skills was slowest in English.

English dyslexic children are slower and make more errors when reading words and nonwords compared to German dyslexics (Landerl et al., 1997). The differences were pronounced for stimuli which required phonological recoding, even when nondyslexic English and German children were compared. Landerl et al. concluded that the consistency of grapheme-phoneme relations affects working memory demands of recoding. Frith et al. (1998) asked 7- to 12-year old children to read words and nonwords. Young English children read nonwords and words of low frequency less accurately than German children. By the age of 12, reading speed was highly comparable in both groups, but recoding of long and complex nonwords was still error-prone for English-speaking readers.

Goswami et al. (2001) employed a priming task with pseudo-homophones and demonstrated that the activation of phonological information appears to be relatively automatic for German children but not for English children. For phonological recoding, readers of German most likely rely on psycholinguistic units at a small grain-size (graphemes, phonemes; cf. Ziegler and Goswami, 2005, for details on the psycholinguistic grain size theory), whereas for English readers, these units are of small and large size (e.g., whole-word phonology, rhyme-based analogies). This increases the number of units English readers have to learn. Ziegler, Perry, Jacobs, and Braun (2001) corroborated the major impact of grain size with a cross-language study in which adults were asked to read words and nonwords. The effect of word length on naming latency was stronger in German than in English, suggesting more small-unit processing, whereas the effect of body neighborhood (words sharing the same orthographic rhyme) was stronger in English. Lallier, Carreiras, Tainturier, Savill, and Thierry (2013) provide recent electrophysiological evidence for the link between orthographic transparency and grain size.

It has been demonstrated that phonological codes are activated during reading (McCutchen & Perfetti, 1982; Van Orden, 1987). Frost (1998) proposed a strong phonological model in which semantic codes are accessed via phonology. Furthermore, influences of phonology on semantics are also present in the dual-route cascaded model (Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001) and the triangular model (Seidenberg & Mcclelland, 1989). Since the relation between spelling and sound is opaque in English, phonological processing demands more cognitive resources, and therefore fewer resources are available for semantic processing.

4.3.2 SENTENCE PROCESSING

Further evidence of differences between English and German has been reported in recent psycholinguistic literature on sentence processing. Limitations in the cognitive resources of the reader play a major role in sentence understanding. Before discussing language contrasts, I will provide a very brief introduction into sentence processing. Two important concepts are *memory* and *expectations* (for reviews, see Levy, 2013; Vasishth, 2011). In the model developed by Lewis and Vasishth (2005), memory is necessary for storing an incremental tree-structured representation of the sentence to construct dependencies between the currently processed and the preceding words. Furthermore, information has to be retrieved to integrate the current word into the sentence representation. The current word is a cue for the recall of the appropriate integration site. Both difficulty and correctness of the retrieval process depend on the interplay of several factors, for example decay and interference. Hence, complex syntactic structures should be associated with high retrieval costs.

Besides memory limitations, sentence comprehension is affected by the reader's expectations regarding how the sentence may continue (Hale, 2001; Levy, 2008). As discussed in the Introduction, words which are strongly predicted from the sentential context receive shorter fixations than unpredictable words (e.g., Ehrlich & Rayner, 1981). Whereas the concept of predictability is based on concrete words and is experimentally measured in cloze tasks, the surprisal theory (Hale, 2001) is based on a probability model of a grammar. This grammar includes rules of combinations of words and assigns a probability to these combinations. Hence, given the preceding words, there is a set of compatible structures of how the sentence will continue. Memory retrieval costs and expectation costs (surprisal) have been found to independently affect fixation durations in reading (Boston, Hale, Vasishth, & Kliegl, 2011; Patil, Vasishth, & Kliegl, 2009).

Processing difficulty is modulated by the grammatical structure of the preceding context. For example, if a verb occurs after its dependents (a verb-final structure), the integration of the verb in the preceding representation demands more resources than in non-verb final structures. Furthermore, the distance between linguistic entities and their dependents—i.e., the number of words between them—determines processing difficulty. It has been demonstrated that there are both positive and negative relationships between distance and processing difficulty. In English, processing predominantly becomes more difficult if the distance increases (locality effect; e.g., Gibson, 1998), whereas increasing distance predominantly results in easier processing in German (anti-locality effect; e.g., Konieczny, 2000). Memory limitations serve as an explanation for locality effects; anti-locality effects can be explained by an increasing strength of the prediction for the upcoming verb. However, there is recent evidence of both types of effects in English (Jaeger, Federenko, Hofmeister, & Gibson, 2008) and German (Levy & Keller, 2013; Vasishth & Drenhaus, 2011). These results suggest that processing difficulty is modulated by a trade-off between expectation and memory limitations.

Why is it less likely for German readers to show locality effects than for English readers? Both languages differ in word order: German has the order subject-object-verb (at least in subordinate clauses) and English has the order subject-verb-object. Levy and Keller (2013) argue that “native speakers of verb-final languages are simply more practiced and therefore more skilled at comprehending nonlocal syntactic configurations” (p. 215). It has been demonstrated that the average length of dependencies in sentences is higher in German than in English (Gildea & Temperley, 2010; Park & Levy, 2009). Of course, there are several other important differences between these two languages with respect to sentence parsing, for example case marking and agreement properties (MacWhinney, Bates, & Kliegl, 1984). Vasishth, Suckow, Lewis, and Kern (2010) provide further cross-linguistic evidence of differences in syntactic processing between German and English. They presented sentences with double center embeddings, for example: “*The carpenter who the craftsman that the peasant had carried to the bus-stop had hurt yesterday supervised the apprentice.*” In an alternative ungrammatical version the middle verb (*had hurt*) was omitted: “*The carpenter who the craftsman that the peasant had carried to the bus-stop supervised the apprentice.*” English sentences were presented for English readers while German subjects read German sentences. German subjects’ fixation times on both the final verb and the region after the final verb were shorter in the grammatical than in the ungrammatical condition. Interestingly, English readers were faster in the ungrammatical condition, compared to the grammatical version. This indicates that they may have experienced the structure of the ungrammatical sentences as legal. This is in agreement with a study in which the subjects’ task was to rate the grammaticality of presented English sentences. Ungrammatical structures were preferred over grammatical structures (Christiansen & Macdonald, 2009). Obviously, German readers are able to maintain more accurate expectations of the upcoming sentence structures in German sentences than English readers in their native language.

4.3.3 SUMMARY AND EXTENSIONS

Both orthographic regularity and sentence parsing differences contribute to behavioral differences observed in reading English and German. Semantic preview benefit might be easier to obtain in highly transparent orthographies due to a larger amount of available cognitive resources. The correspondence from spelling to sound in Finnish is even higher than in German. Though unrelated emotional previews did neither result in preview benefit or cost (Hyönä & Häikiö, 2005), semantic parafoveal preprocessing has been demonstrated within Finnish compounds (White et al., 2008). In contrast to Roman writing systems, the role of phonology is less dominant in logographic languages like Chinese, in which semantic access is more direct as well as easier (Frost, 2012). As a result, semantic preview benefit has been repeatedly demonstrated in Chinese (e.g., Yan et al. 2009).

In addition, results of sentence processing studies indicate that the ability to maintain predictions of upcoming words in memory depends on the grammatical structure of the language. The dominant role of expectations in German might be an indicator of parafoveally oriented processing. Therefore, upcoming words in German may be preprocessed to a higher degree than in English. Structural and parsing differences between languages potentially serve as another explanation of why semantic preview benefit was highly reliable in the present thesis but not in Rayner et al. (1986). Furthermore, these differences in parafoveal processing might be the reason why preview effects of word *n* + 2 are more consistently reported in German (e.g., Kliegl et al., 2007) than in English (e.g., Rayner et al., 2007).

4.4 CONCLUSION

The extraction of meaning during reading is not limited to the fixated word but extends to the upcoming word. The degree of parafoveal processing is most likely a function of the writing system and the reader’s exposure to it. Comparing bilingual readers and their preview benefit in different orthographies could disentangle both sources of variation. The study of semantic preprocessing with gaze-contingent display changes appears to be independent of conscious perception of parafoveal previews. The present experiments revealed evidence of time-dependent facilitation due to semantic relatedness. However, inhibition effects are less clear and need to be followed up in future research. The parafoveal fast-priming technique allows insights into the time course of parafoveal processing. The results obtained with this paradigm are more in agreement with theories of parallel processing of words. To increase insight into the time course of reading, different previews (e.g., phonological and orthographical) could be compared. Generally, features of pretarget, preview, and target could be manipulated to assess their impact on the time course of reading.

APPENDIX

A TO TRANSFORM OR NOT TO TRANSFORM. REANALYSIS OF CHAPTER 2 DATA

All analyses of fixation durations in Chapter 2 were based on untransformed data. Although this is common practice in the field of eye movements in reading, assumptions of linear (mixed) models might be violated. In the context of reaction-time data, it has been demonstrated that the transformations of the dependent variable can substantially improve statistical models (Baayen & Milin, 2010; Kliegl et al., 2010). In the following, I will assess important assumptions (see Pinheiro & Bates, 2000) and how they are met with untransformed and log-transformed fixation durations. Furthermore, differences between results of the original analyses and the analyses based on log-transformed data will be discussed.

A.1 A COMPARISON OF MODELS WITH UNTRANSFORMED AND LOG-TRANSFORMED VARIABLES

A.1.1 DEPENDENT VARIABLE AND RESIDUALS

One of the assumptions of linear regression is the normal distribution of residuals. The normal distribution of the dependent variable is *not* part of the assumptions although, empirically, both distributions are strongly related. Figure A.1 displays the histogram of the distribution of the dependent variable target gaze duration from Experiment 1. The solid line indicates kernel density estimates. Furthermore, a log-normal (dotted line) and a normal distribution (dashed line) were fitted using maximum-likelihood estimation (Venables & Ripley, 2002). Inherently, fixation durations are greater than zero. The empirical distribution in Figure A.1 is positively skewed, a typical characteristic of fixation durations. The log-normal distribution is more similar to the empirical distribution than the normal distribution.

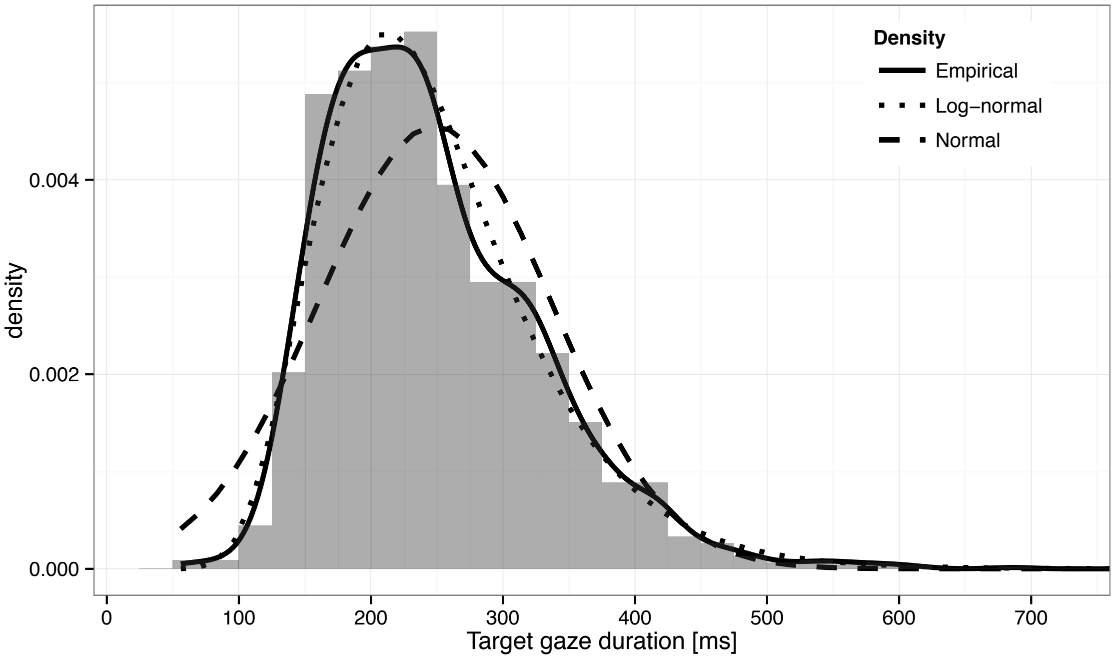

Figure A.1. Distribution and three different density curves of target gaze duration.

In the reanalyses, all fixation-duration measures were log-transformed. Is this justified by the statistical model? Two example models were created: In both, target gaze duration of Experiment 1 is used as dependent variable, while the predictors are the differences between unrelated and related primes nested under the three prime durations as well as linear and quadratic trends of prime duration. This reflects the structure of contrasts used in the analyses of the four experiments in Chapter 2. Furthermore, for both random factors, subjects (36 levels) and items (102 levels), varying intercept and slopes for all predictors were specified. Due to convergence problems, correlations between random effects were excluded (see below). Each model therefore includes six fixed effects and twelve random effects.

First, normality of the errors was assessed with conditional residuals (see Nobre & Singer, 2007, for a discussion). Normality can be evaluated with a QQ-plot (the Q stands for “quantile”). It allows comparing two distributions by plotting their quantiles against each other. Figure A.2 displays normal QQ-plots (as a function of normal-distribution quantiles) for model residuals based on log-transformed (left panel) and untransformed data (right panel). Distributions are similar if the points lie on one line.

Though not being perfectly linear, the relation between sample and theoretical quantiles is better for the log-transformed data. The distribution of the residuals based on untransformed data is positively skewed and has two extreme outliers: The difference between the actual data and the model predictions is larger than 500 ms in two cases. If normality is violated, a few outliers can have a disproportionally large influence on parameter estimation. In summary, the normality assumption is met with the log-transformed, but not with the untransformed data.

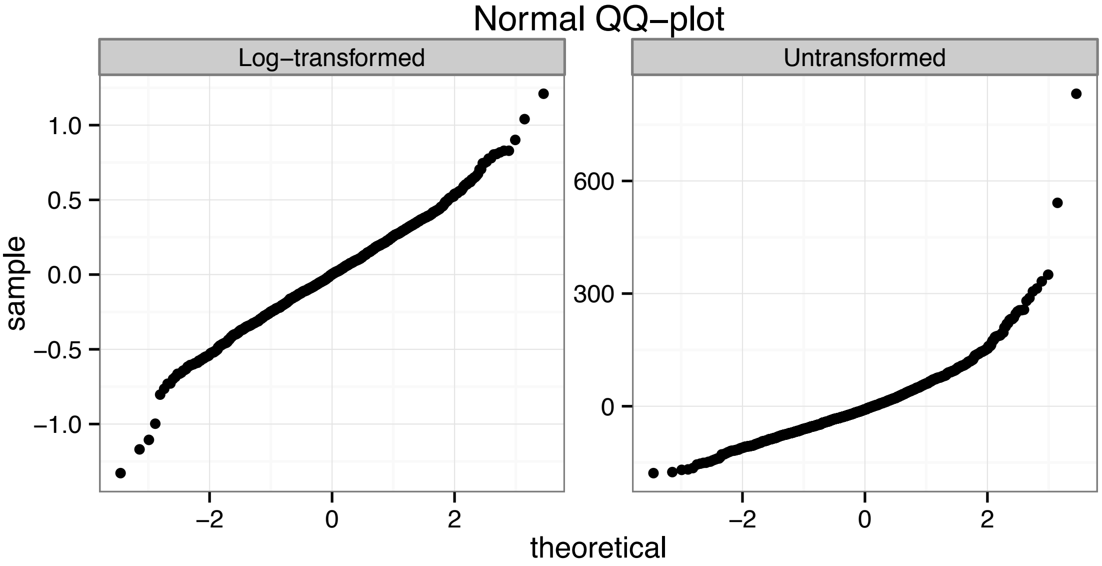

Figure A.2. Normal QQ-plots of residuals of models based on log-transformed and untransformed gaze duration.

Figure A.3 displays the relationship between fitted values and residuals by experimental condition. The residuals of both models appear to be independent from the experimental conditions. However, the cone-shaped patterns in the panels of the untransformed data indicate heteroscedasticity: The variance of the residuals increases with fitted values. Homogeneity in the variances is one assumption of linear regression. Heteroscedasticity can result in too wide or too large confidence intervals. This problem is not present in the model with the log-transformed data.

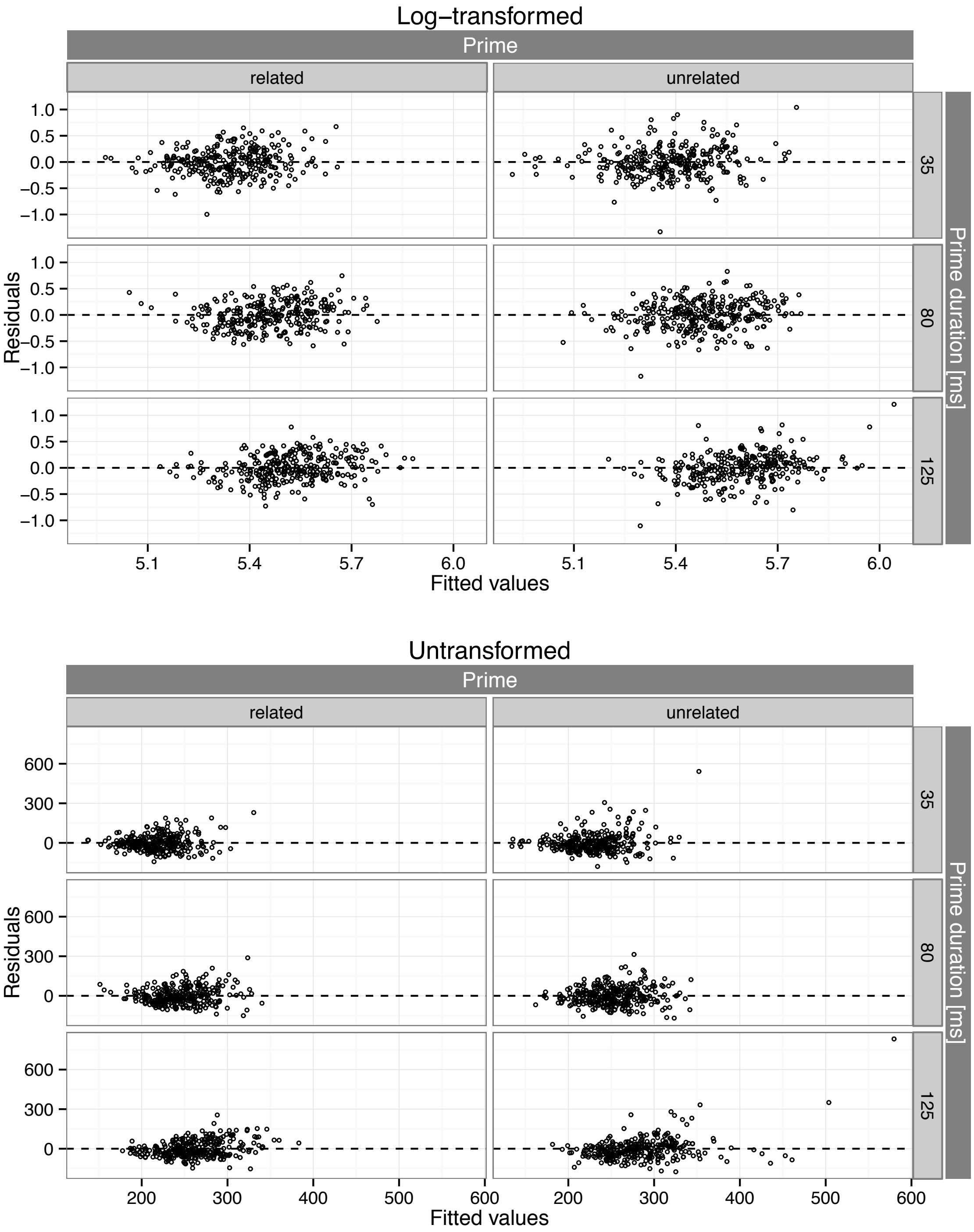

Figure A.3. Residuals versus corresponding fitted values as a function of prime and prime duration. The models are based on log-transformed (upper panels) and untransformed gaze duration (lower panels).

A.1.2 RANDOM EFFECTS

Being an extension of linear models, linear *mixed* models (LMMs) incorporate additional assumptions regarding the random effects (see Pinheiro & Bates, 2000). The estimated conditional modes (also known as best linear unbiased predictors; C. R. Henderson, 1975) should be distributed normally. For the comparison of both models, I will focus on effects associated with the random factor items only since the results of both models were very similar for subjects. This is most likely due to the higher number of factor levels for the former random factor. The differences are most pronounced for the varying intercept and the varying slope of the preview effect at 125 ms prime duration (D125). Normal QQ-plots for these random effects are displayed in Figure A.4. The distribution of the conditional modes of both the intercept (top panels) and the D125 effect (bottom panels) are more in agreement with a normal distribution if the data is log transformed (left panels). The distributions of untransformed data (right panels) are again slightly positively skewed.

In addition to the log-transformation of the dependent variable, all predictors' slopes were also specified as varying slopes for both subjects and items. The full model, including variance components for all terms of the experimental design, is favoured for statistical analyses (Schielzeth & Forstmeier, 2009; see also van de Pol & Wright, 2009). Coverage probability of confidence intervals associated with fixed effects is better for LMMs including random slopes than for models including intercepts only (Barr, Levy, Scheepers, & Tily, 2013; Schielzeth & Forstmeier, 2009). If also correlations between random effects were included, the models did not converge. Hence, these parameters were excluded. In a recent simulation study, Barr et al. (2013) demonstrated that models without random correlations are very similar to full models with respect to coverage probability and power. The authors rank both kinds of models in the first position of desirable model designs and conclude, their "simulations suggest that removing random correlations might be a good strategy, as this model performed similarly to maximal [LMMs]“ (p. 276). In summary, the reanalysis of the Chapter 2 reading data is justified by both (a) a more appropriate transformation of the dependent variables and (b) recent evidence with respect to model design.

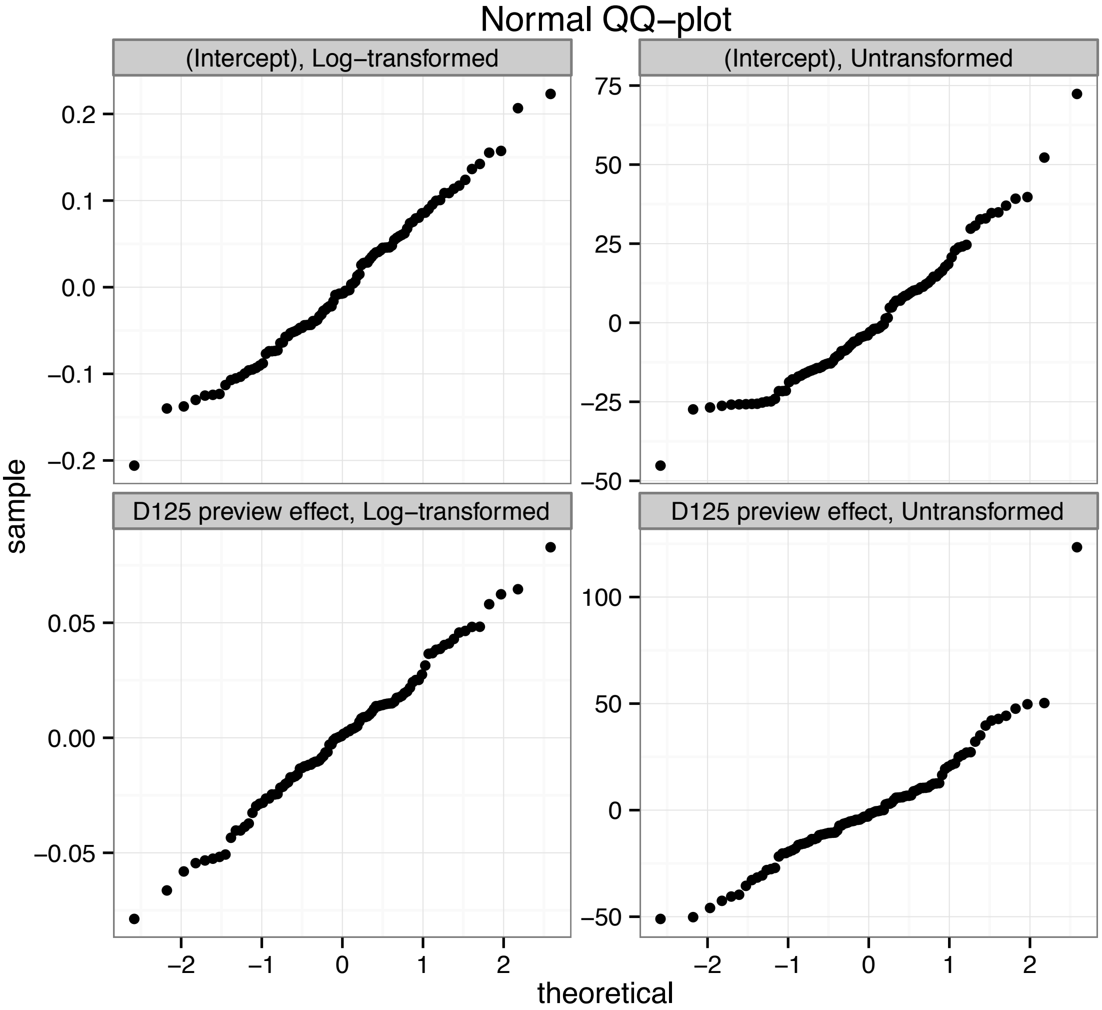

Figure A.4. Normal QQ-plots of random effects of intercept and D125 preview effect associated with the random factor items. The plots are based on log-transformed (left-hand panels) and untransformed gaze duration (right-hand panels).

A.2 REANALYSIS OF CHAPTER 2 DATA

The results of all four experiments reported in Chapter 2 were reanalysed with log-transformed fixation-duration measures in a linear mixed-model. Preview type and prime duration were specified as varying slopes of both subjects and items.

Results of the statistical analyses concerning pretarget matched the pattern of effects of the original analyses. In contrast, some differences were obtained at the target. Hence, results will be reported for the target only.

A.2.1 EXPERIMENT 1

The new results generally replicated the ones based on untransformed fixation durations aside from two exceptions: The just significant D35 priming effect in gaze durations (t = 1.97) was not reliable (t = 1.91). This corroborates the view of this effect as not being very trustworthy. Furthermore, whereas the overall priming effect remained significant for gaze durations (t = 2.6), the result could not be replicated for first-fixation durations (original: t = 2.02; new: t = 1.70).

A.2.2 EXPERIMENT 2

The only difference between the analyses based on untransformed and log-transformed data was the difference between unrelated and related primes at the D80 condition. The effect was more pronounced for both gaze durations (original: t = 1.4; new: t = 2.6) and first-fixation durations (original: t = 1.6; new: t = 2.2).

A.2.3 EXPERIMENT 3

The statistical analyses based on log-transformed fixation durations and varying slopes matched the pattern of effects of the original analyses.

A.2.4 EXPERIMENT 4

The new results generally replicated the ones based on untransformed fixation durations aside from one exception: The significant quadratic effect of prime duration in gaze durations (t = −2.7) was not reliable (t = −1.67). This replicates results from Experiments 1−3 in which no significant quadratic trends of prime duration were obtained.

A.3 SUMMARY

The use of untransformed fixation durations as dependent variable lead to the violation of several assumptions of LMMs including normality of residuals, homogeneity, and normality of random effects. The log-transformation is an easy way to overcome these issues. Although the model based on log-transformed data was more valid statistically, the interpretation of coefficients in terms of milliseconds is less convenient and necessitates additional calculations. However, the use of log-transformed fixation-duration data should be preferred in reading research. The analyses in Chapter 3 are based on this transformation.

Although most results were very similar between analyses with untransformed and log-transformed data, there were important differences. The D35 priming effect of Experiment 1 was not reliable, therefore being in agreement with Experiments 2–4. Furthermore, there was a reliable D80 priming effect in Experiment 2, indicating that early extraction of semantic information is not limited to salient stimuli. However, the effect was still not significant in Experiment 1 and therefore appears to be weak.

B RANDOM EFFECTS OF PREVIEW BENEFIT IN THE CHAPTER 3 ANALYSES

Linear mixed models (LMMs) allow analyses of differences between subjects and differences between items in the preview benefit and other effects (e.g., Kliegl et al., 2010). In addition to the classic fixed affects, random effects (conditional modes) and the correlations between them reveal additional insights into parafoveal preview benefit.

The selection of the random-effects structure used for the analyses in Chapter 3 was done with a drop-one selection procedure, starting with the full model including all varying intercepts and varying slopes of the main effects of the experimental design (but no correlation parameter between variance components). Varying slopes that did not significantly contribute to the goodness of fit of the model (assessed via likelihood ratio tests) were removed. Once the model could not be reduced further without impairing goodness of fit, correlation parameters between remaining variance components were included and their contribution to goodness of fit was tested. The rationale for checking the contribution of correlation parameters only for significant variance components is that, by implication, terms without reliable variance have also zero covariance with other terms. Since the analyses cover variance components and correlation parameters, an assessment of the significance of the associated terms was necessary.

In the following, I will discuss the reliably contributing variance components and focus on the analyses with target gaze duration as the dependent variable. The pattern is very similar to the models including single- and first-fixation duration.

B.1 VARIANCE COMPONENTS IN THE MODELS OF CHAPTER 3

B.1.1 EXPERIMENT 1

In the model selected for the LMM analysis of target gaze duration as dependent variable, target words (items/sentences) vary reliably in mean gaze duration (intercept) and in the size of the preview effect. In addition, a parameter for the correlation between preview benefit and mean gaze durations was estimated. Thus, there are four variance components in this model (variance of the mean log gaze duration for both subjects and items, variance of item-related preview benefit, and the correlation parameter between item-related mean and preview benefit). This model's goodness of fit was significantly better than the one of the simple model without a parameter for item variance in preview benefit (log likelihood: −1204.7 vs. −1199.1, $\chi^2(2) = 11.2$, $p < .01$, AIC[15]: 2419.3 vs. 2412.1). This model was also better than a model without a parameter for the correlation between variance components (log likelihood: −1202.1 vs. −1199.1, $\chi^2(1) = 6.1$, $p = .01$, AIC: 2416.3 vs. 2412.1).

The model estimates were used to generate "predictions" for each target word's mean single fixation duration as well as each target word's preview effect.[16] Figure B.1 displays 95% prediction intervals for conditional modes of intercept and semantic preview effect for 102 experimental target words, sorted by the conditional modes for the intercept. The fixed effect of semantic preview benefit was incorporated to the corresponding conditional modes. Target words receiving longer fixations were associated with smaller preview benefit effects; the estimated random-effect correlation is $r = -.66$. Furthermore, 99 out of 102 conditional modes are positive, indicating the semantic preview benefit was not due to a minority of distinct items but a general finding.

The conditional modes incorporating the fixed-effect parameter of the preview benefit effect of 102 items predicted from the LMM estimates are also displayed in Figure B.2 (filled circles). In addition, the plot includes unadjusted within-item values as open circles and arrows pointing to their corresponding conditional means. The model-based shrinkage is due to the unreliability of within-item values. Unreliable values (e.g., outliers and values based on a small number of few observations) are "shrunken"

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[15] AIC means *Akaike information criterion* (Akaike, 1973) and is defined as $AIC = 2k - 2ln(L)$, where k and L represent the number of parameters in the statistical model and the likelihood, respectively. One variance component is counted as one parameter.

[16] These "predictions" are the conditional modes, given the data evaluated at the estimated parameters (see Bates, 2010, for a discussion of this terminology).

towards the population mean. This shrinkage removes unreliable variance and unveils a stronger correlation than obtained for the within-word based computations (i.e., open circles). In summary, the analysis of variance components and correlation parameters revealed that items receiving shorter mean fixations were on average associated with larger semantic preview benefit.

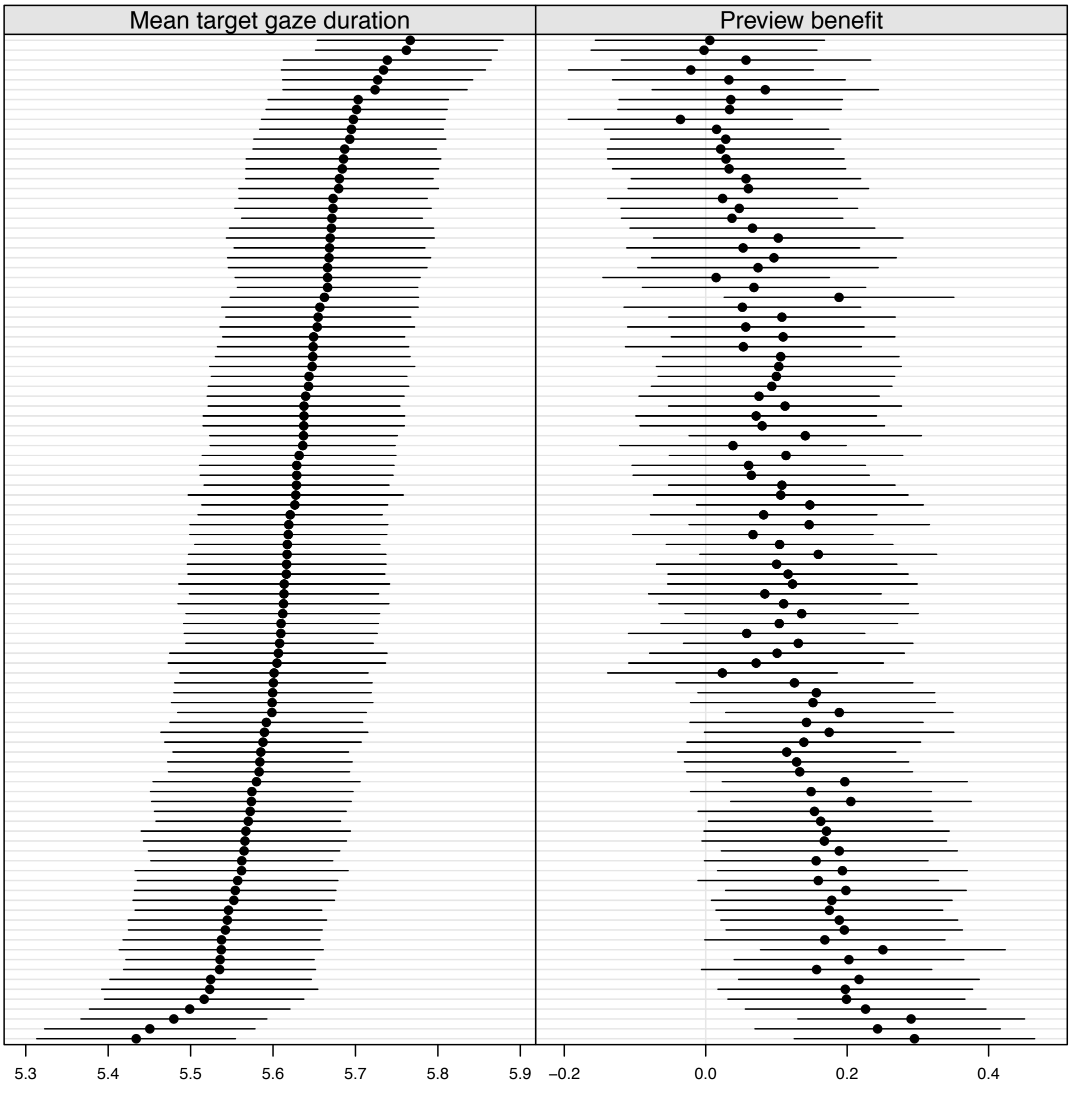

Figure B.1. Caterpillar plots for 102 target words' conditional means of the intercept (log target gaze duration; left) and the semantic preview-benefit effect (right) (Experiment 1). Target words are ordered by mean. Horizontal lines indicate 95% prediction intervals.

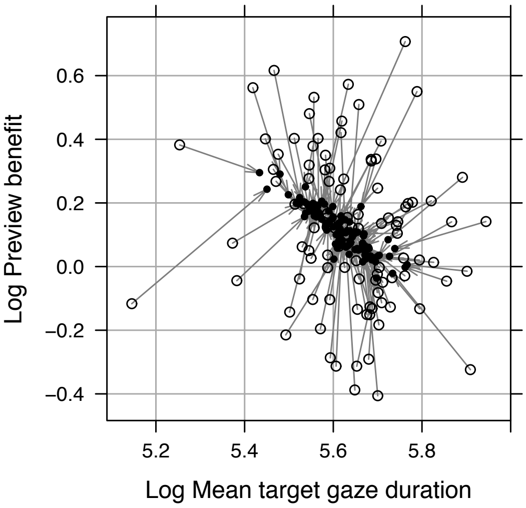

Figure B.2. Scatterplot of the semantic preview-benefit effect associated with the items (Experiment 1). Within-item means and conditional modes are represented by open and filled circles, respectively. Arrows connect the values and indicate shrinkage for each target word. See text for details.

B.1.2 EXPERIMENT 2

In the model selected for the LMM analysis of target gaze duration, items and subjects varied reliably in mean gaze duration (intercept). In contrast to Experiment 1, an item-related variance component of preview was removed in the model-selection procedure since it negligibly contributed to the model's goodness of fit, but a parameter for a subject-related variance component of capitalization was included. The correlation parameter for the two subject-related variance components did not significantly improve the goodness of fit ($\chi^2(1) = 0.7$, $p = .40$) and, therefore, was not included. The final model included three variance components and fitted significantly better than the simple model without the subject-related variance component for the capitalization effect (log likelihood: −863.5 vs. −858.8, $\chi^2(1) = 9.4$, $p = .002$, AIC: 1741.1 vs. 1733.6).

B.1.3 EXPERIMENT 3

In the model selected for the LMM analysis of target gaze duration, items and subjects vary reliably in mean gaze duration (intercept). This replicates results from Experiments 1 and 2. Moreover, item-related variance components of the semantic preview effect (contrast 1: unrelated vs. related preview) and of the display-change effect (contrast 2: related vs. identical preview) significantly improved the goodness of fit. Additionally, the three correlation parameters for intercept and both preview effects were significant as well. Figure B.3 displays conditional means of intercept, related vs. identical preview effect, and unrelated vs. related preview effect for 100 items (filled circles).

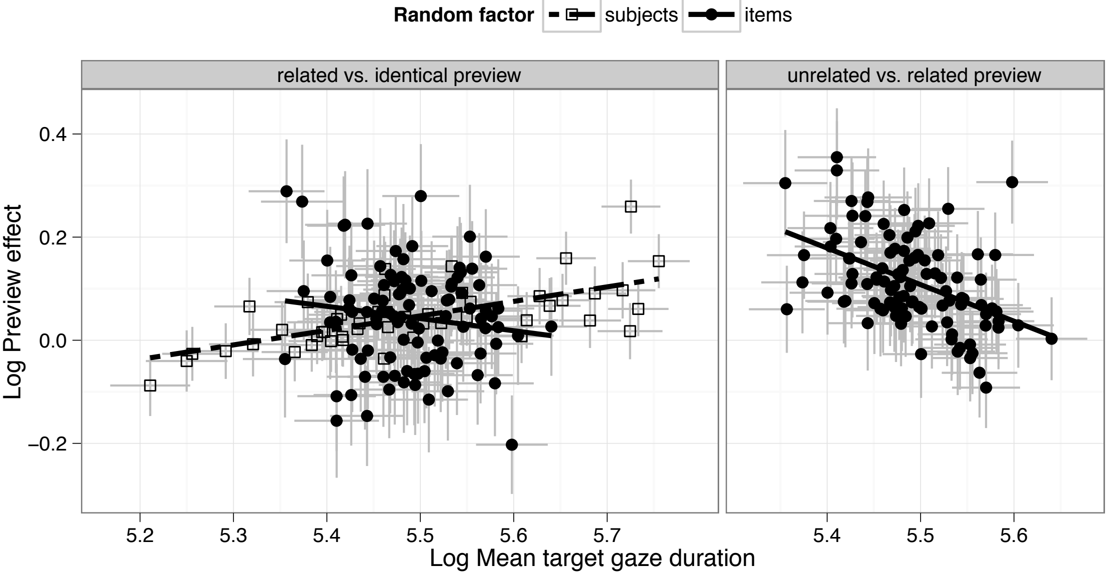

Figure B.3. Scatterplot of conditional modes of related vs. identical preview effect (left-hand panel) and unrelated vs. related preview effect (right-hand panel) against conditional modes of the intercept together with linear regression lines (Experiment 3). Subjects and items are represented by open squares and filled circles, respectively. No variance term for the unrelated vs. related preview effect for subjects was included in the model (see text for details). The gray bars indicate standard errors of the conditional modes of preview effect (vertically) and of the conditional modes of the intercept (horizontally), respectively.

A significant negative parameter for the item-based correlation (*r* = −.36) between the conditional means of intercept and semantic preview effect replicates a result of Experiment 1. Target words receiving longer fixations were associated with smaller semantic preview benefit. The largest correlation parameter was obtained for the correlation between the two preview effects (*r* = −.71); that is, target words traded off effect sizes: Items with a large semantic preview benefit were less sensitive to the display-change effect (and vice versa). Finally, the correlation parameter for semantic preview effect and varying intercept was negative, too (*r* = −.12), hence smaller related vs. identical preview effects were obtained on items receiving longer fixations.

The inclusion of these variance terms is justified by the corresponding test statistics. The inclusion of a correlation parameter for item-related variance components of mean and semantic preview effect significantly improved the goodness of fit (log likelihood: −984.7 vs. −982.6, $\chi^2(1) = 4.2$, *p* = .04, AIC: 1997.5 vs. 1995.2). Further model improvements were achieved with correlation parameters for item-related variance components of mean and display-change effect as well as of item-related semantic preview benefit and display-change effect (log likelihood: −972.4, $\chi^2(2) = 20.4$, *p* < .001, AIC: 1978.9).[17]

The final model also included subject-related variance components for the intercept and for the display-change effect as well as a correlation parameter for them. Figure B.3 (left-hand panel) displays the scatterplot of corresponding conditional means for 48 subjects (open squares). Interestingly, the correlation parameter was significantly positive (*r* = .49; log likelihood: −969.7, $\chi^2(1) = 5.4$, p = .02, AIC: 1975.5). The dashed regression line in the left panel of them Figure B.3 illustrates this result.

Finally, the subjet-related correlation parameter between the variance components associated with varying intercept and varying slope of the display-change contrast could potentially be accounted for by including self-reported display-change awareness as a fixed effect in the LMM. However, the correlation parameter remained positive when the predictor display-change awareness and the corresponding interactions were added to the main model (*r* = .36). This finding indicates that the correlation between the display-change contrast and mean target gaze duration was not

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[17] It is impossible to specify a model with only two of these three correlation parameters. Therefore, I cannot test the contributions of the two correlation parameters between (a) intercept and display-change effect and (b) display-change effect and semantic preview separately.

completely due to the positive correlation between target gaze duration and self-reported display-change awareness.

B.2 CONCLUSION

The inspection of variance components and correlation parameters may turn out to serve as a useful heuristic for a better understanding of the mechanisms at work in the boundary paradigm. Significant variance components and correlation parameters demonstrate how LMMs uncover information not available with traditional analyses. For example, a negative correlation between fixation durations and semantic preview benefit for items was observed. Targets receiving longer fixations were associated with smaller semantic preview benefit, indicating semantic preprocessing is more efficient if the target itself can be processed easily. There was no evidence for a significant correlation including semantic preview benefit for subjects. Conversely, there was a strong positive correlation between the intercept and the display-change contrast (related vs. identical preview) for subjects, but a small negative correlation for items. Hence, the costs associated with a display change might have been higher for slower-reading subjects, but lower for target words receiving long fixations. Though the current finding can serve as evidence for the significance of the inspection of random effects, more research is necessary for comparisons and the derivation of general trends.

C TECHNICAL ASSESSMENT OF DISPLAY-CHANGE DELAYS

Display changes were employed in all experiments reported in this thesis. In the experiments of Chapter 2, the parafoveal fast-priming technique was used. In this paradigm, a random-letter string is replaced by the preview when the boundary is crossed. During the pretarget fixation, the target replaces the preview. In the experiments reported in Chapter 3, the classic boundary paradigm (Rayner, 1975) was used, and hence, the target replaced the preview during the saccade crossing the boundary.

Since visual input is suppressed during saccades (Matin, 1974), a display change should preferably occur as soon as possible after the boundary is crossed. Inherently, this is only possible with the boundary paradigm and for the first display change in the parafoveal fast-priming paradigm. If the preview is replaced by the target during the saccade from word *n* to word *n* + 1, the actual target is present at the target location when the fixation starts. In contrast, delayed display changes—taking place during the target fixation—are more noticeable and could thereby interfere with the reading process. If the display change occurred during the target fixation, fixation times could be inflated due to saccadic inhibition (e.g., Reingold & Stampe, 2000).

Saccadic inhibition would affect both related and unrelated previews and thereby be subordinate. In contrast, comparisons between identical preview (i.e., without noticeable display change) and nonidentical previews could be subject to confoundation. Only the replacement of previews, which are different from the target, can potentially cause interference.

Although an immediate display change is desirable, it is inherently delayed due to several technical properties. Unfortunately, most of these delays are not directly accessible. For the present technical assessments a setup was created which allows measuring the whole time from a (virtual) eye movement to the actual display change.

C.1 ASSESSMENT 1

C.1.1 HOW DOES AN EYE-TRACKING SYSTEM TRACK THE EYE?

In many video-based eye-tracking systems, light-emitting diodes (LEDs) illuminate the eyes. These diodes emit infrared light which is not visible for human beings but for the cameras of the eye-tracking system. This allows tracking the eyes in darkness or in settings with reduced illumination.

The amount of light reflected by the pupil is low, compared with the other parts of the eye and the surrounding parts of the face. Hence, the pupil appears as a darker area in the images recorded by the cameras of the eye-tracking system. Image processing algorithms identify the pupils' center of mass. The coordinates of this pixel are used for calculating gaze location (after mapping screen and recorded pupil image in the calibration procedure). For more technical details on eye tracking, see Duchowski (2007).

C.1.2 VIRTUAL EYE MOVEMENTS

The illumination of the eye is of relevance to the measurement of delay: In the first setup, an infrared LED was used to emit infrared light to the camera of the eye-tracking system. Two small circular pieces of coated black paper were used as “artificial pupils”. The eye-tracking system identified these stimuli as pupils since they were positioned on a bright background. The additional LED was positioned in direction to the camera recording the right “eye”. When the LED was powered, it emitted light to the infrared-sensitive video camera. Due to this direct lighting, the contrast between artificial pupil and background was clearly reduced, thereby not allowing the eye-tracking system to continue identifying a pupil in the images recorded by the camera. See Figure C.1 for an illustration of this technique.

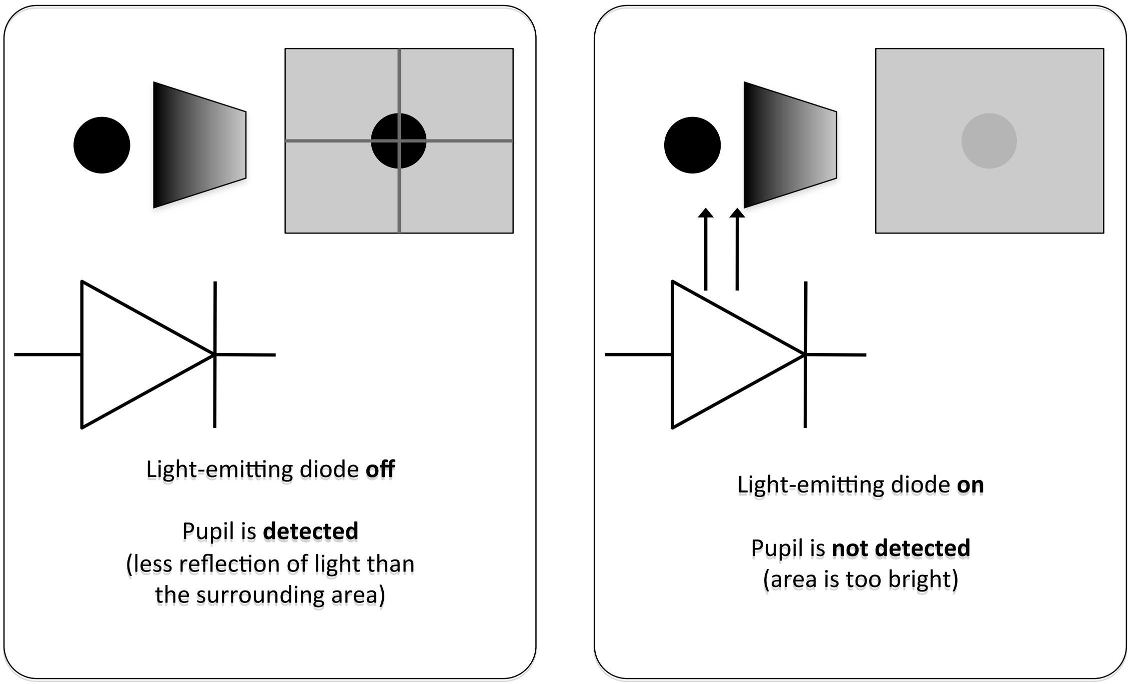

Figure C.1. Illustration of the missing-pupil technique. The LED is directed towards the camera of the eye-tracking device. If it is activated, the area becomes too bright and thereby the pupil can no longer be detected.

C.1.3 DISPLAY CHANGE

Initially a black screen was presented on the monitor of the remote computer. In all assessments, virtual eye movements triggered the appearance of a white rectangle on the screen. The time between both events depicts the whole display-change delay.

C.1.4 HARDWARE AND SOFTWARE

Measurement device

The *Black Box ToolKit* (BBTK; Plant et al., 2004) is a device designed for high-accuracy timing measurement. It has several interfaces for signal generation and signal detection. The device is very fast as it operates at sub-millisecond sampling rates (around 48 kHz).

The BBTK includes *opto-detectors* allowing detection of visual activity. An opto-detector consists of a photodiode connected to an adjustable elastic strap. The time of a display change can be measured easily with the opto-detectors: When a bright stimulus replaces a dark stimulus, photons of sufficient energy strike the photodiode and thereby create free electrons. The resulting current can be measured in the BBTK. If a user-defined threshold is reached, an event is registered. Using the tuning potentiometer, the luminance sensitivity threshold was set as low as possible to minimize reaction time. The threshold was just high enough to guarantee that the black screen does not trigger an event. One opto-detector was attached to the center of the monitor—the location of the display change—by means of the elastic strap.

The manufacturer of the BBTK reported the results of timing tests with an oscilloscope (Plant, 2004). The delay of opto-detector input timed from the diode to the parallel port is below 100 ns. This value is considerably below one millisecond and hence negligible with respect to the measurment of display-change delay.

Host computer

The BBTK was connected with the host PC via the parallel port. This separate computer allows accurate measurements since the BBTK software runs with highest priority. The operating system of the host PC was Windows XP (Microsoft Corporation, Redmond, WA). In the BIOS of the computer, the mode of the parallel port was set to *Enhanced Parallel Port*, a signaling method for parallel communication with higher rates of data transfer.

Light-emitting diode

The camera of the eye-tracking system was illuminated by an HDSL-4230 LED (Hewlett Packard, Palo Alto, CA). The LED emitted infrared light at 875 nm wavelength (range: 860−895 nm), had a width of 5 mm, a viewing angle of 17°, and optical rise and fall times (10%−90%) of 40 ns. Radiant on-axis intensity was 75 mW/sr. The LED was connected to the 5 V output line (channel L3) of the BBTK. The BBTK delay of powered output timed from the parallel port to the output pin is below 100 ns (Plant, 2004).

Eye-tracking device

Pupil-like stimuli were monitored with an EyeLink II system (SR Research, 2009) with a sampling rate of 500 Hz, an instrumental spatial resolution of 0.01°, and an average accuracy of better than 0.5°. Recording was binocular.

The manufacturer of the EyeLink II system addressed delays (SR Research, 2006) and reported the delay from an eye movement to the availability of the data at the remote computer. At 500 Hz sampling rate, this delay is 3 ms, 5 ms, and 7 ms on average, for filter levels of 0, 1, and 2, respectively. This delay includes the half sample time (1 ms), which is the average delay from an eye movement to the time the camera takes an image.

The manufacturer also measured the delay of a gaze-contingent display change with an artificial pupil and a light sensor. The sampling rate of the eye-tracking device was 500 Hz; the filter was disabled. A monitor with 160 Hz refresh rate was employed. The code was written in C. The reported average delay was 7 ms.

Remote computer

The remote computer controlled the screen presentation and was connected to the PC of the eye-tracking device via an Ethernet cable. The operating system Mac OS 9 was running on a Power Mac G4 machine (Apple Inc., Cupertino, CA).

Screen

An Iiyama Vision Master Pro 514 monitor (Iiyama Seiki Co., Nagano, Japan; 1024 × 768 pixels; 53 cm [21 in.]; vertical refresh rate 150 Hz) was connected to the remote computer via VGA D-Sub. Theoretically, the maximum delay caused by the monitor is 6.67 ms (the reciprocal of 150 Hz). This is the time a refresh period takes. Since the display change can be triggered at any time, refresh cycles and display change cannot be synchronized. On average, it theoretically takes half the time of a refresh period to present the new image.

Screen luminance was measured with a PR-650 SpectraScan Colorimeter (Photo Research, Inc., Chatsworth, CA) at the center of the screen: The luminance of the white rectangle was 92.3 cd/m^2, the luminance of the black background was lower than 3.4 cd/m^2.

Programing language and technical details

The Screen presentation was controlled with MATLAB (The MathWorks, Natick, MA) using the Psychophysics toolbox (Brainard, 1997; Pelli, 1997) and the Eyelink toolbox (Cornelissen et al., 2002). The conditions in the assessments closely matched the conditions in the gaze-contingent experiments (number of pixels, pixel depth, refresh rate). Furthermore, the average size of the rectangle and its position were similar to the experiments reported in this thesis as well. A white rectangle with the size of 62 × 20 pixels was presented in white at the center of the screen. The size of the rectangle corresponds to the size of a five-character word in 20pt bold Courier New, the font which was used in all experiments. The mean length of previews and targets was five letters. Hence, the size of the white rectangle reflects the size of a typical word stimulus.

Procedure

Figure C.2 shows the technical setup. An opto-detector was attached to the center of the monitor and was connected to a BBTK input line (channel L3). If power of the output channel (L5) was turned on, the LED emitted light. Initially, a black screen was presented. The algorithm, programed in MATLAB, continuously requested the fixation position of both eyes from the eye-tracking system. The display change was initialized as soon as the pupil position of either "eye" was missing in the transferred data. In the measurements, only the image of the camera for the right eye was manipulated.

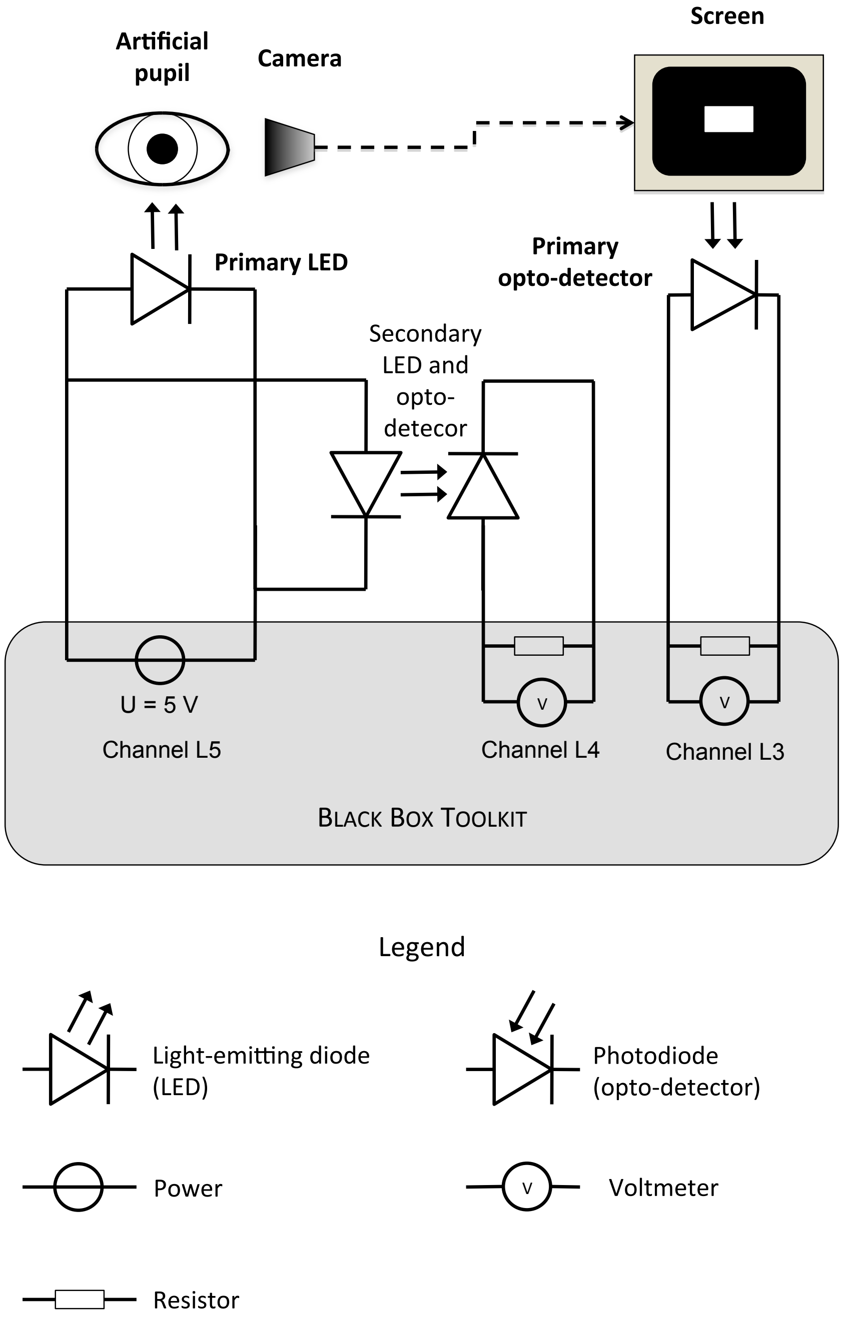

Figure C.2. The measurement setup. When the active line (channel L5) is activated, the primary LED starts emitting light. The event is registered by the eye-tracking system and triggers a display change on the screen of the remote computer. After several steps, a white rectangle appears. As a result, the primary opto-detector is activated, which can be registered in channel L3. The display-change delay is operationalized as the difference between the times when the channels L5 and L3 are activated. The secondary LED, in parallel with the primary one, and the secondary opto-detector allow measuring the LED delay (see text for details). The representation of the parts inside the BBTK is simplified.

After several steps with unknown duration a bright rectangle appeared on the screen causing the opto-detector to generate current that could be measured by the BBTK. After the MATLAB program initialized the display change, the algorithm running on the remote computer continued requesting data from the eye-tracking system. When valid pupil positions were present for both eyes, the white rectangle was replaced with a black rectangle of the same size. Hence, the black screen was restored. Then, again, the white rectangle was presented when pupil data was missing. The algorithm was continuously repeated in a loop and thereby allowed multiple measurements of the display-change delay.

A measurement program was created with the BBTK software. The following procedure was repeated two-hundred times on the host computer:

```
If there is no activation on either input/output:
    Turn on 5 V output line (channel L5)
    Wait 50 ms
    Turn off output line
    Wait 50 ms
End
```

I will refer to a series of 200 display-change measurements as a *measurement run*. The waiting periods of 50 ms are considerably longer than the expected display-change delays and thereby allow multiple succeeding measurements.

Additional devices for measuring BBTK/opto-detector/LED delay

The exact delay between the activation of the 5 V channel and the LED is unknown. Theoretically, this delay should be clearly below millisecond range given the rise time of the LED. To assess the magnitude of this delay, additional devices were connected: A second LED (the same model as the primary LED) and a second opto-detector (the same model; BBTK channel L4) were employed to measure the time the LED needs to start emitting light. Both LEDs were connected in parallel. Thereby, the delay between the activation of the output line and the LED should be identical for both diodes.

To avoid confusion, the LED directed towards the second opto-detector is referred to as secondary LED. Accordingly, the opto-detector on near the secondary LED is referred to as secondary opto-detector. The primary LED directed towards the camera of the eye-tracking devices and the primary opto-detector attached to the screen are of main interest for the measurements; the secondary ones are employed to access the delay between the power line (channel L5) and the primary LED.

Options with potential impact on display-change delay

Although the display-change delay is influenced by a multitude of factors, the user can only change a subset of potential relevant technical parameters. Factors associated with the presentation of the image and the settings of the heuristic filter in the eye-tracking device were manipulated in the first assessment. This allowed evaluating the contribution of these parameters on the display-change delay.

Options related to presenting a new image

The Eyelink toolbox offers several options for storing the image and copying the image to the graphics adaptor for the screen presentation. The `Screen` command is used for both operations (specified via arguments). These options potentially influence the delay between the time the software initializes the display change and its physical realization (the appearance on the screen). The following subsections on memory flag and copy mode are very technical and can be skipped without loss of continuity.

Storing the image

The `Screen` function, together with the argument *'OpenOffscreenWindow'*, opens an offscreen window that allows for creating an image for subsequent display. The argument passed to the *flag* parameter specifies where the image is stored. The possible values are *‘noNewDevice’*, *‘keepLocal’*, *‘AGP’*, and *‘VRAM’*.

If *‘noNewDevice’*, the default value, is specified, no new GDevice record is created. Instead, the default GDevice record for a video card on the system is used. According to the Psychophysics toolbox documentation, Apple recommends the default value. The three further possibilities allow explicit control over the place where the pixel image is stored. The value *‘keepLocal’* allows keeping the offscreen image in the main memory of the system. This negates the advantages of the graphics acceleration card. If *‘AGP’* is specified, the offscreen image is created in the AGP memory. This is a certain area in main memory which can be directly accessed by the graphics card. The option ‘*VRAM’* is used to create the image in the VRAM of the graphics card. Writing to VRAM takes relatively long, but copies from VRAM to screen are very fast. The drawback of this option is its fragility as the image could be lost if, for example, resolution or pixel depth are changed.

Copying the image

To copy images between two on- or offscreen windows, the argument *'CopyWindow'* is passed to the `Screen` function. The copying routine is specified with the argument for the *copyMode* parameter. There are several arguments which could be used to change the image (e.g., addition or multiplication) and two arguments which allow simple copying: *'srcCopy'* and *'srcCopyQuickly'*.

The default value is ‘*srcCopy’*; in this case copying is done with the CopyBits routine by Apple. If ‘*srcCopyQuickly’* is specified, the routine of the VideoToolbox (Pelli, 1997) is used. Both approaches have very similar speed.

Heuristic filter

The delay of the eye-tracking device is determined by multiple hardware and software characteristics. The heuristic filter has a major impact on this delay. It is used to reduce noise in the eye-movement data and can be set to one out of three levels. If level 0 (no filter) is chosen, the gaze position is registered immediately. Filter levels 1 and 2 cause additional delay of one and two measuring points, respectively. The additional information is used to smooth the data. Since the eye-tracking system operates at 500

Hz, one filter level is associated with a delay of 2 ms. The manufacturer of the eyetracker does not recommend disabling the heuristic filter (SR Research, 2006). The EyeLink II system has separate link and file filter settings. The link data is transferred to the remote computer; the file data is saved on the local computer. In all technical setups of the present measurements, link and file filter levels were identical.

C.1.5 DESIGN

All combinations of heuristic filter level (no filter vs. filter level 1 vs. filter level 2), memory flag (noNewDevice vs. keepLocal vs. AGP vs. VRAM), and copy mode (srcCopy vs. srcCopyQuickly) were used rendering 24 measurement runs.

C.1.6 RESULTS AND DISCUSSION

Delay between power line and LEDs

The secondary LED and the secondary opto-detector were employed to measure the delay between the time the power line was activated and the time the LED emitted light. Since the measured delay depends on the time the activation of the secondary opto-detector is registered in the BBTK, it does not exactly reflect the delay between power-on and LEDs.

The average delay was 30.4 µs (*SE* = 129 ns); the median was 30.0 µs. Except one outlier (430 µs), all values were between 20.0 µs and 80.0 µs. The vast majority of values were on the median: 86% of all delays were equal to 30.0 µs. As expected, the delay between the time the power line is activated and the time the LEDs emit light of sufficient intensity is very short and thereby negligible with respect to the measurement of the whole display-change delay.

Display-change delay

The display-change delay is operationalized as the delay between the time the power line is turned on and the time the input of the primary opto-detector (positioned at the screen) is registered. Theoretically, the delay between the activation of the secondary and the primary opto-detector could be interpreted as the display-change delay.

However, since the delays of both power line and LED are included, the measure is more conservative and cannot underestimate the actual delay.

Figure C.3 shows the delays as a function of filter level, memory flag, and copy mode. Obviously, the results vary between individual measurement runs (consisting of 200 observations). This variation seems to be unrelated to the experimental factors. Due to this variation, a mixed model (Baayen et al., 2008; Kliegl et al., 2010) is warranted. All effects were estimated with the lmer program from the lme4 package (Bates, Maechler, & Bolker, 2012) in the R environment for statistical computing (R Development Core Team, 2012). The model included filter level (levels: 0, 1, 2; numeric; centered on 1), memory flag (as repeated contrasts: noNewDevice vs. keepLocal, keepLocal vs. AGP, AGP vs. VRAM), and copy mode (as sum contrast: srcCopy vs. srcCopyQuickly) as fixed effects. The combination of all experimental factors (i.e., the individual measurement runs) was employed as the random factor. For this random factor, a random intercept was part of the model. Due to the structure of fixed effects (repeated contrasts) the intercept represents the mean (at filter level 1), and each fixed effect is estimated relative to the mean of all remaining effects.

The estimated intercept was 16.3 ms. The filter level had a major impact on delay time (b = 7.3 ms, t = 51). Neither the difference between both copy modes (b = −0.19 ms, t = −0.82) nor any memory flag contrast (all $|t|$s < 1.79) was significant.

An alternative version of the statistical model was created, in which both memory flag and copy mode were specified as treatment contrasts (with the default values—noNewDevice and srcCopy, respectively—as reference categories). This model allows evaluating the influences of the different parameters relative to a prototypical baseline model. The estimated intercept for this model was 16.8 ms. The effect of filter level remained highly significant (t = 5). The difference between both copy modes was not significant (t = −0.82). Compared to the default memory flag, keepLocal (b = −0.6 ms, t = −1.79) and AGP (b = −0.3 ms, t = −0.95) did not result in reliably longer delays, but the delay was significantly shorter if the image was stored in the VRAM (b = −0.68 ms, t =

−2.06). This difference is relatively low considering the duration of the refresh period of the monitor which is 6.67 ms.

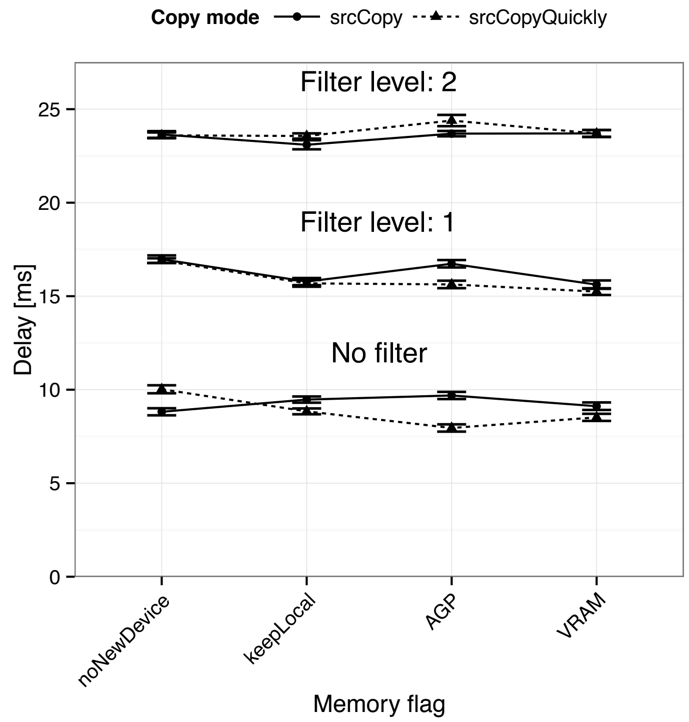

Figure C.3. Display-change delay (Assessment 1) as a function of filter level, memory flag, and copy mode. Error bars indicate standard errors.

The large effect of about 7 ms per filter level was not expected. The mean values for no filter level, filter level one, and filter level 2 were 9.1 ms, 16.1 ms, and 23.7 ms, respectively. Since one additional filter level is based on one additional sample, the impact of an increase in the filter level by one should be reflected in a 2-ms delay increase (SR Research, 2006).

C.2 ASSESSMENT 2

Since there was some variation between measurement runs, the first assessment was replicated with three measurement runs per filter level. The influence of both memory flag and copy mode was relatively small; therefore the default values were used.

The mean delay for measurements without heuristic filter was 8.7 ms (*SE* = 134 µs). Filter levels 1 and 2 resulted in average delays of 16.3 ms (*SE* = 120 µs) and 23.7 ms (*SE* = 138 µs), respectively, replicating the results of Assessment 1.

Minor differences between the values of Assessments 1 and 2 are possibly due to slight variations in the setup. Subtle changes in LED angles and threshold levels could have lead to sub-millisecond differences.

Again, the differences between filter levels were 7 ms on average and hence larger than expected. In Assessments 1 and 2, missing pupil data triggered display changes. Most likely, there is some special processing around blinks. To address this possibility, the display-change trigger was changed in the next assessments.

C.3 ASSESSMENT 3

The missing-pupil trigger for the display change seemed to be accompanied by unexceptionally large increases in the delay if the heuristic filter was used. Therefore a modified setup was created including a trigger which more closely matched the characteristics of a gaze-contingent experiment with the boundary paradigm.

C.3.1 CHANGE IN VIRTUAL GAZE POSITION

The angle of the primary LED was set up in such a way that the camera identified a different pupil center when the LED was turned on or off due to a change in the infrared brightness. This technique is illustrated in Figure C.4. If the LED was turned on, only a part of the pupil stimulus remained sufficiently darker than the surrounding area, causing a shift of the center and thereby a different “fixation” position in the eye-tracking system. Due to this setup, the pupil position jumped instantly when the LED was turned on or off.

The distance between both virtual fixation positions was 249 pixels horizontally. The boundary was located in a distance of five pixels (2% of the whole distance) to the right of the first position. As soon as the boundary was crossed, the display change was initialized. This technique reflects the experimental conditions of the gaze-contingent experiments in the present study.

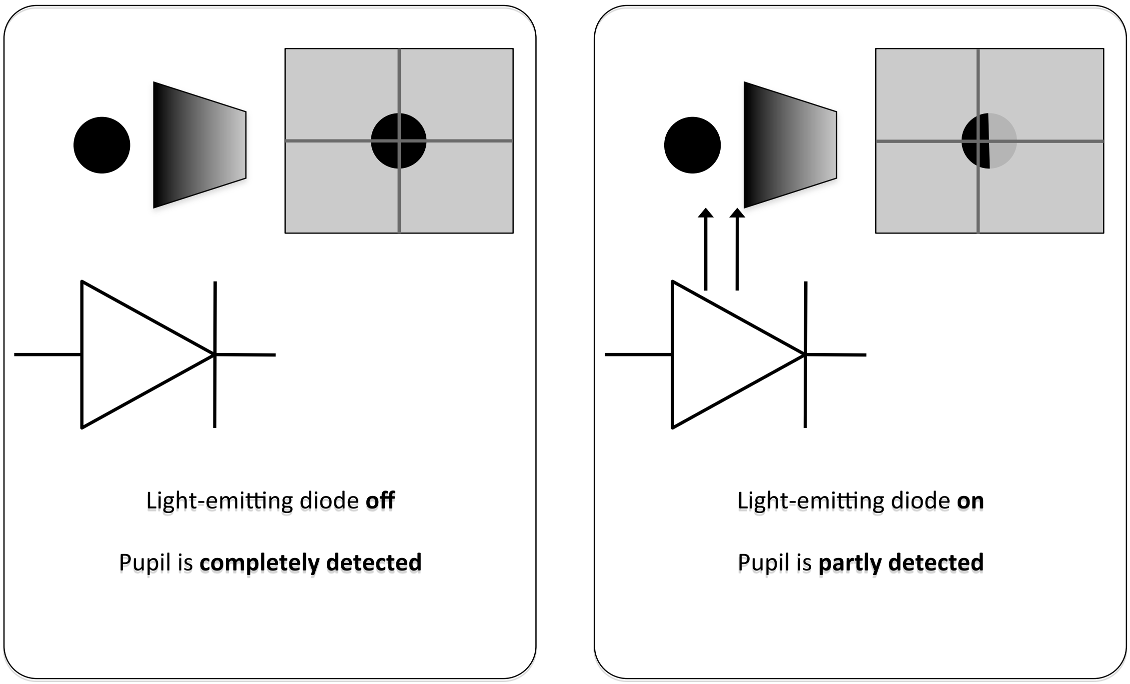

Figure C.4. Illustration of the gaze-shift technique. The LED is directed towards the camera of the eye-tracking device. If it is activated, a part of the artificial pupil becomes too bright and thereby the center of the pupil is shifted towards the darker area of the pupil.

Besides the position of the primary LED and the program on the remote PC, the setup was identical with Assessment 2. The default values of the memory flag and copy mode parameters were used. For each filter level, three measurement runs were executed.

C.3.2 RESULTS AND DISCUSSION

Figure C.5 shows the display-change delay as a function of filter level. If the heuristic filter was turned off, the average delay was 8.56 ms, replicating results of Assessments 1 and 2 (the new value was slightly lower). The average delays for filter levels 1 and 2 were 9.05 ms and 9.55 ms, respectively. Hence, the increase in display-change delay associated with an increase of one in the filter level was about 0.5 ms.

These differences between filter levels are much lower than the ones obtained with the missing-pupil technique. This corroborates the hypothesis that the algorithm of the eye-tracking device treats blinks in a special way. Due to the EyeLink software being proprietary, the exact algorithm is unknown. It appears that if the heuristic filter is used, the eye-tracking system does not send the information of a missing pupil immediately, but waits until a sufficient number of succeeding data indicates the loss of the pupil. Most likely the waiting period is employed to avoid losing data when the pupil is missing only in a few camera images. After all, real blinks are considerably longer than seven milliseconds. However, this information—which is not part of the EyeLink documentation—is of value for programing gaze-contingent experiments and interpreting data recorded by the eye-tracking system.

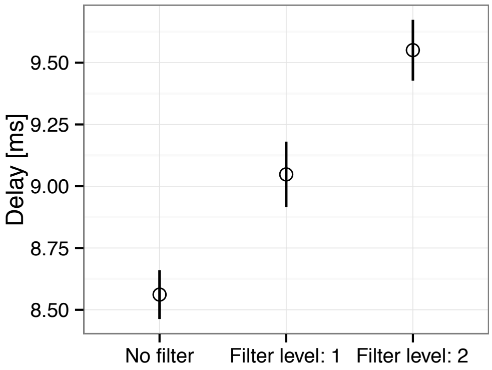

Figure C.5. Display-change delay (Assessment 3) as a function of filter level. Error bars indicate standard errors.

The display-change delay increased by 0.5 ms when a heuristic filter of level one was used, compared to a no-filter condition. The delay increased by additional 0.5 ms with filter level 2. These differences are considerably lower than the delays between two camera images of the eyetracker (2 ms). In accordance with SR Research (2006), the filter algorithm adds one sample delay for each filtering level. Yet this delay refers to the availability of a new pupil position. Since the filter algorithm is employed to smooth the data, the boundary could be crossed by interpolated pupil positions, too. This would result in shorter delays.

Because the boundary was very close to the start position (2% of the whole distance), the measures could be anticonservative. In an actual gaze-contingent experiment, the relative position of the boundary inherently varies. In a further assessment, the boundary position was changed and the distance varied.

C.4 ASSESSMENT 4

To more closely match the average condition of an experiment with the boundary paradigm, the boundary was located halfway between the virtual (horizontal) start and end positions. Moreover, the distance was manipulated: 22, 35, and 81 pixels. These distances are referred to as short, medium, and long.

C.4.1 DELAY DATA

Figure C.6 shows the mean display-change delays as a function of filter level and distance. As expected, if no filter was used, the delay was virtually unaffected by distance: The mean values in the short, medium, and long condition were 8.72 ms, 8.76 ms, and 8.52 ms, respectively. The small differences are most likely due to slight variations in the experimental setup. As is apparent from Figure C.6, the influence of filter level seemed to vary with distance. An LMM analysis with distance (as repeated contrasts), filter level (as repeated contrasts), and all interactions as fixed effects and individual measurement runs (three per combination of filter level and distance; 3 × 3 levels) as random factor was calculated.

Results revealed a significant increase between no filter and filter level 1 ($b = 0.8$ ms, $t = 3.97$) and between filter levels 1 and 2 ($b = 0.5$ ms, $t = 2.20$). The difference between medium and short distance was not significant ($b = 0.3$ ms, $t = 1.58$), but the difference between long and medium distance was reliable ($b = -0.6$ ms, $t = -3.07$). None of the interaction terms reached significance (all $|t|$s < 1.0).

However, the question remains as to what could have caused this special pattern of delays. The most noticeable results are the increased delays in the medium-distance condition with activated heuristic filter. The virtual eye-movement data reveals interesting patterns.

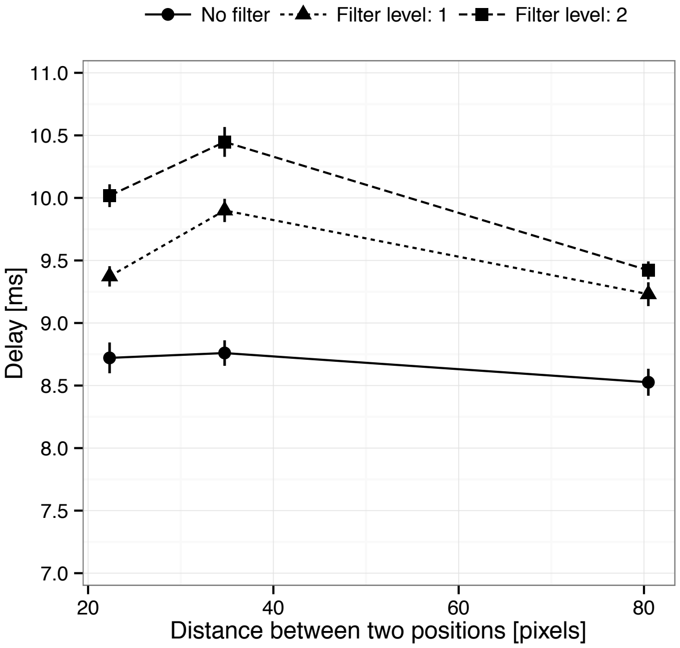

Figure C.6. Display-change delay (Assessment 4) as a function of the filter level and the distance between the start and end positions. Error bars indicate standard errors.

C.4.2 VIRTUAL EYE-MOVEMENT DATA

Figure C.7 shows one complete measurement run (i.e., 200 times the LED is turned on and off) per filter and distance conditions. The horizontal gaze position is displayed as a function of time. The gray lower and upper horizontal lines indicate the start and end positions, respectively; the dashed black line indicates the position of the boundary. Points represent individual virtual pupil positions. The black points roughly indicate positions during the "movement" from start to end position. They have been created using the following criterion: The difference between the actual position and the last position or the difference between the next and the actual position is bigger than two pixels. Though not being perfect, this criterion allows identifying the virtual pupil positions associated with the activation of the LED.

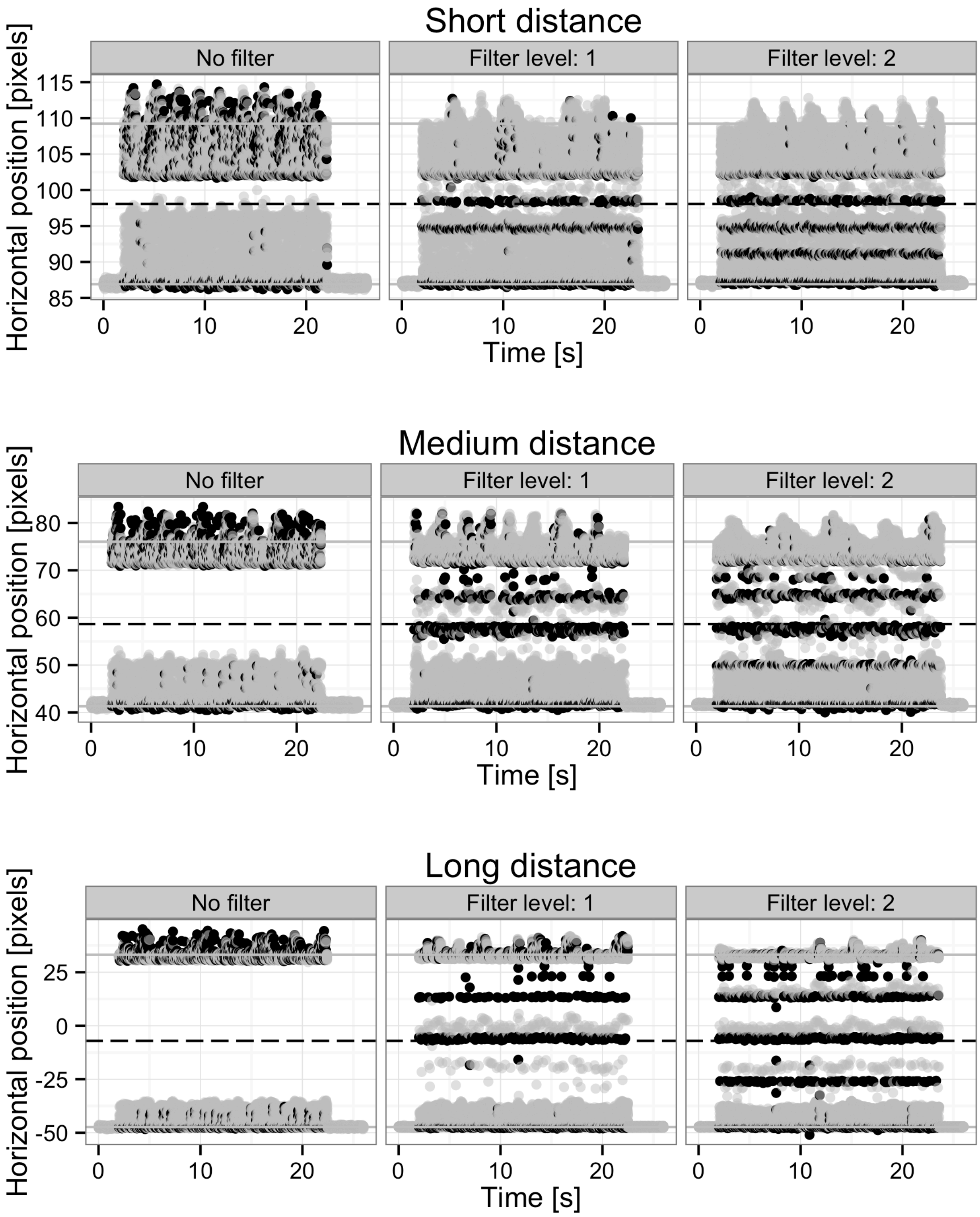

Figure C.7. Virtual eye-movement data of complete measurement runs. Accentuated (black) points roughly represent data of movements to the right. The upper and lower solid gray lines represent start and end positions, respectively. The dashed black line indicates the location of the boundary.

Besides the higher amount of noise in the no-filter data, the most noticeable result in Figure C.7 is the increase in the number of points between start and end positions. Apparently, the interpolated pupil positions are very similar within one measurement run. Whereas one group of points in both the short and long-distance condition was slightly right to the boundary, one group of points was slightly left to the boundary in the medium-distance condition—and hence did not trigger the display change. This helps understanding the slightly longer display-change delays in the condition with medium distance, compared with the other two conditions. The difference is most likely due to small variations in the experimental setup. Since the data points are very close to the boundary, minor variations could have distinctly influenced delays.

Figure C.8 shows virtual pupil positions for a smaller time range and thus allows retracing the path of positions in more detail.[18] Both the start and the end position were not reached directly, but with small steps towards the goal (at the end of the path). More interestingly, there are variations in the number of interpolated pupil positions between virtual "movements" from start to end position. Since the average number of virtual fixation positions left to the boundary increased with filter level, average display-change delays were longer if the heuristic filter was employed.

C.5 GENERAL DISCUSSION

The results of the display-change delay measurements constitute proof of the validity of all gaze-contingent experiments in this thesis. The same devices and software that were used for all experiments in this thesis were also used for the delay measurement. Besides minor differences in the MATLAB script, the assessments reflect the actual experimental situation. Therefore, the measured display-change delays with filter level one should be very similar to the average delays in the reported experiments.

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[18] The time scale of Figure C.8 is not related to the time scale of Figure C.7.

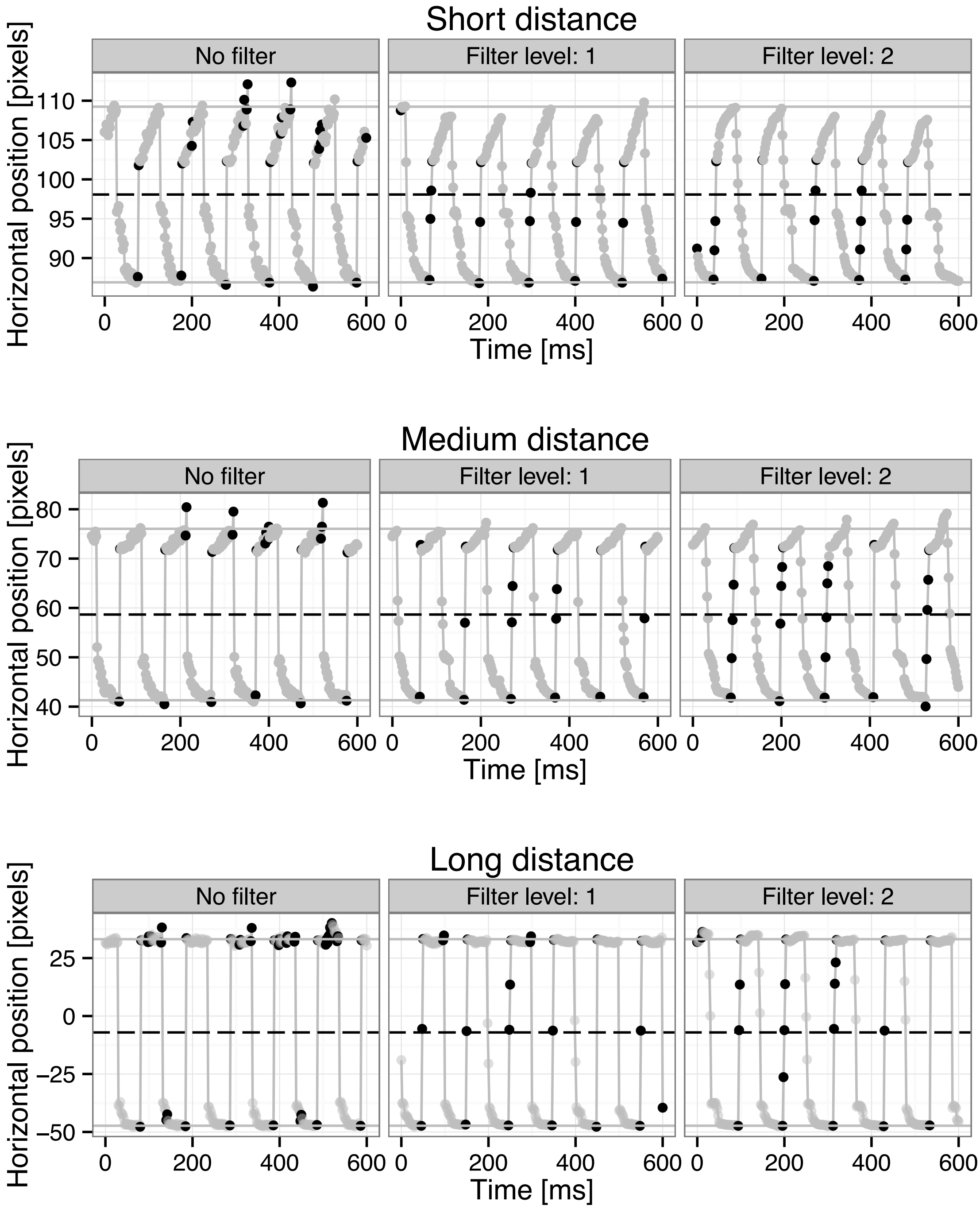

Figure C.8. Subsets of virtual eye-movement data. Accentuated (black) points roughly represent data of movements to the right. Upper and lower solid gray lines represent start and end positions. The dashed black line indicates the location of the boundary.

The missing-pupil technique employed in Assessments 1 and 2 was inappropriate for simulating eye movements with activated filter level. However, this technique allows interpreting the results of eye-movement data preceding blinks. The gaze-shift technique (Assessments 3 and 4) is well suited for simulating gaze-contingent experiments.

When no filter was used, mean delays were between 8.6 ms (Assessment 3) and 8.7 ms (Assessment 4) and increased by 0.5 (Assessment 3) and 0.6 (Assessment 4) per filter level. The average delays without heuristic filter were slightly longer than the one reported by SR Research (2006), i.e., 7 ms, which was obtained by employing a faster screen (160 Hz) and C code. Most likely, these technical differences contributed to the -differences in measured delays.

In the experiments reported in this thesis, all subjects' eye movements were recorded with filter level one. Thereby, the delays between the point in time when the eye crossed the boundary and the display changed were below 10 ms on average. The measured delay is in agreement with recent boundary studies (e.g., Yang, Rayner, et al., 2012). Furthermore, this delay is considerably shorter than the duration of saccades during reading, which typically last between 20 and 40 ms (Rayner, Foorman, Perfetti, Pesetsky, & Seidenberg, 2001). Hence, the employed technical devices are sufficiently fast to warrant the use of the classic gaze-contingent boundary paradigm (Rayner, 1975) in which the display change takes place during the saccade crossing the boundary.

However, the delays have implications for the parafoveal fast-priming paradigm and display-change paradigms in general. For the experiments reported in Chapter 2, this implies that the actual prime duration was longer than the specified one. The presentation of the prime was triggered when the gaze crossed the boundary located before the pretarget. Therefore, the display-change delay is negligible for the actual time the prime was presented. However, this does not hold for the time the prime was replaced by the target. Two characteristics of the paradigm are potentially subject to technical delays: Firstly, since the counter of the prime duration started as soon as a fixation was detected, this event is subject to the delay between the physical eye-movement and the availability of the data on the remote computer. Secondly, the delay between the initialization of the display change by the computer and its physical realization influenced the actual time the prime was replaced with the target. In conclusion, the actual prime durations were, on average, between nine and ten milliseconds longer than the specified prime durations. This should be taken into account when interpreting the results.

Finally, the BBTK offers a relatively easy way to assess display-change delays. Yet the advantages come at a high cost: Currently, the BBTK has a price of more than £1,400 even for the simplest version. This price appears to be quite high with a view at the technical configuration of this device. The open-source microcontroller board *Arduino* (D'Ausilio, 2012) is a low-cost alternative as a basic version can be purchased for less than €40. Of course, several additional technical components, like LEDs and photodiodes, are not included, but they are relatively cheap. However, the Arduino input-output board is controlled with a special programming language, which may be harder to learn than the BBTK software. In contrast to the BBTK, Arduino is an open-hardware project. Thus, its setup is transparent. The current assessment can most likely be implemented with Arduino, too. Schubert, D'Ausilio, and Canto (2013) demonstrated an example of the measurement of response latencies with this microcontroller board.

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