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SEMANTIC PREVIEW BENEFIT IN EYE MOVEMENTS DURING READING:

A PARAFOVEAL FAST-PRIMING STUDY

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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

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

When we read a text, we sample the visual input during a sequence of fixations, connected by rapid, jump-like eye movements called saccades. It is an important psychological question how our cognitive and oculomotor systems interact during this sequential sampling process. 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, White, Kambe, Miller, & Liversedge, 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, Richter, Shu, & Kliegl, 2009). There is, however, no undisputed evidence that *semantic* information can be processed parafoveally in alphabetic scripts (Rayner et al., 2003, for a review; see also below). 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 presenting 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).

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* (PB) 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*[1] and *n*+1 no overlapping visual features are required. For example, alternating the case between fixations (McConkie & Zola, 1979; Rayner, McConkie, & Zola, 1980) or change of letter positions (Johnson, 2007; Johnson, Perea, & Rayner, 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 a very effective parafoveal preview (Balota, Pollatsek, & Rayner, 1985; Inhoff, 1989a; Rayner, 1978; Rayner et al., 1982; Rayner et al., 1980; Rayner, McConkie, & Ehrlich, 1978).

Aside from orthographic codes, phonological information (i.e., the sound of a word) can also be processed parafoveally (Ashby, Treiman, Kessler, & Rayner, 2006; Chace, Rayner, & Well, 2005; Henderson, Dixon, Peterson, Twilley, & Ferreira, 1995; Miellet & Sparrow, 2004; Pollatsek, Lesch, Morris, & Rayner, 1992). Strong evidence for the existence of phonological parafoveal processing comes from studies by Ashby and colleagues (Ashby, 2006; Ashby & Martin, 2008; Ashby & Rayner, 2004) 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, 1989b; 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, Kambe, Pollatsek, & Rayner, 2001; Hyönä & Häikiö, 2005; Rayner, Balota, & Pollatsek, 1986; Rayner et al.; 1980). Rayner 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.

The three other studies cited above used the boundary paradigm 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.

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. 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, Bertram, and Hyönä (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 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, Murray und Boissiere, 2004; Murray, 1998; Murray and Rowan, 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, Starr, and Greenberg (2000) did find some evidence for semantic *parafovea-on-fovea 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, and Shindler (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.

Priming studies

Although the work of Altarriba et al. (2001), Rayner 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, Longoni, & Zoccolotti, 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 and disappears after 30 to 150 ms followed by a short ISI 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 employing the boundary paradigm? Earlier results of this kind (Bradshaw, 1974; Marcel, 1978) were criticized for various methodological problems (Inhoff, 1982; Inhoff & Rayner, 1980; 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, etc.) 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.

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, Inhoff, Slowiaczek, & Bertera, 1981; Rayner & Pollatsek, 1981). For example, Rayner et al. (1981) masked visual information within a window of seven or seventeen 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 of 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.

Time course of semantic information extraction

As reviewed above, so far there have been no reports 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. 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, studies employing the fast priming paradigm (Ashby & Rayner, 2004; H. Lee, Kambe, Pollatsek, & Rayner, 2005; H. Lee et al., 1999; H. Lee, Rayner, & Pollatsek, 2002; Y. Lee, Binder, Kim, Pollatsek, & Rayner, 1999; Rayner, Sereno, Lesch, & Pollatsek, 1995) indicate 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.

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 hypothesize this might also be true for the semantic properties of a parafoveal word. One problem with using 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 non-significant results in earlier boundary experiments.

To our knowledge, no study so far has examined semantic preview benefit 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*, respectively (see Figure 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 include 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., Henderson & Ferreira, 1990; Kliegl, Nuthmann, & Engbert, 2006).

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, respectively. 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.

Method

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.

Apparatus

Subjects were seated with a distance of 60 cm (23.62 in.) in front of an Iiyama Vision Master Pro 514 Monitor (1024 x 786 pixels; 53.34 cm [21 in.]; vertical refresh rate 150 Hz; font: Courier New bold). 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. The experiment was run in MATLAB (The Mathworks, Natick, USA) 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, Ontario, 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.

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 the pretarget and target words were all between 4 and 8 letters long to maximize single-fixation probabilities. All frequency-norms are based on the DWDS corpus (Geyken, 2007; Heister et al, in press; 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 1 reports details about these frequencies for target words and related and unrelated primes.

Foveal pretarget words. Pretarget words were between 4 and 8 letters long and of high type frequency (range: 84 to 6552 per million) to increase the possibility of having a broad perceptual span and gaining information from the parafoveal target word. Mean (standard deviation) of the base-10 logarithmic frequency was 2.5 (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 used 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 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, 2006), and the rest (46 %) was selected by the first author. Six persons independently rated them as semantically related, i.e. 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 ISI 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. Unrelated primes were constructed using three criteria: (1) same length as the target word, (2) identical overlap of characters with the target word as the related prime and (3) minimizing the frequency differences between related and unrelated prime. 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 characters *e* at second and *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 will occur on a noun. Training sentences also contained target words of different word classes.

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.

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 two 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 was answered by clicking on one of the response alternatives. A large portion of questions required comprehension at the semantic level, rendering 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 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 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 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 1c). The sentence remained in this final form until the end of the trial (Figure 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*.

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 %). 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 %).

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 duration, which was 125 ms in the D125 condition, a lower level cutoff of 125 ms was adopted. 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

The experimental conditions (two prime types x three prime durations) were analyzed 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). Refixation and skipping were analyzed 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 ANOVAs (F1 and F2); 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 & Mächler, 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.

Results

Pretarget word

Table 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, neither 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.

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, i.e. the value of *b* is the mean increase in the dependent variable (e.g., ms of fixation duration) given an increase of 1 ms in prime duration. In summary, the later parafoveal display changes occurred at word *n*+1, the faster the saccade program originating from word *n* was executed.

Target word

Table 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 1804 observations.

Figure 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, 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).

Refixation rate of target words was relatively low at 11%. The refixation rate was a significant 4% higher for unrelated than 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 non-significant 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 ($|z|s < 1.4$).

Finally, we analyzed 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, trials were included 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 left and right eye, respectively. The focus of this study is on 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.

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 was numerically in the expected direction also 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.

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 shorter 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, Carr, & Wilhelmsen, 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 in Sereno and Rayner’s second experiment as well as by Sereno (1995) and H. 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 close to 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 using prime durations through 60 ms (H. 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 to foveal fast-priming experiments (H. 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 that 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.

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 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 match Inhoff et al.'s results also 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 rate probability after fixating the target word, but regression rates (15 %) did not differ with respect to prime duration ($|z|$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 conditions in which the target was delayed for 70 ms and 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 are important enough to warrant a second experiment that establishes their stability.

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[2].

Method

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.

Material

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

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.

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.

Results and Discussion

Pretarget word

Table 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).

Target word

Table 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. Like in Experiment 1, the probability of target skipping was low, that is 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).

Figure 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).

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 0.46 and thus slightly left from the target-word center. Along the six experimental conditions there was a narrow range from 0.44 to 0.49 and none of the prime contrasts was significant ($|t|$s < 0.9) but landing position was significantly shifted rightwards with increasing prime duration ($b = 0.0004$, $SE = 0.0001$, $t = 3.3$, for the overall linear trend).

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 evaluate 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 to 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).

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 raised 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, 21 ms). Since this pattern revealed a non-significant 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, Experiment 3 was designed to facilitate visual information uptake from the prime word by presenting the primes in bold face whereas all other parts of the sentences – targets and sentence frames – were presented in normal face. We assumed that a parafoveal word appearing in bold face would be more salient than the preceding and succeeding words. Therefore, we expected the parafoveal prime would enhance the semantic preview benefit for succeeding fixations(s) on the target presented in normal face.

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), 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.

Method

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.

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.

Procedure

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

Data analysis

Data analysis 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.

Results and Discussion

Pretarget word

Table 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 ($|t|\text{s} < 1.39$).

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).

Target word

Table 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, that is only 3.3%. None of the contrasts was significant (|z|s < 1.21).

Target gaze durations are shown in Figure 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).

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).

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 0.45 and thus slightly left from the target-word center. Between the six experimental conditions there was a narrow range from 0.44 to 0.47 and none of the contrasts was significant (|t|s < 1.2).

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 refixation rate was also significantly higher for related than for unrelated primes. The differences in the profiles between the two experiments are suggestive of 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[3].

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 is 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 (see below). Thus, irrespective of preview kind – 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 by presenting it in a different typeface did not disrupt the general reading process by prematurely attracting 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 even is for real. To put this speculation on solid ground, it seemed advisable to consolidate our knowledge of the early effect in a new experiment.

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, it is 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 allows us to investigate early priming effects under multiple conditions extending the debatable one (35 ms) from Experiment 1.

Method

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.

Material

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

Procedure

The experimental procedure differed from the one of 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.

Data analysis

Data analysis also followed the procedure described for Experiment 1. Since in Experiment 3 the maximum prime duration 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.

Results and Discussion

Pretarget word

Table 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).

Target word

Table 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, that is only 3.1%. None of the priming contrasts or prime duration trends was significant (|*z*|s < 1.5).

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 5).

First-fixation durations showed a numerical, but non-significant 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.

Mean landing position was 0.43 and thus slightly left from the target-word center. Along the six experimental conditions there was a narrow range from 0.42 to 0.44 and none of the contrasts was significant (|*t*|s < 1.44).

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.

GENERAL DISCUSSION

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 of this, the visual parafoveal information guiding the saccade program differs from the visual foveal information obtained after the saccade finished. This might cause disturbance in the visual system since the mismatch between pre- and post-saccade 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 where 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. Importantly, 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 timeframe. In contrast, the parafoveal fast-priming paradigm employed in the present study affords a detailed analysis of the time course of parafoveal processing.

Semantic preview benefit is time dependent and depends on 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 between 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 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 keeps constant and thus the related priming effect is no longer present. H. 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.

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 employing the fast-priming paradigm (H. Lee et al., 1999; Sereno, 1995; Sereno & Rayner, 1992) found 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 primary due 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 very 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 producing 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 (1986) found that since conscious awareness of primes depends on the subject, the subjective threshold necessary to produce priming effects could vary widely between subjects. To estimate the degree to which the priming effects in our Experiments can be generalized, we analyzed individual differences in the effect trends. For this purpose, we ran 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.

Timeline of parafoveal information extraction

Based on 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, less linguistic information could be obtained 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 35-ms and 80-ms delay of the target word. Furthermore, Experiment 4 showed that differences emerge already between delays of 20 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 Experiment1 provides some support for the first explanation.

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, Rayner, & Pollatsek, 2003; Reichle et al., 2006; 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 (L1) starts. In this stage, frequency and predictability of a word has an influence. The finishing 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 (L2) in which the meaning of a word is extracted. When L2 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 when assuming very short processing and attention shift stages, serial processing will 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 finished 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, it must also be recognized that it is highly unlikely that any of the available PG models would correctly reproduce the current pattern of results in their current implementation.

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. Based on our results, 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 showing 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.

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TABLES

Table 1. Mean (M) and standard deviation (SD) of the untransformed and the $\log_{10}$ lemma frequencies for target words, related primes (RP), and unrelated primes (UP) as well as 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)

Table 2. Means (M) and standard deviations (SD) 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.

Table 3. Means (M) and standard deviations (SD) 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.

Table 4. Means (M) and standard deviations (SD) 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.

Table 5. Means (M) and standard deviations (SD) 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.

Table 6. Means (M) and standard deviations (SD) 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.

Table 7. Means (M) and standard deviations (SD) 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.

Table 8. Means (M) and standard deviations (SD) 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.

Table 9. Means (M) and standard deviations (SD) 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.

FIGURE CAPTIONS

Figure 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 and arrows indicate fixations and saccades, respectively. Translation: “With the excavation skulls/bones had shown up.“ Unrelated prime: “Stiefel“ (“boots“).

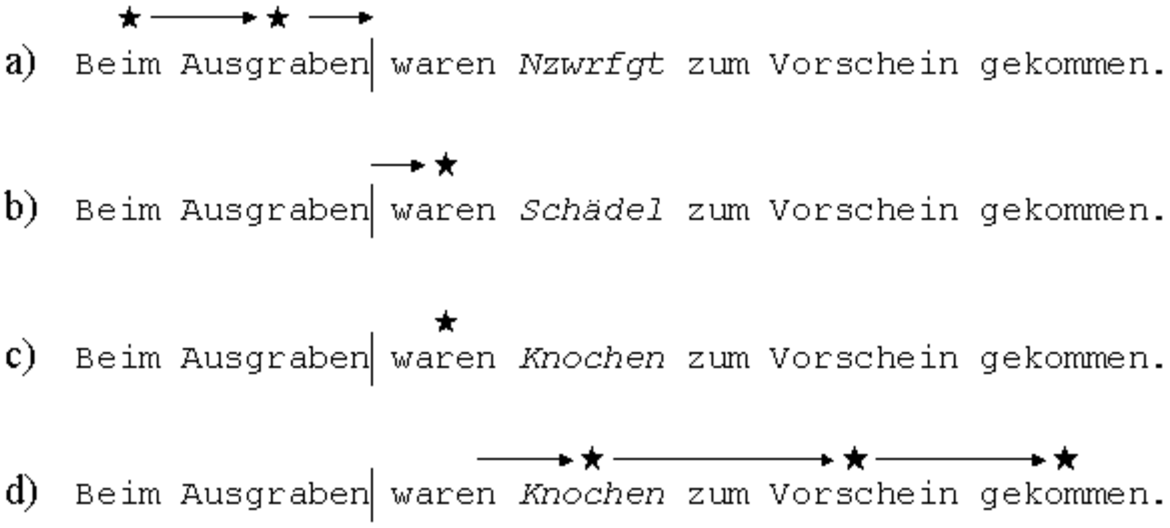
Figure 2. Gaze duration on the target word as a function of prime and prime duration (Experiment 1). Error bars denote standard errors computed from the residuals of the LMM, that is after removal of between-subject and between-item random effects.

Figure 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.

Figure 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.

Figure 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.

Figure 1



a) Beim Ausgraben| waren *Nzwrfgt* zum Vorschein gekommen.

b) Beim Ausgraben| waren *Schädel* zum Vorschein gekommen.

c) Beim Ausgraben| waren *Knochen* zum Vorschein gekommen.

d) Beim Ausgraben| waren *Knochen* zum Vorschein gekommen.

Figure 2

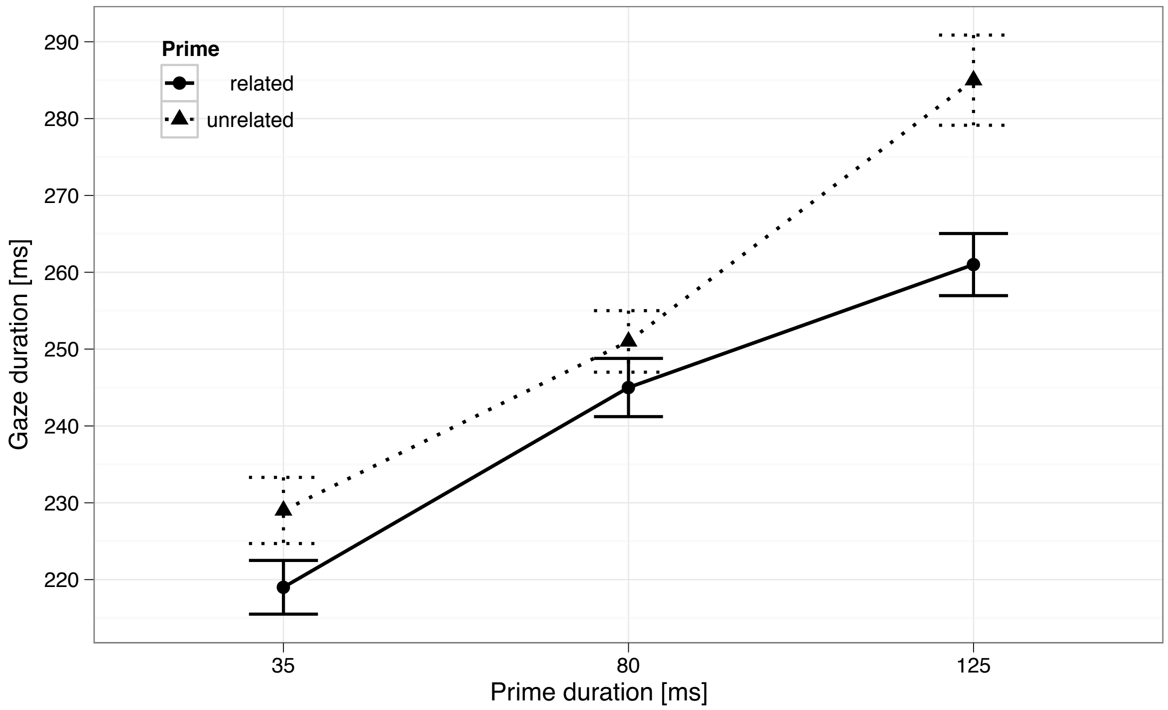

Prime
related
unrelated
Gaze duration [ms]
290
280
270
260
250
240
230
220
35
80
125
Prime duration [ms]

Figure 3

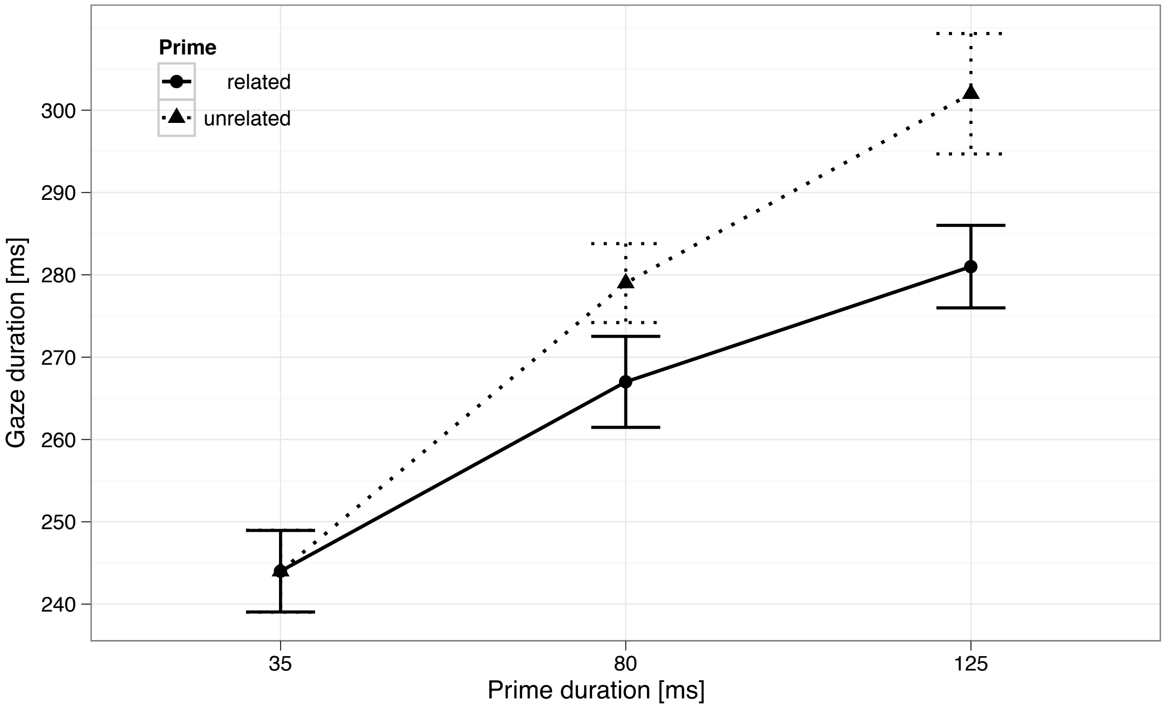

Prime
related
unrelated
Gaze duration [ms]
300
290
280
270
260
250
240
35
80
125
Prime duration [ms]

Figure 4

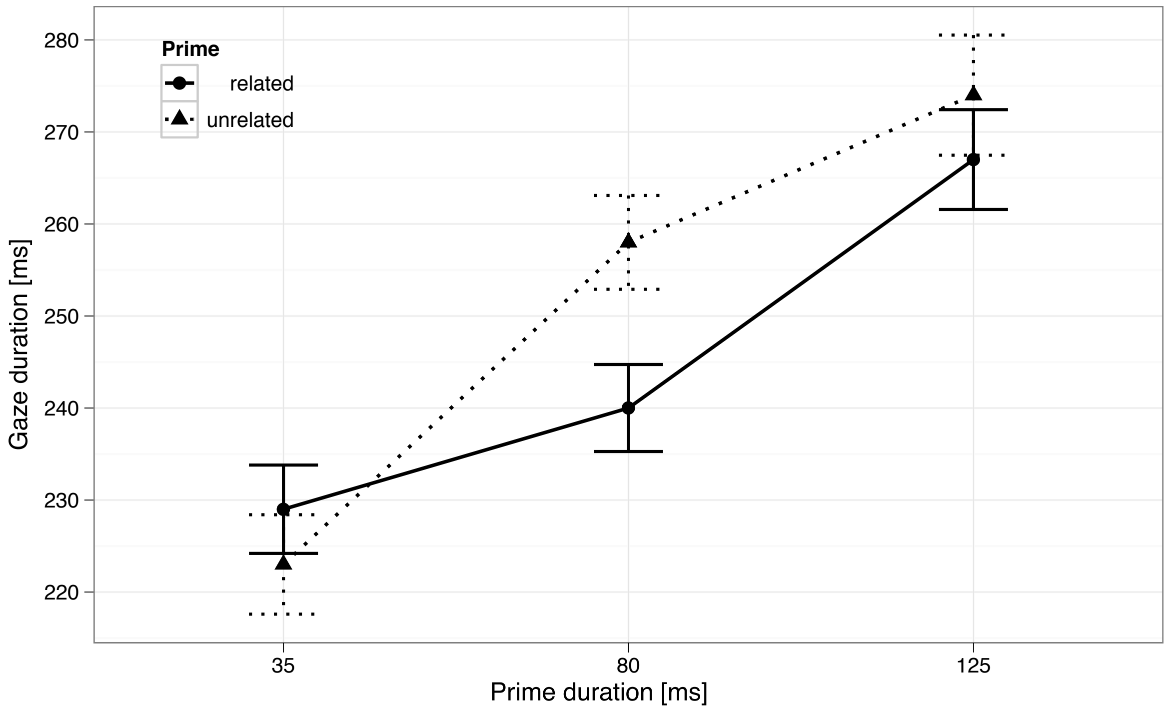
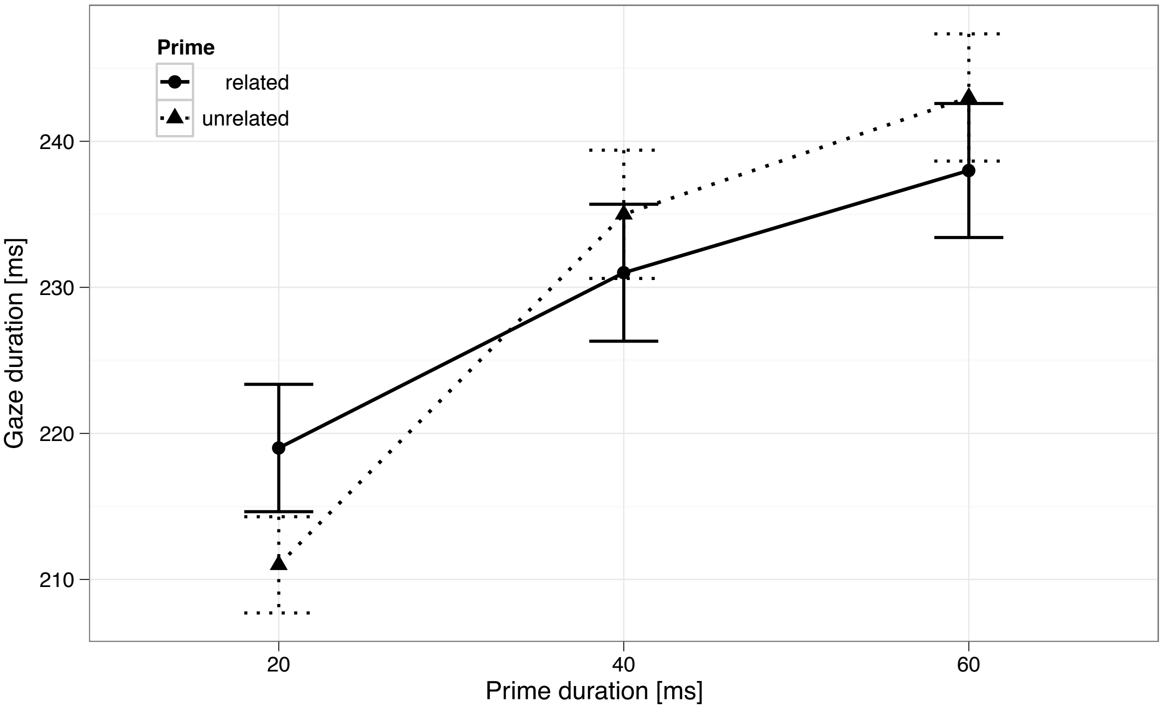

Prime
related
unrelated
280
270
260
250
240
230
220
Gaze duration [ms]
35
80
125
Prime duration [ms]

Figure 5


Prime
related
unrelated
Gaze duration [ms]
240
230
220
210
20
40
60
Prime duration [ms]

FOOTNOTES

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[1] 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.

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

[3] 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 non-significant 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.