Trans-saccadic parafoveal preview benefits in fluent reading:
A study with fixation-related brain potentials

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ABSTRACT

During natural reading, a parafoveal preview of the upcoming word facilitates its subsequent recognition (e.g., shorter fixation durations compared to masked preview) but nothing is known about the neural correlates of this so-called preview benefit. Furthermore, while the evidence is strong that readers preprocess orthographic features of upcoming words, it is controversial whether word meaning can also be accessed parafoveally. We investigated the timing, scope, and electrophysiological correlates of parafoveal information use in reading by simultaneously recording eye movements and fixation-related brain potentials (FRPs) while participants read word lists fluently from left to right. For one word – the target – (e.g., "*blade*") parafoveal information was manipulated by showing an identical ("*blade*"), semantically related ("*knife*"), or unrelated ("*sugar*") word as preview. In *boundary trials*, the preview was shown parafoveally but changed to the correct target word during the incoming saccade. Replicating classic findings, target words were fixated shorter after identical previews. In the EEG, this benefit was reflected in an occipitotemporal *preview positivity* between 200-280 ms. In contrast, there was no facilitation from related previews. In *parafoveal-on-foveal* trials, preview and target were embedded at neighboring list positions without a display change. Consecutive fixation of two related words produced N400 priming effects, but only shortly (160 ms) after the second word was directly fixated. Results demonstrate that neural responses to words are substantially altered by parafoveal preprocessing under normal reading conditions. We found no evidence that word meaning contributes to these effects. Saccade-contingent display manipulations can be combined with EEG recordings to study extrafoveal perception in vision.

INTRODUCTION

Readers sample each line of text with a series of eye fixations connected by rapid, jerk-like eye movements (EMs), called saccades. While useful visual input is only obtained during fixations (typically lasting 180-250 ms), saccades serve to move new text into the fovea, the central part of the visual field, covering 1-2°. The sharp drop-off in retinal acuity outside the fovea and visual crowding (Pelli et al., 2007) limit the amount of information that readers can extract from parafoveal and peripheral words (Rayner, 1998).

The question of how much information readers extract at which point in time from not-yet-fixated words is a central issue in reading research (Rayner, White, Kambe, Miller, & Liversedge, 2003). Over the last 35 years, eye tracking studies have gathered strong evidence that readers take up information not only from the currently fixated word, but also from upcoming words in the direction of reading (McConkie & Rayner, 1975; Rayner, 1975). While these studies suggest that extrafoveal preprocessing is a fundamental aspect of word recognition under natural reading conditions, the brain correlates of reading have almost exclusively been studied in the absence of oculomotor behavior and parafoveal information (Kutas, Van Petten, & Kluender, 2006). Consequently, little is known about the neural dynamics of the actual reading process and the impact of parafoveal preprocessing on brain systems involved in word recognition (Sereno & Rayner, 2003).

Furthermore, while there is general agreement that readers extract some information from upcoming words, it is controversial whether preprocessing is limited to low-level features and sub-lexical information or whether it extends to lexico-semantic properties. The present study investigated the electrophysiological correlates and scope of parafoveal processing in fluent reading by combining a recently established method for EEG analysis - the recording of fixation-related potentials (FRPs, Dimigen, Sommer, Hohlfeld, Jacobs, & Kliegl, 2011) – with experimental techniques from eye movement research.

Eye tracking studies on parafoveal processing have mostly used the *Boundary Paradigm* (Rayner, 1975). In this paradigm, one target word in a sentence (henceforth called word n+1) is masked by an uninformative preview string, for example an unrelated word of the same length. Only during the saccade from the preceding word n to word n+1, once the eyes cross an invisible boundary on the screen, the preview is changed to the correct target word. Because visual thresholds are elevated during saccades (Ishida & Ikeda, 1989; Matin, 1974) readers usually remain unaware of this manipulation (Slattery, Angele, & Rayner, 2011).

The benchmark finding obtained in this paradigm is the *identity preview benefit*: After valid (identical) previews, target fixations are 20-50 ms shorter than after uninformative previews. By varying the preview-target relationship, EM studies have shown that readers still benefit from preview when the word's visual features change during the saccade (i.e., the preview "ROUGH" facilitates "rough"; Inhoff, Starr, & Shindler, 2000; McConkie & Zola, 1984; Rayner, McConkie, & Zola, 1980) or when preview and target are not in the exact same physical location (Rayner, McConkie, & Ehrlich, 1978). This suggests that the benefit is not primarily based on a trans-saccadic fusion of visual low-level features. Instead, it has been proposed that readers extract more sparse and abstract representations, in particular case-independent letter identities and orthographic codes from the initial two or three letters (Rayner, 1998; Rayner et al., 2003) of the upcoming word. In addition, some benefit is observed after phonologically related (homophone) previews (Chace, Rayner, & Well, 2005; Henderson, Dixon, Petersen, Twilley, & Ferreira, 1995; Pollatsek, Lesch, Morris, & Rayner, 1992).

A neural correlate of trans-saccadic preview benefit?

Studies with event-related potentials (ERP) have investigated visual word recognition in great detail (Barber & Kutas, 2007; Kutas et al., 2006; Pulvermüller, Shtyrov, & Hauk, 2009) but rarely during actual fluent reading. Instead, stimuli are usually presented as a comparatively slow stream of isolated words while subjects fixate the screen center. In natural reading, on the other hand, typical preview benefits correspond to a reduction of 5 to 25% of the fixation time spent on a word. Assuming that fixation times are a reasonable approximation of the duration of the underlying word recognition process, this suggests that preview could have a profound impact on the time course and morphology of psycholinguistic ERPs.

The first goal of the present study was therefore to identify an EEG correlate of the preview benefit present under fluent reading conditions. The EM literature affords several hypotheses about functional loci and neural correlates of the identity preview benefit. Given its reported robustness against changes in low-level features, we hypothesized that EEG effects should not primarily manifest on the earliest stages of visual processing (up to and including the visual P1 component, peaking at around 100 ms). Instead, preview might modulate the N400, a centroparietal-negative ERP component sensitive to various types of foveal priming, including masked priming by full or partial word repetitions (Holcomb & Grainger, 2006, 2007). However, with a peak around 400 ms, the N400 seems to occur too late to be a neural equivalent (i.e., a causal predecessor) of changes in oculomotor measures

(Dimigen et al., 2011; Rayner & Clifton, 2009), because EM benefits are already observed during the first fixation on a previewed word (e.g., Rayner, Balota, & Pollatsek, 1986; White, Rayner, & Liversedge, 2005). This led us to hypothesize that (a) some neural correlate of preview should be measurable within a typical fixation duration (i.e., within 180-250 ms or less, considering delays needed to program the next saccade) and (b) identity previews might influence ERP components in a middle latency range - such as the occipitotemporal N1 component - which are often linked to mid-level vision, orthographic processing, and early word form processing in the ventral stream.

Do readers access parafoveal word meaning?

Whereas benefit has been demonstrated for orthographically and phonologically related previews, there is debate whether readers also extract semantic codes parafoveally (Rayner et al., 2003). In such a case, readers should benefit from semantically associated parafoveal prime words (e.g., the preview "tune" should shorten subsequent fixations on "song"). Recently, evidence for such semantic preview benefit was reported for reading Chinese (Yan, Richter, Shu, & Kliegl, 2009) and German (Hohenstein, Laubrock, & Kliegl, 2010). Furthermore, there is evidence for semantic preview benefit between the constituents of long Finnish compound words (White, Bertram, & Hyönä, 2008). However, other boundary studies found no changes in fixation time following semantically related previews (Altarriba, Kambe, Pollatsek, & Rayner, 2001; Rayner et al., 1986) or previews consisting of emotionally arousing "shock words" (Hyönä & Häikiö, 2005). The existence of a semantic preview benefit and the boundary conditions under which it occurs therefore remain controversial[1].

ERPs are highly sensitive to semantic priming (Kutas & Federmeier, 2011) and the issue of parafoveal semantics has been investigated in several stimulus-locked ERP studies. Importantly, these studies did not use display changes but tested for *parafoveal-on-foveal* effects (POF, Kennedy, Pynte, & Ducrot, 2002). In principle, if parafoveal information becomes rapidly accessible, features of an upcoming target word could also be reflected in fixation times or EEG measures while the eyes still rest on the word *before* the target. A POF effect is therefore defined as any influence of the properties of the next word *n*+1 that arises while the reader is still fixating word *n*. Therefore, the boundary paradigm investigates the *consequences* of having had a preview for a given word that is now being fixated, whereas

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[1] The fact that readers often skip short function words (e.g. "the") demonstrates that words can be identified without a direct fixation if they are fully predictable from the context. It is controversial whether readers extract semantics from parafoveal content words that are subsequently fixated (rather than skipped, see Rayner et al., 2003 for a discussion) and only such cases are analyzed here.

POF effects reflect immediate influences of information about a word that is still in the parafovea on the processing of the currently fixated word. These different but complementary approaches can be combined to obtain a full picture of preprocessing effects.

Like EM studies, ERP studies have produced partially conflicting results. Two studies (Baccino & Manunta, 2005; Simola, Holmqvist, & Lindgren, 2009) presented word pairs that were associated or non-associated in meaning. The first word was presented in the screen center, flanked parafoveally by the second word. ERPs were time-locked to word pair onset and analyzed up to the moment that participants initiated a saccade to the parafoveal word. Baccino and Manunta reported an effect of semantic association on the ERP within 215 ms after stimulus onset (but found no effect on behavior), indicating that parafoveal word meaning was retrieved to some extent. However, Simola and colleagues did not replicate a semantic POF effect under similar conditions.

Another recent approach has been to adapt traditional serial visual presentation (SVP) by moving a whole sentence word-by-word across the screen while participants keep a central fixation (Barber, Ben Zvi, Bentin, & Kutas, 2010; Barber, Donamayor, & Kutas, 2010). Interestingly, this paradigm revealed congruency effects in the ERP when a parafoveal word mismatched a highly predictive sentence context (Barber, Van der Meij, López-Perez, & Kutas, 2011, see also Kretzschmar, Bornkessel-Schlesewsky, & Schlesewsky, 2009). However, this congruency effect is not necessarily semantic in nature, since strong expectancies (and slow presentation speeds in some of the studies) may have allowed participants to determine the contextual fit of the upcoming word based on partial orthographic information. More generally, it is difficult to generalize results from SVP to fluent reading. While participants in SVP studies have no incentive to shift or bias attention towards extrafoveal regions, readers shift attention to the saccade target as a part of oculomotor preparation (Hoffman & Subramaniam, 1995). On the other hand, stimulus on- and offsets in SVP can artificially increase the salience of parafoveal words.

Present study

A novel approach that bridges the methodological gap between EM and EEG studies is to align the EEG signal to fixation onsets in free viewing situations. Importantly, the technical and data-analytical challenges associated with this technique (e.g., corneoretinal artifacts, overlapping potentials) can be addressed by a combination of correction methods and careful post-hoc analyses (see Dimigen et al., 2011 for a review) and large psycholinguistic effects in the N400 time range have already been successfully replicated in

fixation-related potentials (Dimigen et al., 2011; Hutzler et al., 2007; Kretzschmar et al., 2009; see also Marton, 1991).

In the present study we used FRPs to test the impact of identity previews and semantic previews on word recognition during fluent reading. Participants read lists of German nouns at their own pace from left to right. For one word in the list (e.g. "Frau", *woman*) parafoveal information was manipulated by showing one of three alternative previews: a valid identical preview ("Frau"), a semantically related preview (e.g. "Dame", *lady*), or an unrelated preview (e.g. "Wald", *forest*). Effects were analyzed simultaneously in fixation times and FRPs and both as preview benefits and as POF effects. The resulting 3×2 design is illustrated in Figure 1: Half of the trials used the boundary paradigm. A classic EM benefit with as yet unknown correlates in the EEG was expected after identical previews as compared to unrelated ones. In addition, any difference in behavior or EEG following related versus unrelated previews would support the existence of semantic preview benefit. The other half of trials used the POF paradigm. Here, preview and target were simply embedded at neighboring list positions (again called *n* and *n*+1) without a display changes (Baccino & Manunta, 2005; Simola et al., 2009). If meaning is extracted parafoveally, a semantic relation between word *n* and *n*+1 should influence fixation times or FRPs while the reader is still looking at word *n*. In any case, FRPs should reveal the exact point in time when word meaning becomes available to the reader.

METHOD

Participants. Thirty-five participants (24 woman, age 19 to 36, $M = 24.4$ years) entered the analyses. Data of one additional participant was excluded because of EEG voltage drifts. Participants were native German speakers with uncorrected vision and normal acuity (as tested prior to the experiment; Bach, 1996). According to Oldfield's (1971) questionnaire, 31 participants were right-handed and four were ambidextrous (laterality quotient: $M = +88$). Participants received 20 €or course credit for participation.

General task. To approximate a normal reading flow, target words and their previews were embedded in lists of other nouns, here called "fillers". The reading of word lists (Hutzler et al., 2007; Kennedy et al., 2002; Schroyens, Vitu, Brysbaert, & d'Ydewalle, 1999) offers excellent control over behavioral covariates (e.g. incoming saccade amplitude, Dimigen et al., 2011) that can complicate FRP analysis during sentence reading. Each list consisted of five words. The task of the participant was to indicate after each trial whether or not the list contained the name of an animal (see *Procedure* for details). This semantic

decision (e.g., Grainger, Kiyonaga, & Holcomb, 2006) discourages superficial scanning strategies and ensures that participants read for understanding.

Construction of word lists. Filler words were drawn from a pool of 1,248 German nouns with four to six letters ($M = 5.2$, $SD = 0.8$). Their mean type frequency, retrieved from the 100-million word DWDS corpus (accessible via http://dlexdb.de; Heister et al., 2011) was 12.3 per million ($SD = 38.0$). Preview manipulations occurred at two possible locations within the five-word list. In boundary trials, word $n+1$ was located at list position two or four; the preceding filler at position one or three, respectively, functioned as word n (i.e., as the word from which the preview on word $n+1$ is obtained). Please note that the labels n and $n+1$ therefore only refer to the relative positions of the two critical words within a given list, regardless of their absolute list positions. To facilitate parafoveal processing (Henderson & Ferreira, 1990), the filler word at position n was at least of medium frequency ($M = 46.3$, $SD = 73.3$). Its length was equiprobably four, five, or six letters ($M = 5.0$).

In POF trials, words n and $n+1$ were embedded either at positions two and three or at positions four and five in the list (thereby replacing the filler word at position n). The relevant word to investigate preprocessing effects ($n+1$ in boundary trials, n in POF trials) was therefore always located at list position two or four. Please note that in POF trials with an identical preview, the same word was repeated at positions n and $n+1$.

Preview-targets pairs. The basis for the construction of target nouns and their preview nouns was a set of 312 pairs of semantically associated German nouns (e.g. "Frau" – "Dame", *woman – lady*; or "Wald" – "Baum", *forest – tree*). Pairs were selected from a larger set of pairs after a semantic rating (see below). The nouns of each pair had the same length (between 4-7 letters, $M = 5.4$) and were either synonyms, associatively related, conceptually related (e.g., part-whole relation), or both associatively and conceptually related. Additionally, pairs included a few strongly associated antonyms (e.g., "Ebbe" – "Flut", *ebb tide - high tide*). Mean word frequency was 31.6 ($SD = 54.0$) for previews and 19.2 ($SD = 40.1$) for targets. A full list of pairs is provided in Appendix A.

From these 312 related pairs, 312 unrelated pairs were created by exchanging the previews of two pairs with the same word length, yielding two new pairs without noteworthy semantic associations *(woman – tree, forest – lady).* In the identical preview condition, the target word served as its own preview *(tree – tree*, *lady – lady).* Thus, for example, the target word *lady* had *woman/forest/lady* as possible previews and *tree* had *forest/woman/tree* as previews (in German all of these words have the same length). In the following, such a set of

two related word pairs, their two unrelated recombinations, plus their identical previews is called "preview-target unit".

Table 1. **Similarity measures for related and unrelated preview-target pairings**

Similarity measure	related	unrelated	*p*	
Semantic				
Association rating (*N*=15)	4.50	1.52	0.00	***
Mutual Information (log10)	5.12	4.71	0.00	***
Visual				
Letters with matching stroke direction (%)	66	66	0.77	*n.s.*
Visual confusability, letter 1	0.26	0.26	0.92	*n.s.*
Visual confusability, letters 2 & 3	0.07	0.06	0.65	*n.s.*
Visual confusability, mean of all letters	0.11	0.11	0.53	*n.s.*
Orthographic (position-specific)				
Same letter 1 (%)	0	0	--	*n.s.*
Same letter 2 (%)	8	8	1.00	*n.s.*
Same final letter (%)	15	15	0.89	*n.s.*
Hamming distance	4.89	4.89	1.00	*n.s.*
Orthographic (position-invariant)				
% of bigrams shared	11	10	0.74	*n.s.*
% of trigrams shared	1	1	1.00	*n.s.*
Dice's coefficient (bigram-based)	0.04	0.04	0.78	*n.s.*
Phonological				
Same phoneme 1 (%)	0	0	--	*n.s.*
Same phoneme 2 (%)	3	4	0.25	*n.s.*
Same final phoneme (%)	15	15	0.89	*n.s.*
Levenshtein distance (phoneme-based)	4.63	4.68	0.44	*n.s.*

Notes: Given are means across words. Similarity measures and the matching procedure are explained in Appendix A.

Semantic rating. In a pre-experiment, all pairs of the preview-target units were rated for association strength. Fifteen native German-speaking university students (13 women, *M* = 27.4 years, range: 20-43 years) used a scale from 1 to 5 on a keyboard to indicate how related both words are. In each trial, the two nouns appeared next to each other on the midline of the screen in the same font as in the experiment proper. Related and unrelated pairings were

presented in random order and participants were asked to give their first, spontaneous impressions (mean RT = 2.2 s).

With a mean score of 4.50 (*SD:* 0.34), related pairs were rated as significantly more related than their recombinations, $t(311) = 129.1$, $p < .0001$, which received a mean score of 1.52 (*SD*: 0.26). In addition, all preview-target units fulfilled the following criteria: (1) both related pairs scored > 3.5, (2) both unrelated pairs scored < 2.5, and (3) the two related differed from the two unrelated pairs by > 1.5 points.

As an additional measure of semantic association, we computed collocation norms for all pairs from the DWDS corpus. The resulting measure, *Mutual Information* describes the likelihood that two words co-occur within the same sentence of a text corpus. As expected, Mutual Information (logarithmized to base 10) was higher for related than for unrelated pairs, $M = 5.12$ vs. 4.71, $t(311) = 10.5$, $p < .0001$.

Non-semantic matching. For the experiment, it is crucial that any differences between the related and the unrelated preview condition can be unambiguously attributed to semantic processing. Since both conditions used the same words, lexical properties such as word frequency were matched. Nevertheless, it is possible that semantically related words are more similar to each other than unrelated words on visual, orthographic, phonological, or syntactic dimensions. To rule out priming based on non-semantic properties, preview and target never started with the same letter or phoneme. In addition, related pairs were matched to unrelated pairs on 19 non-semantic measures of word similarity (see Table 1, see also Appendix A for details).

Balancing. To avoid word repetition, a given participant was presented either with the two related (*Frau-Dame* and *Wald-Baum*), the two unrelated (*Frau-Baum* and *Wald-Dame*), or the two identical combinations (*Dame-Dame* and *Baum-Baum*) of a given unit. These two pairings viewed by a given participant were embedded in different lists of fillers. As a result, no filler, preview, or target was ever repeated during the experiment (except, of course, for the immediate word repetition in POF trials with an identity preview).

Lists were constructed with the aim of minimizing orthographic, phonological, and semantic overlap between fillers and the embedded words of the preview-target unit. Fillers never started with the same letter and were orthographically dissimilar (all Dice coefficients < 0.5; Lambert, Donderi, & Senders, 2002) to the words of the embedded preview-target unit. Furthermore, high collocation values between fillers and previews/targets were avoided. Across participants, it was balanced whether a particular list was presented in the related, identical, or unrelated condition, whether it was shown in the boundary or POF paradigm,

and whether the manipulation occurred at the early or late list position. During the experiment, lists belonging of all experimental conditions were presented randomly intermixed (i.e., boundary trials and POF trials were also intermixed).

Animal lists. Remaining fillers were used to create 60 additional lists which contained the name of an animal equiprobably at one of the five list positions. The embedded animal names had a length of 4-6 letters, a mean lemma frequency of 4 ($SD = 5$), and included both common (e.g., "Schaf", *sheep*) and less common (e.g., "Marder", *marten*) animals (see Appendix A). Except for the embedded animal name, word lists with an animal were indistinguishable from lists used in regular trials. They followed the same design principles, contained the same preview manipulations in the same proportion as regular trials, and were presented randomly intermixed with them.
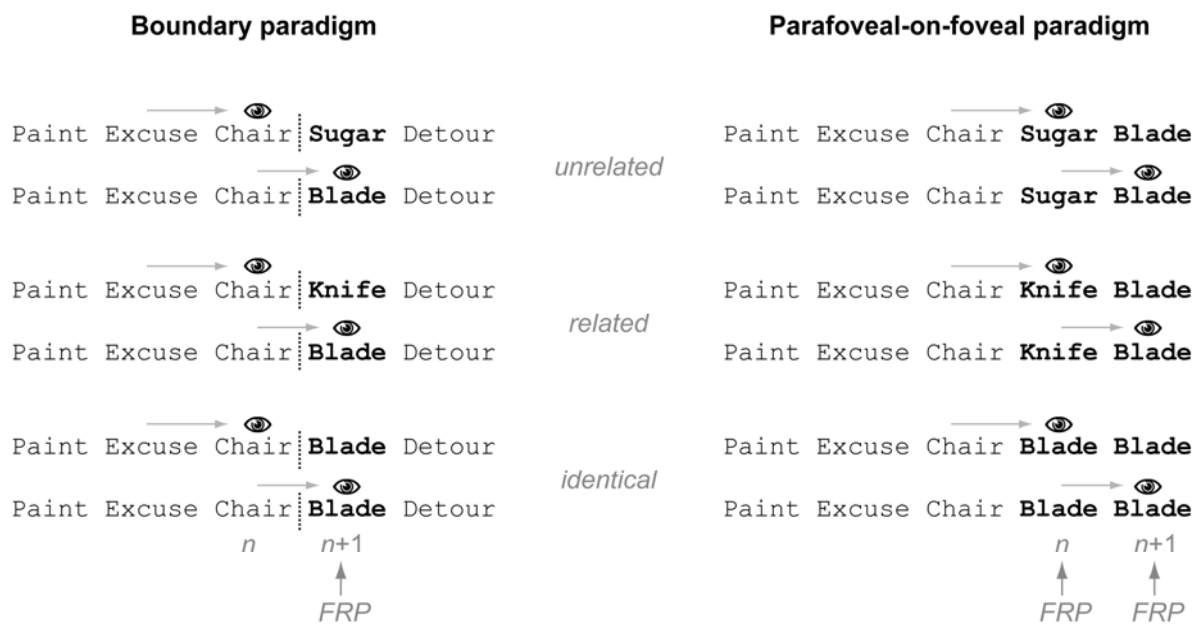

Figure 1. Illustration of paradigms used. Subjects read lists of nouns silently from left to right. Preview was manipulated for one noun, embedded at varying list positions. *Left panel*: In boundary trials, preview was manipulated with a saccade-contingent display change. While participants looked at pre-boundary word *n* (here: *chair*), the parafoveal preview for word *n+1* was unrelated (*sugar*), related (*knife*), or identical (*blade*) to the later target word. During the saccade from *n* to *n+1*, upon crossing an invisible boundary (dashed line), the preview was exchanged to the target (*blade*). Right panel: In *parafoveal-on-foveal* trials, preview and target were simply shown at neighboring list positions. Again, the two words were unrelated (sugar-blade), related (knife-blade), or identical (blade-blade). Labels "FRP" mark fixations used as EEG time-locking points. In the actual experiments, critical words were not highlighted in bold and German nouns were used (here: *Messer/Klinge/Zucker/Bonbon*).

Procedure. After providing written informed consent, participants were seated in a dimly-lit, electrically shielded chamber at a distance of 60 cm from a CRT monitor (22 inch Iiyama VisionMaster Pro 514, resolution: 1024x768 pixels, vertical refresh rate: 160 Hz). The screen was surrounded by a grey cardboard mask, which homogenized the peripheral visual field. In a 15-min block before the experiment proper, the EEG was recorded while participants performed calibration EMs that were later used for ocular artifact correction. Afterwards, participants received instructions that they would read lists of words and should indicate after each trial whether or not the list had contained the name of an animal. Participants were also told that words sometimes occurred twice in a list (in POF trials with identical preview) but that this was irrelevant for the task.

The trial scheme is illustrated in Figure 2A. Trials began with the presentation of a small black point on the left side of the screen. After a fixation on this point was registered, a list of five words appeared on the horizontal midline, together with a second small fixation point on the right side of the screen. Words were separated by one character space and presented in a black monospaced font (Courier) on a white background. One character extended 0.43° horizontally. As required by German orthography, the first letter of each noun was capitalized. From the left fixation point, the distance to the left edge of word one in the list was 3.1° and at least 5.1° to the left edge of word two. The visual angles between the center of word n and the left edge of word $n+1$ varied between 1.29° and 1.94° (depending on the length of word n) with an average of 1.51° ($SD = 0.18$) in boundary trials and 1.56° ($SD = 0.29$) in POF trials.

In boundary trials, the invisible boundary was located in the middle of the space between word n and $n+1$. The average delay between the gaze crossing the boundary and stimulus replacement was 9.7 ms (= 3.5 ms computation time + 3.2 to 9.4 ms [0.5 to 1.5 display cycles] needed for the cathode ray to return to the screen center); this delay was shorter than the duration of the boundary-crossing saccade ($M = 25.1$ ms, $SD = 6.5$). The technical protocol was the same in the identical condition; here, the preview string was exchanged against itself.

Following list onset, participants read the five words, moving their eyes freely over the text. After finishing reading, they looked at the right fixation point. After 500 ms of fixation on this point, a screen appeared which prompted "Animal present? (Y/N)" and participants used two buttons to respond with left or right index fingers.

Participants read six lists for practice and 372 lists during the experiment. Sixty of these 372 lists (16.1%) contained an animal name and were excluded from data analysis. The

remaining 312 lists were analyzed according to the design *preview* (identical, related, unrelated) × *paradigm* (boundary, POF), yielding 52 trials per condition.

Display change awareness was assessed in a structured interview after the experiment. Participants were first asked whether they had noticed "anything strange about the visual display of the text" (White et al., 2005). If they answered "no", they were informed that changes had taken place and asked again whether they had noticed any. If they did, participants were asked to (1) estimate the number of changes perceived, (2) report the identity of some of the preview strings, and (3) report the list positions at which changes had taken place.

EM recording. EMs were recorded binocularly with a video-based eye tracker (IView-X Hi-Speed 1250, SMI GmbH, Germany) at a rate of 500 Hz and an instrument spatial resolution of 0.01°. Head position was stabilized via the chin and forehead rests of the tracker. Tracking quality was controlled with a fixation check at the onset of each trial: After trial onset, if eye position deviated more than 0.5° from the left fixation point or if binocular disparity exceeded ±0.5°, the tracker was recalibrated with a 9-point grid. Calibrations were performed whenever a check failed, but at least after every 30 trials.

EEG recording. The EEG was recorded from 42 Ag/AgCl scalp electrodes and four electro-oculogram (EOG) electrodes placed at standard 10-10 positions and referenced against the left mastoid. EEG electrodes were placed in a textile cap. EOG electrodes were positioned on the infraorbital ridge and outer canthus of each eye. An additional ground electrode was placed at FCz. Signals were amplified with BrainProducts DC amplifiers at a band pass from DC to 100 Hz and sampled at 500 Hz. Impedances were kept below 5 kΩ. Eye track and EEG were synchronized via shared TTL trigger pulses sent from the presentation PC (running *Presentation*, Neurobehavioral Systems Inc., Albany, CA) to both recording computers. Offline, the EEG was band-pass filtered from 0.2-40 Hz and re-referenced against the mean of all electrodes (average reference).

Fixation detection. Trials with blinks, missing data in the eye track, or incorrect manual responses were discarded. In the 96% remaining trials, saccades were detected with the binocular algorithm described in Engbert and Mergenthaler (2006; velocity threshold: 5 *SD*). Small saccades were considered part of a fixation if they spanned less than one character. Position data of the right eye was used to assign fixation locations, but left eye data was used for binocular validation. Fixations on inter-word spaces were assigned to the word to the right.

A total of $n = 77,392$ first-pass reading fixations (that is, excluding fixations following regressive saccades) were detected for all participants. In line with previous studies (Kliegl, Nuthmann, & Engbert, 2006), we removed extremely short (< 50 ms, $n = 108$) or long (> 1000 ms, $n = 197$) fixations and those for which the corresponding EEG segment contained non-ocular artifacts ($n = 1,918$, see below). Only trials were analyzed in which word n received a binocular fixation. This criterion excludes trials where word n was skipped and preview effects are unlikely. In *boundary* trials, only trials were considered in which (1) the display refreshed during the saccade (while visual thresholds are elevated due to retinal blurring and saccadic suppression; Ishida & Ikeda, 1989; Matin, 1974) and (2) both eyes crossed the boundary within 10 ms of each other. Rejected early changes usually occurred because the last pre-boundary saccade landed close to the boundary and saccadic overshoot or system noise triggered the change prematurely. Late changes were usually (in 95% of cases) executed within 10 ms after saccade offset, but were rejected anyway. The same criteria were also applied to the identical preview condition. After the exclusion of all bad trials (due to blinks, missing eye tracking data, non-ocular EEG artifacts, skipped words, incorrect responses, or mistimed display changes), 88% of POF trials ($M = 45.5$ trials per participant and preview condition) and 67% of boundary trials ($M = 34.7$ trials) entered final data analysis.

EM analysis. First-pass fixation behavior was analyzed with three dependent variables: first fixation duration (FFD), single fixation duration (SFD), and gaze duration (GD). FFD is the duration of the first fixation on a word, irrespective of whether the word is subsequently refixated. SFD is fixation duration in case that a word only receives one first-pass fixation. GD is FFD plus the duration of all immediate refixations. One participant had no single-fixation cases in some cells of the design; SFDs are therefore reported for 34 participants in boundary trials.

Ocular artifact correction. Reading saccades introduce two types of EEG artifacts: Large corneoretinal artifacts from rotation of the bulbi (Brunia et al., 1989) and a brief myogenic spike potential at saccade onset (Keren, Yuval-Greenberg, & Deouell, 2010). To correct for corneoretinal artifacts, we applied the surrogate variant of *Multiple Source Eye Correction* (MSEC, Berg & Scherg, 1994; Ille, Berg, & Scherg, 2002), which performs well on natural reading data (Dimigen et al., 2011). Like principal component or independent component analysis (PCA/ICA), MSEC is a spatial filter (Ille et al., 2002) that models the recorded EEG as a linear combination of multiple scalp topographies (or components) that define the spatial layouts of artifact and brain activity. With surrogate MSEC, artifact

topographies for each participant are empirically defined by averaging calibration EMs. Activity time courses for these artifact topographies are then estimated in the presence of a "surrogate" dipole model of brain activity (which defines a generic set of brain topographies), thereby reducing the accidental subtraction of genuine brain activity. As surrogate brain model we used BESA model *"BR_Brain Regions_LR.bsa"* without the most frontal regional source (regularization constant: artifact 0%, brain: 2%). Other procedural details were the same as in Dimigen et al. (2011).

Fixation-related potentials. Segments of 1600 ms of artifact-corrected EEG were cut around each fixation onset (–600 to +1000 ms) and baseline-corrected by subtracting a 100 ms pre-fixation baseline. To exclude non-ocular artifacts (drifts or high-amplitude EMG), segments with a peak-to-peak voltage difference >120 µV in any channel were rejected (2% of segments). Remaining segments were averaged to obtain FRPs.

To compute FRPs aligned to word *n* (rather than *n*+1)*,* we included only trials in which GD on *n* exceeded 240 ms and restricted the statistical analysis to the interval between 0 and 240 ms after fixation onset. This selection (cf. Baccino & Manunta, 2005; Simola et al., 2009) guarantees that readers are not already looking at word *n*+1 during the analysis interval, which would yield trivial positive results. The value of 240 ms was short enough to admit data contributions by all readers to all cells of the design and long enough to include the time range for which Baccino and Manunta reported a POF effect of semantic association (215 ms). For behavioral analyses on word *n*, all fixations were included.

Statistics. All results were collapsed across the two possible word positions in the list. EM measures were subjected to ANOVAs on the factor *preview*, separately for boundary and POF trials. Degrees of freedom were adjusted by multiplication with Huynh–Feldt's epsilon. We report the original *df*s, the Huynh-Feldt adjusted *p*-values, and effect sizes as partial eta squared (η_p^2). For FRP statistics, repeated measures ANOVAs on factors preview (3) × electrode (46) were conducted on mean FRP amplitude in consecutive 40 ms windows between 0 and 600 ms after fixation onset. In these ANOVAs, preview effects are only meaningful in interaction with electrode because the average reference sets the mean across electrodes to zero. To correct for multiple comparisons across time windows, these *p*-values were further corrected (p_{corr}) by applying the false discovery rate procedure by Benjamini and Hochberg (1995) as implemented by Groppe et al. (2011). Post-hoc contrasts between preview levels were computed for windows with a significant interaction.

Table 2. **Reading times on post-boundary word *n*+1 in boundary trials**

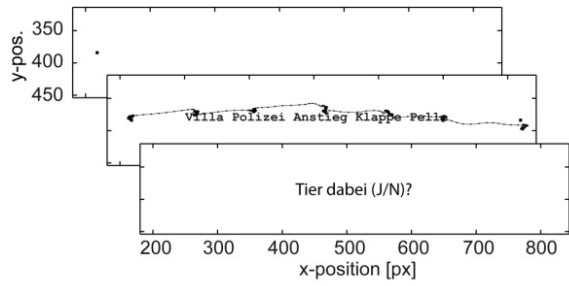|	Reading times on word *n*+1		
	Identical Preview	Related Preview	Unrelated Preview
First fixations (ms)	303 (25)	316 (27)	317 (26)
Single fixations (ms)	325 (29)	347 (38)	345 (33)
Gaze duration (ms)	350 (28)	370 (33)	365 (33)

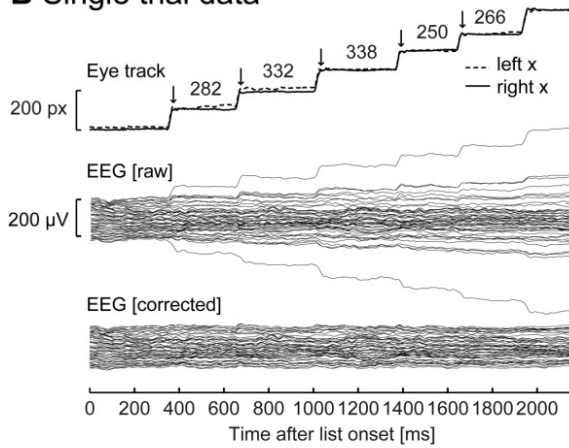*Note*. Given are mean and SEM.

RESULTS

Animal task. Participants responded correctly to the animal question after 97% of the trials (range: 92-99%). For lists with an animal, the mean false alarm rate (reporting an animal although none was present) was 1% and the miss rate (not recognizing the animal) was 16%. The rather high miss rate was likely due to the inclusion of some low frequency animals. For example, the animal with the worst detection rate, "Wisent" (*European bison*), was missed by 21 participants, indicating that it was unfamiliar to most participants.

Display change awareness. Of 35 participants, 11 remained completely unaware that the display was manipulated. These "unaware" participants did not recall seeing anything unusual about the display, even when they were informed about the changes after the experiment. The remaining 24 participants were conservatively labeled as "partially aware". Of these, 16 never realized that words were exchanged, but noticed for example a faint flicker on the screen once. Three of the partially aware participants had realized that words had been exchanged and reported that they had been able to determine the identity of a preview string at least once. The remaining five participants had realized that some previews were semantically related words. On average, the 24 partially aware participants estimated that they noticed 3.9 changes (min.: 1, max.: 10), or 2.7% of all visible changes. These instances were likely due to trials with badly timed changes that were excluded from analyses. Only four participants were able to correctly report the two list positions at which changes could occur during the experiment.
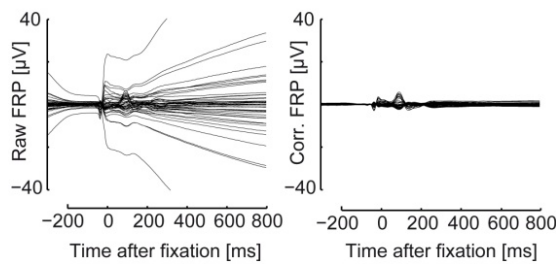
A Trial scheme

B Single trial data

C Corneoretinal correction

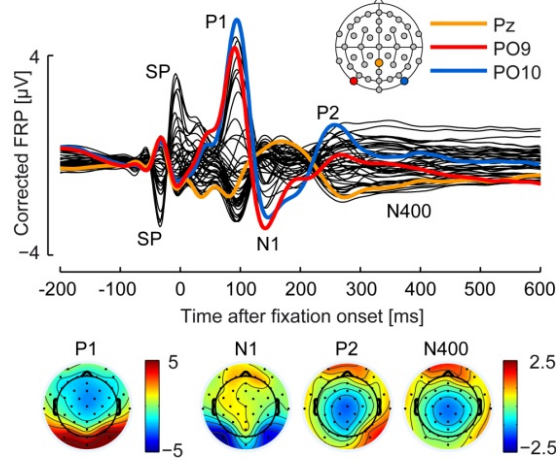

D Fixation-related potential

Figure 2. **A.** Trial scheme. Following a fixation check on a point on the left, the list appeared and participants read it at their own pace. Gaze position of the right eye is plotted for this trial. After participants finished reading, they were asked whether one of the words was an animal. **B**. Synchronized horizontal eye track, raw EEG, and MSEC-corrected EEG for the trial shown above. Arrows mark fixation onsets, numbers indicate fixation durations (in ms). **C.** Grand-mean fixation-related potential (FRP), averaged across all fixations, conditions, and participants. All EEG channels are plotted superimposed and shown before (left) and after (right) MSEC. **D.** Detailed view of the artifact-corrected FRP. Scalp topographies are shown for the peaks of the P1, N1, P2, and for the N400 range (300-400 ms). The biphasic potential before fixation onset is the muscle spike potential (SP).

EMs in list reading. Participants read the list for an average of 2.3 s before looking at the right fixation point. First fixations, single fixations, and gaze durations lasted on average 298, 321, and 378 ms, respectively. Reading times increased moderately from the first (SFD: $M = 299$ ms) to the penultimate (SFD: $M = 338$ ms) word in the list. As in sentence reading, words were typically fixated slightly left to their center. Most saccades were oriented rightward but there were some (3%) regressions towards earlier words in the list, and 36% of words received one or more refixations. The mean amplitude of inter-word saccades was 2.7° (6.3 characters). Incoming saccade amplitudes did not differ between preview conditions in boundary or POF trials. This is important, because saccade amplitude modulates the neural response after saccade offset (Dimigen, Valsecchi, Sommer, & Kliegl, 2009).

Quality of corneoretinal correction. Visual inspection of the continuous EEG and of averaged FRPs before and after correction suggested that MSEC eliminated corneoretinal artifacts almost entirely (Figure 2B and 2C). Correction quality was similar to that previously obtained for sentence reading (Dimigen et al., 2011). As an objective criterion to test correction quality, we correlated each EEG channel with the (electrically independent) horizontal eye position from the eye tracker before and after MSEC, following the procedure in Dimigen et al. (2011). After correction, all correlation coefficients were $|r| < 0.09$ and the mean of all $|r|$ was 0.03, indicating that artifacts correction worked well. In contrast, MSEC does not remove the brief muscle spike potential at saccade onset but this is not a serious problem for EEG analyses in the time domain (if saccade properties do not differ between conditions).
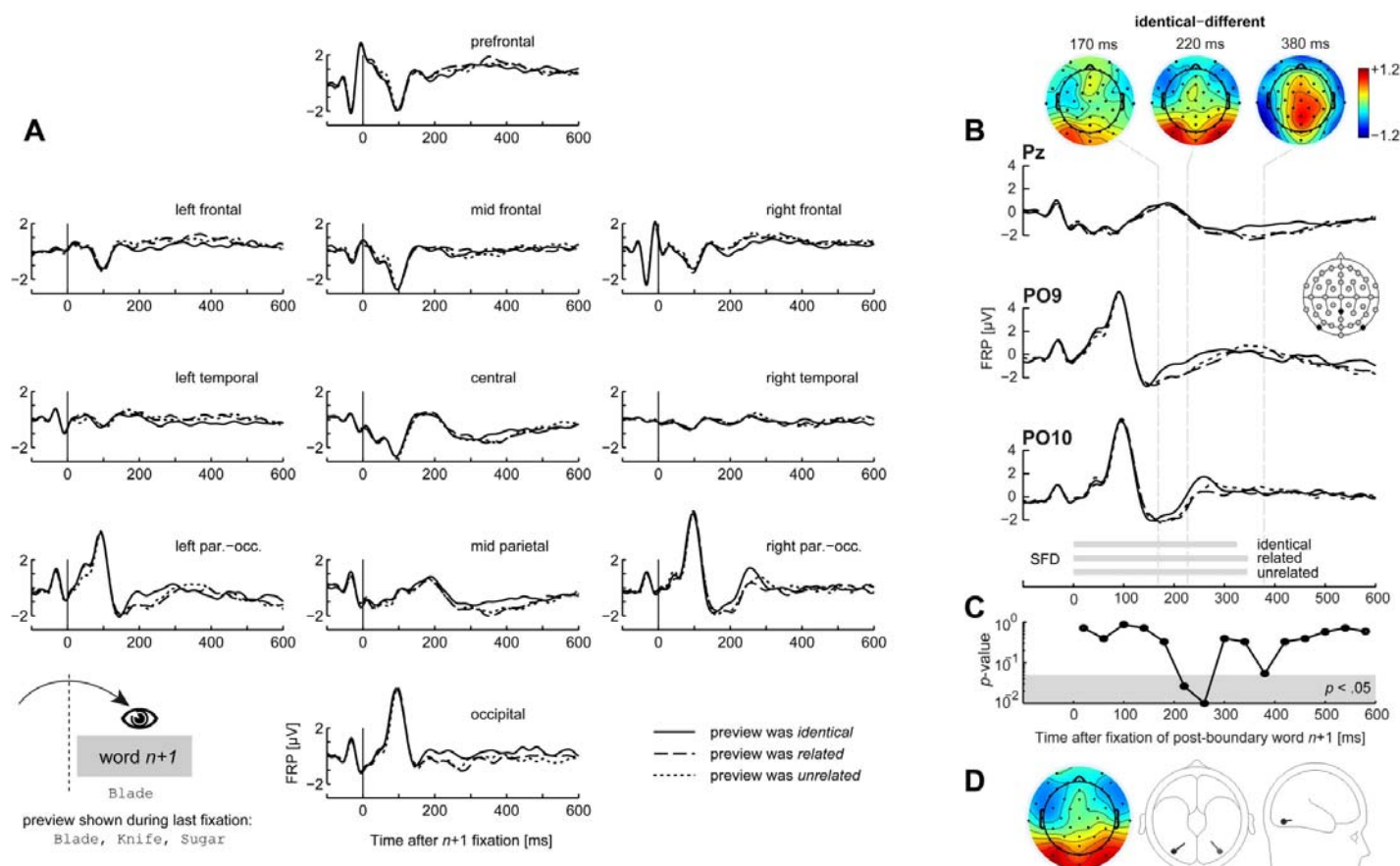
Figure 3. Results from boundary trials. **A.** Grand-average FRPs, time-locked to first fixations on post-boundary word *n*+1. Please note that at time 0, the same word is fixated in all conditions: Conditions only differ in terms of the preview that was available during the *previous* fixation. Electrodes are clustered as follows: Occipital (O1, Oz, O2, Iz), left parieto-occipital (P7, PO7, PO9), right parieto-occipital (P8, PO8, PO10), mid-parietal (P3, Pz, P4, POz), central (FC1, FC2, Cz, Cp1, Cp2), left central-temporal (FC5, C3, CP5, T7, A1), right central-temporal (FC6, C4, CP6, T8, A2), frontal (F3, Fz, F4, AFz), left frontal (AF7, F7, FT9), right frontal (AF8, F8, FT10), and prefrontal (Fp1, Fpz, Fp2). **B.** FRP at parietal (Pz) and left (PO9) and right (PO10) occipitotemporal electrodes. Topographies show the difference between identical minus different (related or unrelated) previews at 170 and 220 ms (*preview positivity*, PP) and at 360 ms (late N400-like trend). Grey bars show single fixation durations (SFD). **C.** *p*-values for the *preview × electrode* interaction. **D.** Effect topography and dipole model of the PP (interval 200-280 ms) suggested bilateral generators in extrastriate or occipitotemporal cortex.

Boundary trials

EMs. Table 2 shows reading times on the post-boundary word *n*+1 as a function of the preview available during the previous fixation of the pre-boundary word *n*. A main effect of preview condition was found for all reading time measures: first fixation duration, $F(2,68) = 5.4$, $p = 0.007$, $\eta_p^2 = .014$, single fixation duration, $F(2,66) = 5.9$, $p = 0.006$, $\eta_p^2 = 0.15$, $\varepsilon = 0.92$, and gaze duration, $F(2,68) = 5.1$, $p = 0.009$, $\eta_p^2 = 0.13$. Post-hoc comparisons showed that all three measures were shorter after identical previews, both compared to semantically related (all ts > 2.5, all ps < 0.02) and unrelated previews (all ts > 2.4, all ps < 0.03). This result replicates the classic identity preview benefit established in many eye tracking studies. The size of this benefit (unrelated minus identical) was 14 ms in FFD ($p = 0.003$), 20 ms in SFD ($p = 0.002$), and 15 ms in GD ($p = 0.025$). In contrast, there was no difference between related and unrelated previews in any measure (all ts < 1, all ps > 0.38). Behavior therefore provided no evidence for a benefit from semantically related previews.

As a control, we also analyzed reading times on the filler that served as pre-boundary word *n*. Please note that in the boundary paradigm, the filler at position *n* and the preview word shown for word *n*+1 are always unrelated words. Therefore, as expected, fixation times on *n* did not differ between preview conditions (all Fs < 1, all ps > 0.50).

FRPs. Figure 3 shows the corresponding grand-average FRPs, time-locked to the first fixation on word *n*+1. The absolute FRP wave shapes were characterized by the biphasic muscle spike potential around time zero (Keren et al., 2010), followed by a dominant occipital P1-N1 complex. This complex consisted of the positive-polarity lambda response (the P1-equivalent in FRPs) peaking 96 ms after fixation at right occipitotemporal electrode PO10, and a negative peak around 140 ms resembling the N1 (or N170) component in stimulus-locked ERPs. The P1 was considerably larger over the right (5.74 µV at PO10) than the left hemisphere (4.61 µV at PO9) during fluent reading, $t(34)=2.87$, $p < 0.01$. Conversely, the following N1 peak was larger over the left (-2.63 µV) than right (-2.20 µV) hemisphere, but this difference did not reach significance (Figure 2D).

Importantly, FRPs aligned to word *n*+1 differed as a function of the preview that had been available during the fixation of *n*. As Figure 3 shows, wave shapes in the three conditions were similar until about 170 ms after fixation onset. However, after the N1 peak, the FRP in the identity preview condition began to diverge from that observed after related or unrelated previews. This effect started at left occipitotemporal electrode PO9 (Figure 3B), spread shortly afterwards also to right-hemisphere electrode PO10, and reached a maximum

size at both electrodes at 252 ms. Statistical testing in 40 ms windows onset yielded a significant *preview × electrode* interaction between 200 to 240 ms, $F(90,3060) = 2.7$, $p_{corr} < 0.026$, $\eta_p^2 = 0.07$, and between 240 to 280 ms after fixation onset, $F(90,3060) = 3.5$, $p_{corr} < 0.01$, $\eta_p^2 = 0.09$ (Figure 3C). Post-hoc contrasts showed that in both intervals, the identical condition differed significantly from both the related and the unrelated condition. Thus, a correct parafoveal preview during the previous fixation led to a modulation of FRP amplitude over occipitotemporal areas, beginning after the N1 peak, reaching a maximum around 250 ms, and lasting until approximately 280 ms. In the following, we will refer to this decreased negativity to previewed words as the *preview positivity (PP)*.

Visual inspection also suggested a possible late effect of preview that was spatially and temporally distinct from the earlier PP. Figure 3B shows that from about 320 to 500 ms, during the traditional N400 time window, voltages at mid-parietal electrodes were more positive after identity previews. Between 360 and 400 ms, this difference was marginally significant, $F(90,3060) = 2.4$, $p_{corr} = 0.05$, $\eta_p^2 = 0.07$ (Figure 3C).

In contrast, we observed no benefit from semantically related previews in FRPs: Amplitudes did not differ significantly after related and unrelated previews in any time window.

As a control, FRPs were time-locked to fixations on the pre-boundary word *n*. As expected, preview condition had no effect on FRPs evoked by this fixation.

Source estimation. In an exploratory analysis we modeled the generators of the PP with equivalent current dipoles in BESA (Brain Electromagnetic Source Analysis, v5.2, Megis). Based on the dipolar PP topography evident in Figure 3D, a dipole pair with a bilateral symmetry constraint was fitted to the mean effect in the grand-average FRP between 200-280 ms using the contrast *identical* minus *different* (related and unrelated condition collapsed). As Figure 3D shows, the solution was compatible with bilateral sources in extrastriate occipital or occipitotemporal cortex (approx. Talairach coordinates: $x = \pm36$, $y = -76$, $z = -12$). However, the model was not entirely satisfactory in terms of residual variance (5.4% at best time point) and can only be treated as an approximation of the underlying source configuration.
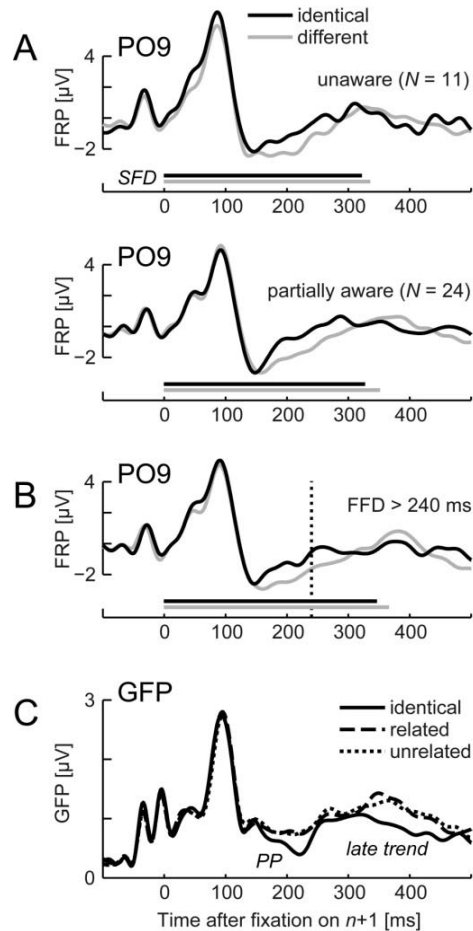
Figure 4. Control analyses for boundary trials. **A.** Preview benefit as a function of display change awareness. Mean single fixation durations (SFD) are plotted as horizontal bars. **B.** Preview benefit in a subset of target fixations lasting longer than 240 ms. **C.** Preview benefit in the EEG's global field power (GFP).

Control analyses. The results presented so far suggest that the preview positivity in FRPs reflects a processing advantage from parafoveal information obtained during the previous fixation. Four alternative explanations were also tested.

First, the effect might be related to the conscious perception of the display change on a few occasions. This explanation seems unlikely, since trials with badly timed changes were excluded. Nevertheless, this hypothesis was tested by comparing results of partially aware and completely unaware participants. Figure 4A shows that identity benefits were significant in both groups, irrespective of awareness. For partially aware participants, the benefit (identical minus unrelated) was 19 ms in SFDs, $t(22) = 2.5$, $p = 0.02$, and -0.98 µV in FRP amplitude (measured at PO9 between 200 and 280 ms; $t(22) = 3.5$, $p = 0.002$). For unaware

participants, the benefit was 22 ms in SFDs, $t(10) = 2.3$, $p = 0.04$, and -0.76 µV in FRPs, $t(10) = 2.5$, $p = 0.03$.

Second, we tested whether the effect is a trivial reflection of the oculomotor effect. A serious methodological challenge for FRP recordings during free viewing is temporal overlap between brain potentials evoked by successive fixations. If fixations are shorter in one experimental condition, potentials evoked by the next fixation will overlap at an earlier latency, compared to conditions with longer fixations. This can produce artificial FRP differences that are merely a reflection of the behavioral effect. To exclude this possibility, we reanalyzed the FRP and included only cases in which the first fixation on $n+1$ lasted more than 240 ms (68% of cases). In this average, shown in Figure 4B, the interval up to 240 ms is free of overlapping potentials from the next fixation. The preview effect was still observed, ruling out this possibility.

Third, the PP modulation might reflect a visually evoked potential (VEP) elicited by the peri-saccadic display change. In the identical condition, the word was exchanged against itself; meaning that there was no visible transient on the screen. Thus, the effect could be part of an additional P1-N1 complex evoked by the change in the other conditions. Importantly, the five ANOVA windows before 200 ms yielded no significant effect of preview. Nevertheless, we scrutinized the early FRP intervals for signs of a VEP in the related and the unrelated condition. As the display refreshed $M = 16$ ms before fixation onset, a P1-like VEP should be observed at occipital electrodes about 90-140 ms later (i.e., around 74-124 ms). No indication of an early VEP was observed (Figure 3). Similarly, as Figure 4C shows, there was no sign of early differences in the EEG's global field power (Murray, Brunet, & Michel, 2008). It therefore seems unlikely that the preview positivity (a relative negativity in conditions with dissimilar preview) is an artifact of the peri-saccadic transient.

Fourth, the effect might be related to residual corneoretinal artifacts. This can be ruled out on several grounds: (1) MSEC removed most of the corneoretinal artifacts. (2) The effect was found at deep posterior electrodes that receive only a small fraction of the artifact. In particular, the effect was also found at electrode Oz. Due to its posterior midline position, this electrode was uncorrelated to eye position even in the uncorrected EEG ($r = 0.006$, $p = 0.74$). (3) The effect was replicated for fixations lasting longer than 240 ms. For these fixations, the interval from 0 to 240 ms (see dashed line in Figure 4B) is by definition free of EM artifacts.

Table 3. **Reading times in parafoveal-on-foveal trials as a function of the relationship between word *n* and *n*+1**

	Reading time on word *n*			Reading time on word *n*+1		
	Identical	Related	Unrelated	Identical	Related	Unrelated
First fixations (ms)	277 (18)	292 (22)	297 (23)	265 (22)	291 (23)	301 (23)
Single fixations (ms)	293 (20)	312 (26)	315 (25)	275 (27)	309 (29)	327 (30)
Gaze durations (ms)	319 (23)	342 (29)	345 (29)	299 (28)	335 (29)	355 (34)

Note. Given are mean and SEM.

Parafoveal-on-foveal trials

In POF trials, preview and target were simply shown at adjacent list positions. This alternative paradigm allows us to test whether properties of the second word *n*+1 exert an influence on behavior or EEG while the eyes still rest on the previous word *n*. At the same time, these trials served as a control for our word materials: Even without any parafoveal preprocessing, we should see robust effects of repetition priming (in case of two identical words) and semantic priming (in case of two related words) once the reader looks directly at word *n*+1.

EMs on word n: The left part of Table 3 shows reading times on word *n* as a function of whether word *n*+1 was identical, related, or unrelated. All EM measures were influenced by the type of word shown parafoveally, as evident in main effects of preview condition on FFD, $F(2,68) = 14.2$, $p < 0.001$, $\eta_p^2 = 0.30$, $\varepsilon = 0.95$, SFD, $F(2,68) = 13.0$, $p < 0.001$, $\eta_p^2 = 0.28$, and GD, $F(2,68) = 12.5$, $p < 0.001$, $\eta_p^2 = 0.27$, $\varepsilon = 0.91$. In each case, the effect was due to the identical preview condition. Reading times on *n* were significantly shorter when *n*+1 was identical, both relative to the related (all $t(34) > 3.8$, all ps < 0.002) and the unrelated condition (all ts(34) > 4.1, all ps < 0.001). In contrast, reading times were not influenced by whether *n*+1 was related or unrelated; FFD: $t(34) = 1.5$, $p = 0.156$; SFD: $t(34) = 0.8$, $p = 0.441$; GD: $t(34) = 0.6$, $p = 0.549$.

FRPs locked to word n. Figure 5 show the corresponding FRPs. The left sides of the time axes in figure 5A and 5B shows the FRP for the first fixation of word *n*. Importantly, the type of word shown at *n*+1 had no effect on FRPs time-locked to *n*. Not only was there no semantic effect, there was also no difference between the unrelated and the identical

condition. Whereas fixation times on *n* were significantly shorter when the parafoveal word was identical to the fixated word, FRPs did not reflect this parafoveal-on-foveal effect.

EMs on word n+1. Once word *n*+1 was directly fixated, the relationship between *n* and *n*+1 clearly influenced reading behavior (Table 3, right side). All three EM measures showed identity priming and semantic priming, as suggested by highly significant main effects of preview condition on FFD, $F(2,68) = 31.9$, $p < 0.001$, $\eta_p^2 = 0.48$, $\varepsilon = 0.89$, on SFD, $F(2,68) = 43.2$, $p < 0.001$, $\eta_p^2 = 0.56$, $\varepsilon = 0.83$, and on GD, $F(2,68) = 42.1$, $p < 0.001$, $\eta_p^2 = 0.55$, $\varepsilon = 0.77$. Post-hoc contrasts revealed that reading times were shorter when both words were identical, as compared to when they were merely related (*t*s > 5.2 and *p*s < 0.001 in all three measures), and shorter when the words were related as compared to when they were unrelated (all *t*s > 2.9, all *p*s < 0.01). Size of the semantic effect was 10 ms in FFD ($p < 0.01$), 18 ms in SFD ($p < 0.001$), and 20 ms in GD ($p < 0.001$).

FRPs locked to word n+1. Clear priming effects were also observed in FRPs time-locked to fixating word *n*+1 (right sides of time axes in Figure 5A and 5B). Results replicated the well-established pattern from foveal priming studies (Rugg, 1985): The N400 component was most negative for unrelated, intermediate for related, and most positive for repeated words and its classic centroparietal scalp distribution was similar for both types of priming (this also suggests that the effect in the identical condition was not an oddball P300 to the unusual word repetition). These results confirm that the word pairs were capable of producing robust priming effects in foveal vision.

Importantly, N400 effects arose at very short latencies after fixation onset. Despite correction for multiple comparisons, window-wise ANOVAs yielded a significant *preview × electrode* interaction starting at 80 ms and lasting until 480 ms after fixation onset (all $F(90,3060) > 2.6$, all $p_{corr} < 0.05$; all $\eta_p^2 > 0.07$; maximum *F*-value of 8.7 between 320-360 ms with $p_{corr} < 10^{-6}$ and $\eta_p^2 = 0.20$). The contrast identical versus unrelated reached significance between 80-120 ms ($p = 0.003$) and remained significant until 480 ms; the contrast related versus unrelated reached significance between 160-200 ms ($p = 0.012$) and also remained significant until 480 ms. Note that these N400 onset latencies are much shorter than those typically seen in experiments with foveal repetition priming or semantic priming (e.g., Rugg, 1987).
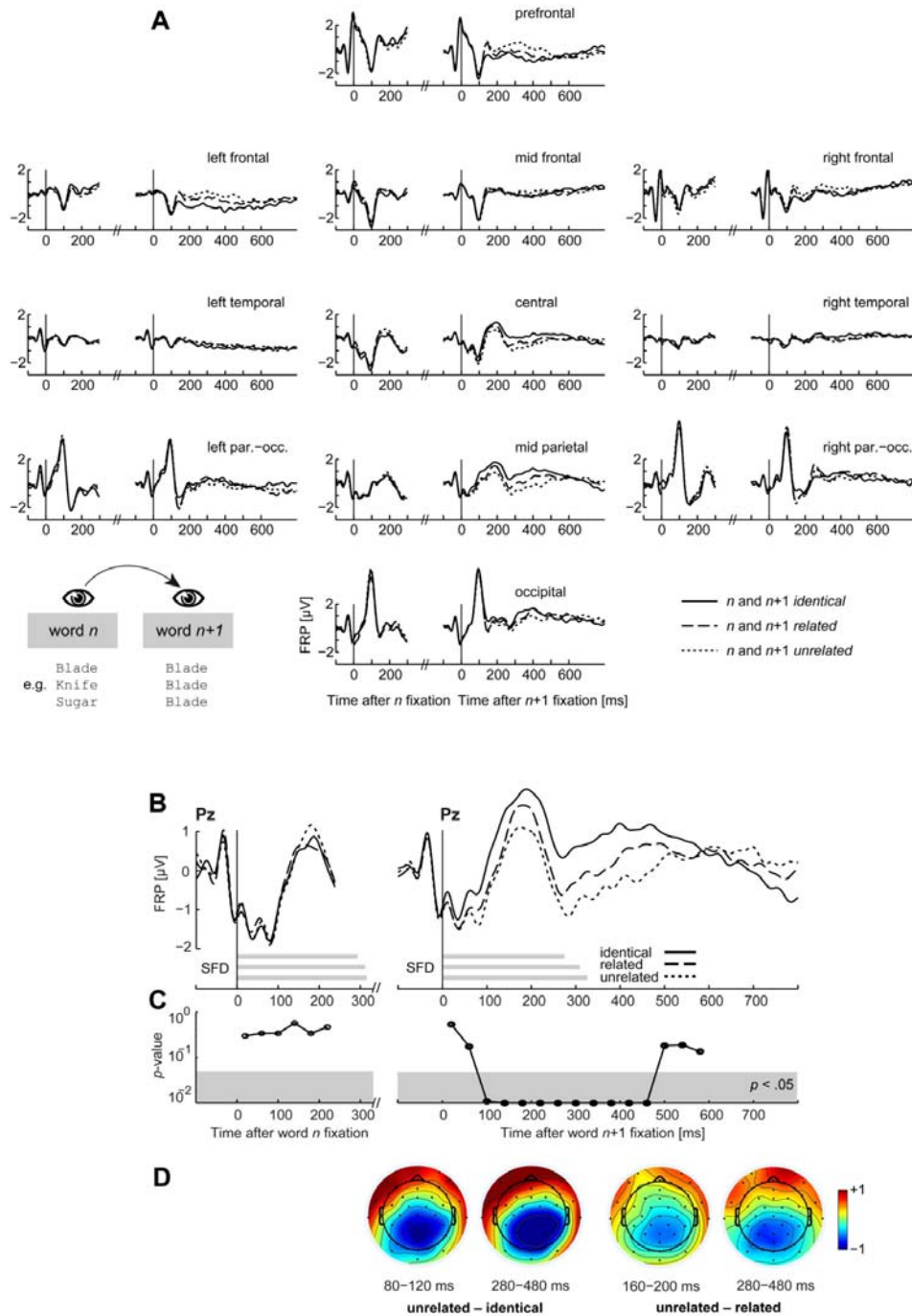
Figure 5. Results from parafoveal-on-foveal trials. **A.** Within each plot, FRPs are shown time-locked to the first fixation on word *n* (left part of time axis) and for the subsequent fixation on word *n*+1 (right part of time axis). **B.** Detailed plot for midparietal electrode Pz. Mean single fixation durations (SFD) in the three conditions are plotted as horizontal bars. **C.** *p*-values for the *preview × electrode* interaction. The relationship between word *n* and *n*+1 did not influence FRPs aligned to of word *n*. However, shortly after word *n*+1 was looked at, N400 priming effects arose at centroparietal electrodes. **D.** Scalp distribution of effects, aligned to fixations on word *n*+1, are shown for the first significant time window and for the N400 time range.

DISCUSSION

Extrafoveal preprocessing of soon-to-be fixated items is a property of natural vision that is rarely considered in EEG studies on visual perception. For the case of reading, a large body of eye-tracking studies has shown that readers spend less time on parafoveally previewed words. In a list reading design, we investigated the impact of this trans-saccadic preview benefit on EEG correlates of word recognition and tested which types of information contribute to this facilitation. Effects were analyzed simultaneously in fixation behavior and fixation-triggered potentials (FRPs) and with two complementary experimental approaches: as preview benefits in boundary trials and as parafoveal-on-foveal (POF) effects.

Results replicate several common observations in oculomotor behavior. In particular, in boundary trials we demonstrated an identity preview benefit but no semantic preview benefit. A key novel finding was a *preview positivity* (PP) – a marked difference in FRP morphology when a correct preview on the fixated word had been available during the preceding fixation. On the other hand, a semantic preview effect was not present in FRPs either. Similarly, parafoveal-on-foveal trials without display changes did not reveal a POF influence of semantic information on EM measures or FRPs time-locked to the first word of the critical word pair. However, N400 effects from identity priming and semantic priming emerged very shortly (around 80 and 160 ms, respectively) after the second word was directly fixated. Like the PP effect, this result suggests that time course and wave shape of EEG correlates of word recognition are different during fluent reading because words are already partially processed once they enter foveal vision. The following discussion will be organized according to the main questions of the present study: whether there is a neural signature of preview benefits and whether this benefit extends to semantic information gleaned from the parafovea.

A neural correlate of the preview benefit?

With an effect size of 20 ms in single fixations, the identity preview benefit in boundary trials was within the range usually observed in sentence reading. What is the neural basis of this classic behavioral facilitation? Based on findings that preview benefit is at least partially robust against trans-saccadic changes in spatial location and in low-level visual features (McConkie & Zola, 1984; Rayner et al., 1980) we hypothesized that EEG effects of identity previews would not manifest on the earliest stages of vision, but possibly in ventral-stream systems linked to orthographic processing.

The overall FRP waveshape resembled that of visual ERPs in many aspects and was also characterized by a P1-N1 complex. In line with a previous report (Dimigen et al., 2011), the visual P1 after fixation was considerably larger over the right hemisphere. However, this asymmetry reversed for the following N1 which was numerically larger over the left hemisphere. The result is reminiscent of the well-established left-hemispheric asymmetry of the N170 component to orthographic stimuli (Bentin, Mouchetant-Rostaing, Giard, Echallier, & Pernier, 1999), indicating that this finding generalizes to fluent reading.

In line with our hypotheses, preview had no significant effect on early FRP intervals, including the P1. However, shortly after the N1 peak, around 170 ms, a difference emerged between the condition with identity preview and the two conditions with related or unrelated previews. This preview positivity consisted in a decreased negativity over low occipitotemporal sites in the identical condition that started over left occipitotemporal electrodes but was soon followed at right-hemisphere electrodes. The activation pattern reached significance between 200 and 280 ms and was compatible with bilateral generators in occipitotemporal cortex.

Importantly, the PP was independent of display change awareness and not an artifact of overlapping brain activity or corneoretinal potentials. Furthermore, there was no indication that FRPs were influenced by visually-evoked potentials (VEPs) to the display change. A peri-saccadic visual transient might elicit a VEP not present in the identical preview condition in which the string was exchanged against itself. However, this explanation for the PP seems unlikely. Whereas sufficiently strong suprathreshold stimuli presented during saccades can elicited VEPs (Anagnostou, Kleiser, & Skrandies, 2000; Skrandies & Laschke, 1997) most studies found that responses to peri-saccadic stimuli are strongly decreased or absent (Chase & Kalil, 1972; Duffy & Lombroso, 1968; Gross, Vaughan, & Valenstein, 1967; Michael & Stark, 1967). This holds true in particular if the stimulation occurs shortly after saccade onset and its intensity is below conscious detection thresholds. In the present study, changes occurred during the saccade, were of low intensity, and not perceived by the subject (when properly timed). Second, a VEP should manifest at least as a P1-like occipital positivity in the two visually dissimilar conditions. In contrast, there were no significant effects of preview condition prior to 200 ms and the following PP effect was a relative negativity (rather than positivity) in conditions with a change.

What processes underlie the preview positivity? It is possible that the benefits from identity previews are compound effects that reflect facilitation at multiple levels (e.g., sub-letter visual features, orthographic representations, phonological and lexical representations).

However, the time range, topography, estimated sources, and left-hemisphere onset of the PP are at least compatible with the notion from EM research that much of the benefit results from a pre-activation of abstract orthographic codes (Rayner, 1998).

A common view in ERP research is that pre-lexical orthographic influences emerge in a time range between 150-200 ms while lexical influences begin 250 to 400 ms after word onset (Barber & Kutas, 2007; but see also Pulvermüller et al., 2009). The occipitotemporal N170 component is usually linked to early orthographic processing (e.g., Bentin et al., 1999; Maurer, Brandeis, McCandliss, 2005) and priming studies find case-independent orthographic priming around 250 ms (Carreiras, Perea, Vergara, & Pollatsek, 2009; Grainger et al., 2006; Holcomb & Grainger, 2006).

Interestingly, identity previews benefits in the current study – the PP and the N400-like trend - show similarities to the pattern of results established with foveal masked priming studies. When a masked repetition prime or partial orthographic prime is presented at short prime-target intervals (Holcomb & Grainer, 2007) a sequence of priming effects is observed: an early effect around 150 ms, called N/P150, a mid-latency effect from about 180 ms to 300 ms, called N250, and a late effect on N400. Only the latter two effects are robust against slight changes in the spatial location of prime and target (Dufau, Grainger, & Holcomb, 2008) as they would occur in a fluent reading situation. The N250, which is rather similar to the PP in terms of timing, has been interpreted as reflecting a mapping of abstract orthographic information to whole-word representations. Although N250 and PP differ in terms of scalp topography, these phenomena could be functionally related, a question that should be investigated in future research.

Unfortunately, little is known about neural effects of parafoveal priming. An exception is an MEG study by Pernet, Uusvuori, and Samelin (2007) who investigated parafoveal repetition priming in the lexical decision task. Primes presented in the right hemifield influenced the magnetic fields evoked by subsequently presented foveal targets beginning 160 ms after target onset in left occipitotemporal and superior temporal regions. While these results were not obtained during fluent reading, there are again similarities to the PP effect reported here.

In addition to the earlier PP, there was a trend for a late effect from identical previews that was temporally and topographically distinct. This pattern consisted of more positive centroparietal amplitudes after identity previews during the N400 time window between 360 and 400 ms. While the finding of the PP suggest that it is primarily EEG components in a

mid-latency range that are sensitive to preview, this trend provides an indication that identity previews can also influence the N400 and later stages of word processing.

Comparision to foveal repetition priming. The study design allows us to compare the effect of a correct parafoveal preview (in boundary trials) to the full-blown effect of trans-saccadic word repetitions (in POF trials). In POF trials with an identical preview, the same word was foveated on two subsequent fixations. When FRPs were aligned to the second word, and if this second word was a repetition of the first one (rather than unrelated to it), the FRP at centroparietal electrodes showed a strong positive deflection resembling the repetition priming effect on the N400 established in ERPs (Rugg, 1985). In these studies, the parietal positivity to repeated words is interpreted as a reduced negativity (i.e. N400) which is usually superimposed on a large positivity but now diminished due to repetition. Our results extend this literature by showing that N400 repetition effects also occur when the same string is fixated twice across an intervening saccade during fluent reading.[2]

If repeated fixations of the same word elicit a large N400 repetition effect, why was the effect of identity previews in boundary trials limited to the PP and a marginally significant trend in the N400 window? A likely explanation for this difference is that a directly fixated (and therefore fully processed) first word also primes lexico-semantic or post-lexical stages once the second word is fixated. In contrast, the PP and the N400 trend after (only partially processed) parafoveal previews would reflect a more pure correlate of unconscious orthographic or phonological priming.

Semantic processing of parafoveal words?

Our second goal was to test whether readers also extract word meaning parafoveally. In boundary trials, we tested whether related previews facilitate target processing. In the current list reading task, we found no evidence for such a semantic preview benefit in behavior or FRPs. In particular, there was neither a PP as seen for identity previews, nor a late N400-like effect.

In POF trials, we tested whether FRPs to word n are influenced by its semantic relatedness to the upcoming word $n+1$. Within the analysis interval of 240 ms, the FRP was not influenced by properties of the upcoming word, irrespective of whether it was unrelated, related, or identical. This result is at odds with results from Baccino and Manunta (2005) who reported a POF effect of semantic association on a P2 component (around 215 ms). Such a

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[2] This repetition effect is interesting because about 15% of all words during reading receive multiple fixations (Rayner, 1998). Refixations during reading may have a similar electrophysiological effect as seen here for two fixations on an identical word.

semantic POF effect was not replicated by Simola and colleagues (2009); however, these authors modified the paradigm and had the parafoveal word appear to the left or right of the foveal word. In the current, more natural reading situation, we also found no semantic POF effect in the P2 window (or any other time window), which is consistent with the lack of a semantic preview benefit in boundary trials.

Latency of semantic access. When did readers retrieve word meaning in our list reading task? Parafoveal-on-foveal trials allow us to estimate an upper temporal limit for access to semantic codes. In line with classic ERP findings (Rugg, 1985), N400 amplitude to the second word was largest after unrelated, intermediate after related, and smallest (most positive) after identical first words. Importantly, the contrast between the related and unrelated conditions reached significance already 160 ms after the second word was fixated. This suggests that the meaning of both words was available no later than at this point in time. Compared to traditional foveal priming studies (e.g. Rugg, 1987) this is an unusually short latency for semantic effects. Together with the benefit observed in boundary trials, this temporal shift is most plausibly explained by assuming that the second word was already at least partially processed by the time it received a direct fixation, thereby leading to an earlier onset of semantic N400 effects. This conclusion is also in line with two recent FRP studies which have found that N400 word predictability effects tend to arise earlier under natural reading conditions with preview (Dimigen et al., 2011; Kretzschmar et al., 2009).

Finally, it should be noted that although people scan lists of words every day (e.g. shopping lists, inventories, email subject lines) this activity differs from sentence reading in several ways. Sentences not only allow context-based predictions about upcoming words, but also include short and highly frequent function words and these properties are known to increase the amount of parafoveal processing (Henderson & Ferreira, 1990; Kliegl et al., 2006). The existence of semantic preview effects in the EEG should be further investigated in the context of sentences.

Conclusions

Parafoveal processing must be considered if one wishes to draw conclusions about reading from studies of word recognition. Here we demonstrated that the wave shape and timing of EEG correlates of word recognition is different under normal reading conditions that allow preview. However, extrafoveal preprocessing is in no way exclusive to reading, but part of any real-world viewing situation. We therefore speculate that other mid-latency EEG components, such as the N170 evoked by scanning scenes, objects, or faces, could be modulated by preview in similar ways as seen here for words. Our results document that

saccade-contingent display manipulations can be combined with EEG recordings during free viewing, opening the door for systematic explorations of the impact of preview on neural correlates of visual perception.

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