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A test of parafoveal-on-foveal effects with pairs of orthographically related words

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One of the main controversies in the field of eye movements in reading concerns the question of whether the processing of two adjacent words in reading occurs in sequence, or in parallel. To distinguish between these views, the present experiment tested the presence of parafoveal-on-foveal effects with pairs of orthographically related words (or neighbours that differed by a single letter) in a controlled but reading-like situation. Results revealed that fixation times on a foveal target word were shorter when the target was accompanied by an orthographically similar parafoveal word than when the parafoveal word was dissimilar. Furthermore, the size of the effect tended to vary with both the relative frequency of target and parafoveal words, and the position of the critical letter. These results were interpreted in the framework of a pure parallel processing hypothesis, where the processing of adjacent words is only limited by visual acuity, and the respective lexical properties of the foveal and the parafoveal words.

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Since the early 1990s, a large body of research has been devoted to the study of visual attention in reading. One of the main issues relates to the question of whether the visual information from two adjacent words is processed in parallel or in sequence. As suggested in several models of eye guidance in reading, it may well be that the processing of the fixated word comes first and only when this word has been identified does the processing of the next word in parafoveal vision begin (Henderson & Ferreira, 1990; Morrison, 1984; Rayner, Reichle, & Pollatsek, 1998; Reichle, Pollatsek, Fisher, & Rayner, 1998). Several different mechanisms have been proposed although the basic principle remains the same. An attentional process filters the visual information and only the information in the attention spotlight is processed up to the word level. At the beginning of a fixation, the spotlight (usually) is on the fixated word and, when the fixated word is identified, it shifts to the next word. Parafoveal processing is then initiated, and will last until a saccadic eye movement brings the eyes onto this word (or onto the next word if the attentional spotlight has shifted again in the mean time). According to Morrison (1984), the programming of a saccade immediately follows an attention shift. In contrast, the E-Z Reader model proposed by Reichle et al. (1998) assumes that saccadic programming starts as soon as a word familiarity check has been completed, which means that it always precedes an attention shift. Thus, in both models, parafoveal processing time cannot exceed the saccadic programming time, and according to the E-Z Reader model, it is even shorter, being then a function of the difficulty of the foveal word.

On the other hand, we could also assume that rather than being processed in sequence, all words within the perceptual span are processed in parallel. This view has been expressed in different variants depending on the role given to attention. At one extreme, and still very close to the sequential attention shift hypothesis, the gradient-shift assumption posits that attention is distributed over several words, with more resources being allocated to the word in the fovea and gradually diminishing towards the word(s) in the parafovea. In addition, the attention distribution is modulated by the processing difficulty, with more resources being absorbed by words that are difficult to process (Engbert, Longtin, & Kliegl, 2002; Inhoff, Radach, Starr, & Greenberg, 2000a; Inhoff, Starr, & Shindler, 2000b; see also, McConkie, 1979; Schroyens, Vitu, Brysbaert, & d'Ydewalle, 1999). At the other extreme, a pure parallel hypothesis envisages that attention does not intervene at all in the processing of the visual information in reading, and that visual acuity is the primary variable that determines which word in the perceptual span is identified first, and when the eyes should move (see Schroyens et al., 1999, for a similar view; see also Schiepers, 1980). Due to visual acuity constraints, parafoveal word processing lags behind the processing of the fixated word. This ensures that in most instances, the winner of the competition is the fixated word, and therefore questions the need for selective processing. In between the above two views, a process-monitoring hypothesis was recently proposed, which does not clearly state the role of visual attention in the processing of adjacent words, but makes the proposal that a signal to move the eyes may result from difficulty being encountered in the processing of either the foveal or the parafoveal word, rather than from the foveal word only (Kennedy, 1998; Kennedy, Pynte, & Ducrot, 2002). Thus, there would be some kind of trade-off in the time spent fixating each of two adjacent words. Furthermore, how much a word is processed in parafoveal vision would be self determined rather than being a function of the time required to process the fixated word, and/or how much resources are allocated to the foveal word.

In favour of a parallel processing view, several arguments were recently put forward which question the validity of the basic assumptions made in sequential processing models. First, Schroyens et al. (1999) noted that parafoveal preview effects get larger with increasing fixation time, suggesting that the processing of the parafoveal word is not limited to the saccadic programming time as was postulated by Morrison (1984). This result is also opposite to the E-Z Reader's assumption that parafoveal processing is initiated later as the difficulty of the foveal word increases since this would predict that parafoveal preview benefit decreases as fixation time increases (Reichle et al., 1998). In addition, the finding that parafoveal processing is less when the foveal load is high (Henderson & Ferreira, 1990; Kennison & Clifton, 1995; Schroyens et al., 1999) does not seem to originate from a sequential processing of the foveal, and parafoveal words. Rather, this would be the result of an interaction between processing associated with both the foveal and the parafoveal word that would operate while the eyes are still on the foveal word, or once they have landed on the parafoveal word. Indeed, as noted by Schroyens et al., foveal-on-parafoveal effects are associated with spillover effects (or instances where processing of the foveal word is not terminated by the time the eyes land on the parafoveal word), and they emerge only at rather short fixation times (less than 240 ms). Furthermore, the likelihood of these effects depends on the frequency of the parafoveal word. These findings, which question but cannot completely rule out the hypothesis of sequential processing, call for clearer evidence for or against a sequential view.

To distinguish between a sequential vs. parallel view for the processing of both foveal, and parafoveal word information, several studies tested whether the processing associated with a fixated word is influenced by the characteristics of the word located in parafoveal vision, starting from the assumption that only a parallel view can predict the presence of parafoveal-on-foveal effects. The effects of different variables were tested including the visual presentation mode for the parafoveal word (i.e., upper vs. lower cases), the orthographic legality of the parafoveal letter sequence, the length and frequency of the parafoveal word or the frequency of the initial letter sequence in the parafoveal word, the semantic relatedness between the foveal and parafoveal words, and the plausibility of the parafoveal word in the sentence (Baccino, Lavigne, Gragnic, & Vitu, 2001; Henderson & Ferreira, 1993; Inhoff et al., 2000a, 2000b; Kennedy, 1998, 2000; Kennedy et al., 2002; Murray, 1998; White & Liversedge, 2004; see also Altarriba, Kambe, Pollatsek, & Rayner, 2001; Bradshaw, 1974). Across studies, parafoveal-on-foveal effects do not appear to be systematic. When the low-level visual and orthographic properties of the parafoveal stimulus are manipulated, parafoveal-on-foveal influences can be observed which result in longer fixation times with unexpected visual or orthographic patterns in the parafovea (Inhoff et al., 2000b). However, this was not confirmed in a recent study (see White & Liversedge, 2004). Furthermore, when it comes to higher level lexical or semantic variables, the picture gets even less clear. First, while some studies fail to report an effect of the parafoveal word frequency on foveal viewing inspection time (Carpenter & Just, 1983; Henderson & Ferreira, 1993), other studies indicate either an increase or a decrease in foveal processing time with low-frequency parafoveal words (Kennedy, 1998, 2000). Second, several studies indicate the presence of semantic and pragmatic parafoveal-on-foveal effects in both isolated word recognition and sentence reading, but the effects are often conditional upon the distance of the parafoveal word from the fixation location and/or the viewing conditions (Baccino et al., 2001; Inhoff et al., 2000a, 2000b; Murray, 1998). Finally, some results suggest to the contrary that semantic information cannot be extracted in the parafovea, and that semantic parafoveal-on-foveal effects are unlikely to occur (Altarriba et al., 2001; see Rayner, White, Kambe, Miller, & Liversedge, 2003, for a review).

The finding of lexical and semantic parafoveal-on-foveal effects may, however, be critical to distinguish between parallel and sequential processing hypotheses. Indeed, low-level visual and orthographic parafoveal influences could be accommodated in sequential attention shift models, assuming that attention is not always perfectly focused on the foveal word at the beginning of a fixation, and that low-level visual information can be extracted in the parafovea before it is completely filtered out, or selective foveal processing operates. As pointed out by Treisman and Souther (1986), the fact that letter migration effects may occur in the processing of two orthographically similar words presented simultaneously in parafoveal vision (see Mozer, 1983) is not strict evidence for a parallel processing of both words. Rather, this would indicate that the filtering of the irrelevant visual information occurs only after the letter level of word processing.

According to Kennedy et al. (2002), the discrepancy in the reported lexical and/or semantic effects comes from the fact that in most studies length and frequency of the foveal word were not controlled, and their data support to some extent this contention. Another possibility relates to the fact that parallel processing does not necessarily imply parafoveal-on-foveal influences. Depending on the respective time course of the processing associated with both foveal and parafoveal words, the characteristics of the parafoveal word may or may not affect the time needed to process the fixated word, and these may either facilitate or interfere with foveal word processing. A primary constraint relies on visual acuity, or the fact that more visual information accumulates from the foveal word, which results in it to be processed more rapidly than the parafoveal word (see Schiepers, 1980). Additional constraints come from the respective lexical properties of each word, and how many of these properties are common to both words. In past attempts to test the presence of parafoveal-on-foveal effects, the pairs of words selected for a presentation in fovea and parafovea differed on several dimensions (orthography, phonology, etc.), and several word properties that are critical to word recognition were not controlled. Both foveal and parafoveal words were therefore processed with different unpredictable speed, and predictions can hardly be made of whether the manipulated characteristics of the parafoveal word should influence (and how) processing of the fixated word.

To shed some light on the question of sequential vs. parallel processing, and to determine whether the occurrence of parafoveal-on-foveal effects is conditional upon the time course of processing associated with both the foveal and the parafoveal word, we investigated parafoveal-on-foveal effects with pairs of stimuli that differed by only one characteristic. As in Segui and Grainger's (1990) orthographic priming study, pairs of orthographic neighbours (or words that differ by a single letter, as defined by Coltheart, Davelaar, Jonasson, & Besner, 1977) were selected, with one of the words being a higher frequency neighbour of the second word. Instead of being presented in sequence as in the original experiment, both prime and target words were presented simultaneously in parafoveal and foveal vision respectively (in the present experiment, the previously so-called prime will be referred to as the parafoveal word). For comparison, the parafoveal word of each related pair was replaced in a control condition with an orthographically unrelated word, but of a similar frequency as the related parafoveal word. In addition, to manipulate a lexical variable, the frequency of both parafoveal word and target was varied, using as a parafoveal word the higher or lower frequency word of a pair, and vice versa for the target. For sake of clarity, the frequency factor will from now on, be referred to as target frequency. Care was taken that both words in a pair were never semantically related, and homophones were avoided as much as possible.

There is a debate going on in the literature whether orthographic neighbours help or hinder the processing of a target word. In general, it is thought that orthographic neighbours facilitate processing (Andrews, 1997), except when a not-fully processed high-frequency neighbour precedes a low-frequency target (see Ferrand, 2001; Grainger & Jacobs, 1996, for complete reviews). This is the case when the high-frequency neighbour is used as a masked prime (Segui & Grainger, 1990) or when the high-frequency neighbour is used as the parafoveal preview in a boundary technique (i.e., the parafoveal view is present as long as the reader's eyes have not landed on the word; once the eyes cross the boundary in front of the word, the preview is changed to the target word; Pollatsek, Perea, & Binder, 1999).

Our prediction is quite straightforward. According to a sequential model of word processing, the qualities of the parafoveal word will not have an effect on the fixation time on the foveal word, although there might be two exceptions to that scheme. First, as mentioned above, early facilitation effects due to feature/letter similarity (or a shortening in fixation times in related compared to unrelated cases) could still be reconciled with a sequential hypothesis as long as the effects do not vary with the relative frequency of the target and parafoveal words. Another exception may also occur if the parafoveal word is more likely to be skipped in one condition than in the other, in which case the preceding fixation duration should increase according to the E-Z Reader model. In contrast, a pure parallel processing view does predict the presence of parafoveal-on-foveal influences, and it additionally assumes that the size and/or the direction of the effects should vary with the relative frequency of both words. In particular, given that low-frequency words are usually associated with longer fixation times, and that high-frequency words are more easily processed in parafoveal vision than low-frequency words, parafoveal preview would be more efficient when low-frequency targets are paired with high-frequency parafoveal words than in the opposite condition (see Inhoff & Rayner, 1986; Schroyens et al., 1999; Vitu, 1991). This could result in greater facilitation in the former case as the majority of findings on orthographic priming point in the direction of facilitation (see for a review, Ferrand, 2001). On the other hand, if a word in parafovea can be compared with a not-fully processed word, then an inhibition may occur at least when a low-frequency target is accompanied by a higher frequency neighbour in the parafovea (see Segui & Grainger, 1990). Finally, the gradient-shift hypothesis proposed by Inhoff et al. (2000b; Inhoff et al., 2000a) also predicts the presence of parafoveal-on-foveal influences, but these would result in an overall facilitation when both words are similar, that would be independent of the relative frequency of target and parafoveal words. Since more resources are allocated to low-frequency foveal words, parafoveal processing should be reduced in those instances, and the amount of facilitation due to feature/letter similarity should not differ from when a high-frequency target is presented with a low-frequency parafoveal word. It must be noted that unlike sequential attention shift models, the gradient-shift hypothesis does not imply that parafoveal-on-foveal effects would be limited to a short time window at the beginning of the fixation.

EXPERIMENT

In our experiment, we tested the presence of parafoveal-on-foveal effects with pairs of isolated words, but in a reading-like situation. On each trial, two four- or five-letter words were presented simultaneously. These two words were either orthographic neighbours or unrelated words. The unrelated trials were made by taking the ''foveal'' target word of the neighbour pair and replacing the ''parafoveal'' word by an unrelated word of the same length and frequency. In all related pairs, one of the words was a higher frequency neighbour of the other word (e.g., avec [with] vs. aveu [confession]). In half of the trials, the high-frequency neighbour was used as target and the low-frequency neighbour as parafoveal word; in the other half the assignment was reversed (counterbalanced across participants). So, we had four types of stimuli (first word = target; second word = parafoveal word): ''avec–aveu'', ''avec–pipe'' [pipe], ''aveu–avec'', and ''aveu–mais'' [but]. Pairs of neighbours were chosen that had different deviating letters. For the four-letter words, a distinction was made between: (1) different first letter, (2) different middle letter, or (3) different last letter. For the five-letter words, we were able to have an equal number of words that differed at each letter position.

To mimic a normal reading situation, the two words were inserted between two x-letter strings. Participants were asked to jump from the first string of x-letters to the first word (or target), then to the second (or parafoveal) word, and finally to the last x-letter string. Their task was then to determine whether one of the two words referred to an animal (none of the test trials contained a word referring to an animal; these were filler trials). In the present situation, reading of the target word was therefore embedded in a series of left-to-right eye movements, and as suggested by previous studies, the eye movement pattern that characterises the reading of our isolated words should be similar to the pattern observed in forward text reading (Kennedy, 2000; Vitu, 1993). In normal text reading, word processing times range from an average gaze duration of 320 ms for low-frequency words to an average gaze duration of 260 ms for high-frequency words (Schilling, Rayner, & Chumbley, 1998). On the other hand, it must be noted that the target and parafoveal words, although being initially presented in parafoveal vision, were masked until an eye movement that crossed an invisible boundary in front of the target word was detected (see Rayner, 1975). This was done to ensure that the visual information related to either word started being extracted at the same time in all conditions.

Method

Participants. Forty-eight psychology students from the University René Descartes, and the Catholic University of Paris (Ecole des Psychologues Praticiens) participated in the experiment which was run at the Laboratory of Experimental Psychology, in Boulogne-Billancourt, France. Participants were between 20 and 30 years old, they were all native French speakers, and they had normal, or corrected-to-normal vision (in the latter case, only participants wearing glasses were accepted). All participants were naive regarding the purpose of the experiment.

Stimulus materials. Pairs of target and parafoveal words were either four or five letters long. For the four-letter words, 120 pairs of orthographic neighbours were selected from the French corpus *Trésor de la langue française* (1971) using the following criteria. Each pair differed in only one letter, controlled as much as possible over the different positions of the word: 40 differed in the first letter, 40 in either the second or the third, and 40 in the last letter (see example stimuli in Table 1). Both words differed in terms of their frequency of occurrence in such a way that one of the words was a higher frequency neighbour of the other word. The mean and the median frequency for the high frequency words corresponded to 265, and 48 occurrences per million (with a minimum and a maximum of 4.6 and 9600 occurrences per million); these values were 7.1 and 2.2 occurrences per million for the lower frequency words (with a minimum and a maximum of 0.1 and 109 occurrences per million).

In the experiment, each word of the neighbour pair could serve both as target and as parafoveal word (counterbalanced over participants). Therefore, two sets of 120 related words were derived from the original list, one where the target words corresponded to the high-frequency neighbours, and one where the target words corresponded to the low-frequency neighbours. Two corresponding sets of 120 unrelated items were then constructed, using the same words as targets, but replacing each parafoveal word with an unrelated word that was matched in frequency to the orthographically related word it was replacing (see Table 1). So, the mean and the median frequency of the first set of unrelated words (replacing the high-frequency neighbours) were 250 and 41; those of the second

TABLE 1

Example pairs of four-letter orthographically similar words that differ by their first, third, and last letter, with the corresponding pair of unrelated words

	Target word	*Parafoveal word*
Letter 1		
Related	pour (for)	four (oven)
Unrelated	pour (for)	clan (group)
Letter 3		
Related	bord (border)	bond (step)
Unrelated	bord (border)	clos (ended)
Letter 4		
Related	mien (mine)	miel (honey)
Unrelated	mien (mine)	clou (nail)

The first word corresponds to the target word, and the second word to the parafoveal word. In the example, the target word is of a higher frequency than the corresponding parafoveal word. Translation is given in parentheses.

set of unrelated words (replacing the low-frequency neighbours) were 5.9 and 2.1. Unrelated words had no more than two letters in common with the target word, and these two letters were never at the same position.

All in all, there were four conditions, two with a high-frequency target paired with a low-frequency related or unrelated parafoveal word, and two with a low-frequency target paired with a high-frequency related or unrelated parafoveal word: ''avec–aveu'', ''avec–pipe'', ''aveu–avec'', ''aveu–mais'' (where the first word corresponds to the target, and the second word to the parafoveal word). In both related and unrelated word pairs, words were never semantically related, and only a few pairs of related words were homophones (2%).

For the five-letter words, a list of 160 pairs of orthographic neighbours was constructed, with words differing in the first, second, third, fourth, or fifth letter. In each pair, both words differed in terms of their frequency of occurrence. The mean and median frequency corresponded to 97, and 40 occurrences per million for higher frequency words (with a minimum, and a maximum of 3.4, and 1624 occurrences per million), and they corresponded to 3.6, and 1.2 occurrences per million for lower frequency words (with a minimum, and a maximum of 0.01, and 63 occurrences per million). Two sets of 160 related word pairs were derived from the original list with the target corresponding either to the lower or higher frequency word of the pair. These two sets were matched with two sets of 160 unrelated word pairs where higher, and lower frequency target words respectively were each paired with an orthographically unrelated word of a similar frequency as the related parafoveal word; the median for the corresponding lower, and higher frequency parafoveal words corresponded to 1.3, and 37 occurrences per million, respectively (mean of 3.3, and 122 occurrences per million). Both words had no more than two letters in common, and these two letters were never at the same position in both words. In both related, and unrelated word pairs, the words were never semantically related.

Two sets of filler items were made, one consisting of 80 pairs of four-letter words, and the other consisting of 100 pairs of five-letter words. Of these filler items, respectively 28 and 36 contained an animal name; the other fillers were pairs of orthographically unrelated items in order to conceal the experimental manipulation. For each word length, the proportion of animal names was 13%, and the proportion of related words was 34%. It must be noted that the pairs that contained an animal name were in half the cases orthographically related, and in the other half unrelated, to discourage the participants from adopting specific strategies.

For both word lengths, two sets of 10 practice trials were prepared for presentation at the beginning of each block of trials (see below). These did not contain an animal name, and were all orthographically unrelated. In addition, two lists of 30 four- and five-letter practice trials were constructed for presentation at the beginning of the experiment. Here, both related and unrelated pairs were mixed with pairs of words that contained an animal name.

Design. For the four-letter words, a 2 × 2 × 3 within-subject design was used, with orthographic relatedness (related vs. unrelated), frequency of the target word (higher or lower frequency than the parafoveal word), and position of the critical letter (first, middle, or last letter of the word) as independent variables. For five-letter words, a 2 × 2 × 5 within-subject design was defined, with orthographic relatedness (related vs. unrelated), frequency of the target (higher or lower frequency than the parafoveal word), and position of the critical letter (first, second, third, fourth, or fifth letter of the word) as independent variables. To ensure that all words were seen in the different conditions across participants, and that each word or its associate was seen only once by each participant, a latin square design was used for both word lengths.

There was a total of 200 pairs of four-letter words, and 280 pairs of five-letter words. These were each presented in two separate blocks of trials, equated in terms of orthographic relatedness, target frequency, position of the critical letter, and number of filler, and of practice trials. Each block started with 10 practice trials, followed by the rest of the items. Words and conditions were presented in a random and different order for each participant in each block. For half the participants, the two blocks made of four-letter words were presented first, followed by the two blocks of five-letter words, and for the other half, four-, and five-letter words were presented in the reverse order. Within each word length, the order of the two blocks of trials was counterbalanced across participants. The first block of trials for each word length was preceded by a separate block of 30 practice trials to familiarise participants with the task, but also with the length of the presented words.

Apparatus. Eye movements were recorded using a fifth-generation Dual Purkinje Image eye tracker (Fourward Optical Technologies, Inc.), sampling the right eye position every millisecond with a spatial accuracy of 1 min of arc (Cornsweet & Crane, 1973). The eye tracker was interfaced with two IBM-compatible microcomputers. The first computer recorded the eye movement parameters, and analysed them online, using the software developed at the University of Leuven by Van Rensbergen and de Troy (1993). The second computer controlled the visual presentation of the stimuli. Eye movement parameters were continuously sent to the second computer, so that the visual display could be changed contingent on the position of the eyes.[1] The first computer was interfaced with two response buttons. The decision to start the next trial was based on the signal of the button press, which indicated the decision made by the participant.

[1] The display changes that were contingent on the execution of a saccade in a particular zone of the screen occurred on average at about two-thirds of the saccade duration (or at about 16 ms from the beginning of the saccade); display changes failed to occur during a saccade in about 6% of all trials across participants and conditions.

Stimuli were displayed in graphics mode on a 17-inch CRT monitor with 60 Hz refresh rate. Each character space and each letter subtended respectively 0.37°, and 0.30° of visual angle, at a distance of 1075 mm from the participants' eyes. Viewing was binocular.

Procedure. When a participant arrived in the laboratory, he or she was seated in an adjustable chair. A bite bar was prepared to minimise head movements. After setting up the eye tracker for the participant, a calibration phase began. Calibration was made using 15 points presented successively on the entire screen (5 points on both diagonal axes, and 5 points around the central horizontal axis of the screen). The first calibration point was presented in the left upper corner of the screen until the participant pressed a button, which made the point disappear, and appear at another location. Participants were asked to press the button only when they were fixating very precisely at the displayed dot location. If the calibration was not satisfactory (the correlation between the actual and the estimated eye location was less than .99 for both horizontal and vertical coordinates), another calibration phase was initiated. Otherwise, a block of trials began.

Each trial began with the presentation of two vertically aligned fixation bars that participants were asked to fixate. When the computer detected that the eyes were fixating within a region of about half a character on each side of the fixation bars, the fixation bars were removed, and an x-letter string centred on the fixation bar was presented. Simultaneously, three masks that corresponded respectively to the target, and parafoveal word and an additional x-letter string were presented to the right of the fixation bar. Each mask consisted in a series of four or five random dot patterns (depending on word length) that contained approximately the same number of pixels as the letters of the corresponding stimuli. The four simultaneously presented stimuli were equally spaced (by about one and a half characters). As soon as a saccade crossed an invisible boundary that corresponded to the last letter of the first letter string, the two words and the last letter string became visible (see for the boundary paradigm, Rayner, 1975). Participants were asked to read both words silently, and then to move their eyes to the last letter string. When the computer detected a fixation to the right of the beginning of the last letter string, and in addition that a delay of 112 ms had elapsed from the beginning of the fixation, all stimuli were removed, and a question mark was displayed at the bottom of the screen, which told participants they could indicate whether an animal name had been presented. After one or the other button press, a ''C'' or a ''F'' was displayed together with a number, which indicated respectively whether the participant's response was correct or false, and the number of the past trial. After a delay of 2 s, the next trial began.

Data analysis. Data analyses examined the first pass eye behaviour on the target word (or first word of a pair) using the following selection criteria: (1) the display change that made the two words and the last letter string visible occurred only during a saccade, (2) there was no button press before the stimuli were displayed, or during fixation on the target word, (3) there was no blink or other signal irregularity during the first eye pass on the target word, as well as during the fixation preceding, and following the first eye pass, and (4) the first fixation on the target word corresponded to the first fixation following the display change (or the appearance of both words). In addition, although there was no selection based on where the eyes initially landed in the target word, fixations on the first x-letter string in front of the target word were not included in the analyses.

After selection, the amount of data available for analysis was greatly reduced for a few participants in several conditions. Since the number of items for each critical letter position in each condition was originally low (5–10 for four-letter words, and 8 for five-letter words), we decided to combine four-, and five-letter words in the reported analyses. Furthermore, critical letter positions were grouped in two classes, referred to as outer and inner letter positions. These included respectively the first and last letter of four-, and five-letter words, and letters 2–3 in four-letter words, and 2–4 in five-letter words. The present grouping procedure was based on previous data indicating that the visibility of the first and last letter of a word in parafoveal vision is enhanced compared to the visibility of inner letters, these being more strongly affected by lateral masking (Bouma, 1973). Furthermore, as suggested by Perea (1998), orthographic priming effects may vary between inner, and outer letter positions.

In all analyses, means or proportions were calculated for each participant, and these were then averaged across participants, such that the weight of each individual participant's contribution to the global mean was similar. Analyses of variance were run on the means for each participant or each item in each condition, and when there were missing data points, these were replaced with the mean of the corresponding condition. F values will be reported by participant (F_1), and by item (F_2).

Results

In a first control analysis, the distribution of initial landing sites in the target words was plotted in the different conditions (not reported here). This revealed first that in most instances the eyes landed towards the centre of the words. An analysis of variance run on the mean initial landing sites in the different conditions revealed that none of the effects were significant (Fs $\leq$ 1.29), which ensured that in all conditions, the presented words were seen in similar visual conditions.

The *mean gaze duration* on the target words (or summed fixation duration before the eyes leave the word) was calculated as a function of orthographic relatedness, and target frequency, for both inner, and outer critical letter positions.

Results showed significant main effects of target frequency and orthographic relatedness, $F_1(1,47) = 16.15$, $p < .0005$, $F_2(1,278) = 51.25$, $p < .0005$, and $F_1(1,47) = 9.95$, $p < .005$, $F_2(1,278) = 12.75$, $p < .0005$, respectively, and a significant three-way interaction, $F_1(1,47) = 5.87$, $p < .05$, $F_2(1,278) = 4.20$, $p < .05$. Figure 1 illustrates these effects. In this figure, it is clear that the effect of target frequency was present for both outer and inner critical letter positions, with high-frequency targets being read faster than low-frequency targets, $F_1(1,47) = 17.71$, $p < .0005$, $F_2(1,143) = 31.69$, $p < .0005$, and $F_1(1,47) = 9.18$, $p < .005$, $F_2(1,135) = 20.09$, $p < .0005$, respectively. For the effect of orthographic relatedness which indicated an overall facilitation, it was almost completely due to the low-frequency target words when the critical letter corresponded to an external letter, while it was mostly due to the high-frequency target words when the critical letter was an inner letter. The effect of orthographic relatedness was significant for both outer, and inner letter cases, $F_1(1,47) = 7.60$, $p < .01$, $F_2(1,143) = 5.86$, $p < .05$, and $F_1(1,47) = 4.02$, $p < .05$, $F_2(1,135) = 7.08$, $p < .01$, respectively. The interaction between orthographic relatedness and target frequency was marginally significant for outer letters in the participant analysis, $F_1(1,47) = 2.80$, $p < .10$, $F_2(1,143) = 2.17$, and it was significant for inner letters in the participant analysis, $F_1(1,47) = 3.98$, $p < .05$, $F_2(1,135) = 2.05$.

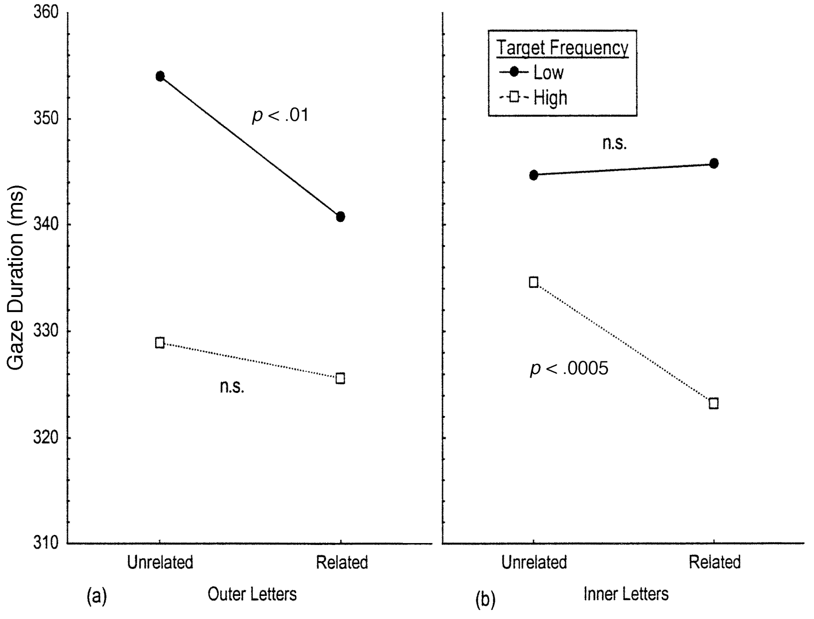

Figure 1. Mean gaze duration (in ms) on target words of high and low frequency as a function of orthographic relatedness, and separately for outer (a) and inner (b) critical letter positions. This analysis was run across four- and five-letter words.

Since the gaze duration corresponds to the delay that elapses between the onset of the target word in foveal vision, and the moment the eyes move to the next word, the effects observed with this dependent variable may either result from differences in the refixation rate (or likelihood of making more than one fixation) or from differences in the duration of individual fixations. The data reported in Table 2 indicate that the target words were refixated in only 26% of the cases, and that the effects of orthographic similarity observed in the measure of gaze duration were not due to variations in the *refixation likelihood* since none of the effects reached significance in either participant or item analysis (Fs ≤ 2.65).

The results obtained with the *mean duration of single fixations* on four-, and five-letter words closely resembled those observed in the gaze duration measure (see Figure 2). The effect of target frequency was significant in both participant and item analyses, $F_1(1, 47) = 8.53$, $p < .005$, $F_2(1, 278) = 13.79$, $p < .005$, although being significant only for outer letter positions, $F_1(1, 47) = 18.87$, $p < .0005$, $F_2(1, 143) = 16.99$, $p < .0005$, and $F_1(1, 47) = 1.60$, $F_2(1, 135) = 1.22$, respectively for outer and inner letters. The effect of orthographic relatedness was marginally significant in the participant analysis, $F_1(1, 47) = 3.30$, $p < .10$, and significant in the item analysis, $F_2(1, 278) = 4.37$, $p < .05$. In addition, the three-way interaction was significant in the participant analysis, $F_1(1, 47) = 7.91$, $p < .01$, and marginally significant in the item analysis, $F_2(1, 278) = 2.74$, $p < .10$. Looking at the data for both positions of the letter changed, we obtained a pattern that looked very similar to the one displayed in Figure 1. The only real difference between both sets of findings was for low-frequency targets with a parafoveal word that differed by one inner letter; this now revealed a tendency for an inhibition with orthographic relatedness, while the general tendency was again facilitating. The effect of orthographic relatedness was significant for outer letters in the participant analysis, $F_1(1, 47) = 7.46$, $p < .01$, $F_2(1, 143) = 1.50$, and marginally significant in the item analysis of inner letters, $F_1 < 1$, $F_2(1, 135) = 3.05$, $p < .10$. The interaction between orthographic relatedness and target frequency was significant only for inner letters in the participant analysis, $F_1(1, 47) = 4.24$, $p < .05$; other Fs ≤ 2.24.

TABLE 2
Likelihood of refixating the target word as a function of target frequency, and orthographic relatedness, separately for outer and inner critical letter positions. This analysis was run across four- and five-letter words

	Outer letters		*Inner letters*	
	Related	*Unrelated*	*Related*	*Unrelated*
Low-frequency targets	.27	.26	.27	.26
High-frequency targets	.26	.25	.26	.24

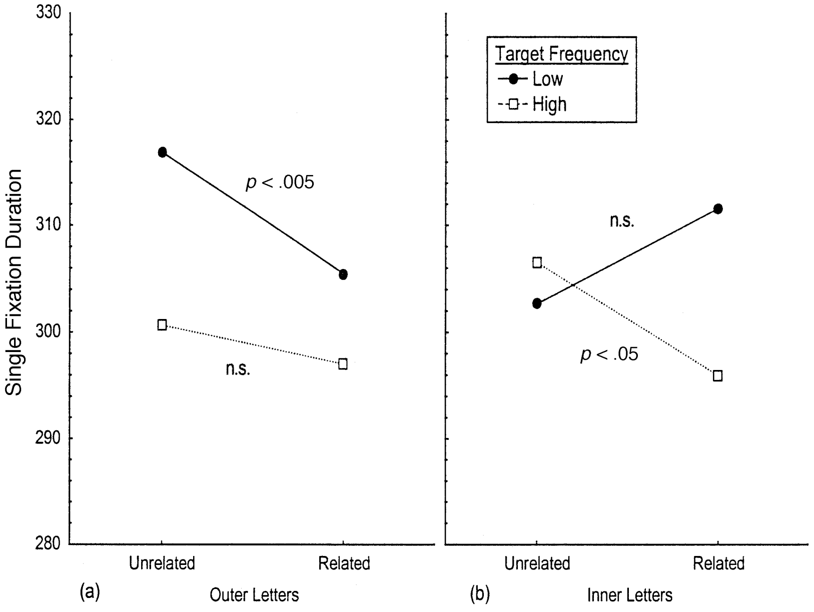

Figure 2. Mean duration of single fixation (in ms) on target words of high and low frequency as a function of orthographic relatedness, and separately for outer (a) and inner (b) critical letter positions. This analysis was run across four- and five-letter words.

As can be seen in Figure 3, the *mean duration of first fixations* (which includes instances where the first fixation on the target word was or was not followed by an additional fixation), revealed again the same trends with target frequency and orthographic relatedness, but in a much weaker manner. The effect of target frequency was significant in both participant and item analyses, $F_1(1,47) = 14.80$, $p < .0005$, $F_2(1,278) = 12.72$, $p < .0005$, although being significant only for outer letter positions, $F_1(1,47) = 23.21$, $p < .0005$, $F_2(1,143) = 16.33$, $p < .0005$. The effect of orthographic relatedness was never significant (Fs ≤ 2.30), and the three-way interaction was only marginally significant in the participant analysis, $F_1(1,47) = 3.20$, $p < .10$; $F_2(1,278) = 1.30$.

Discussion

The aim of the present experiment was to examine the role of visual attention in the processing of two adjacent words, one in foveal vision and one in parafoveal vision, and to determine whether both words are processed in parallel or in sequence. For this purpose, a test of the presence of parafoveal-on-foveal effects due to orthographic relatedness was conducted. A foveal target word was presented in a reading-like situation, and it was accompanied in parafoveal vision

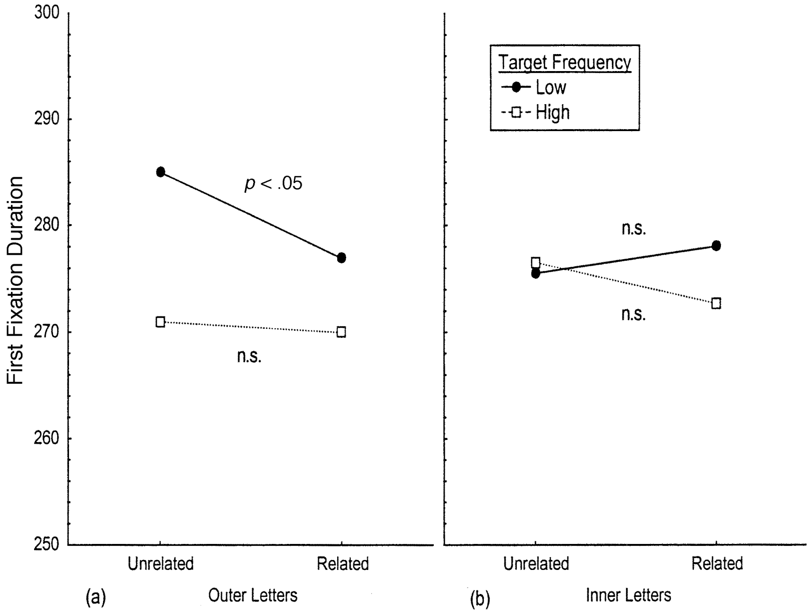

Figure 3. Mean duration of first fixations (in ms) on target words of high and low frequency as a function of orthographic relatedness, and separately for outer (a) and inner (b) critical letter positions. This analysis was run across four- and five-letter words.

by either an orthographically very similar word (a neighbour that differed by a single letter) or a completely different word. In addition, the relative frequency of the target and the parafoveal word was manipulated such that the target corresponded either to the higher or the lower frequency word of the pair. According to a sequential attentional model, the nature of the parafoveal word should not have an effect on the gaze duration of the target word, because processing of the foveal word is supposed to be *finished* before the attention spotlight switches to the next word (Henderson & Ferreira, 1990; Morrison, 1984; Reichle et al., 1998). However, as noted above, an early facilitation due to orthographic similarity may still be reconciled with a sequential view, but only if the effect is similar between high-, and low-frequency parafoveal words. In contrast, a pure parallel processing view predicts an interaction between the processing of parafoveal and foveal words (see Schroyens et al., 1999). This interaction should be reflected in a differential effect of orthographic similarity with the relative frequency of both words. In between both views, distributed parallel processing unambiguously predicts the presence of parafoveal-on-foveal influences of an orthographic type, but it cannot predict differential effects depending on the relative frequency of target and parafoveal words (Engbert et al., 2002; Inhoff et al., 2000a, 2000b).

The present study yielded two results. A first significant finding was that parafoveal-on-foveal influences of an orthographic type do occur when reading pairs of isolated words. In conditions where the foveal target word shared orthographic features with the parafoveal word, the gaze duration, and to a certain extent the duration of single fixations, were shorter than when both words were orthographically dissimilar. The second, but less systematic finding relied on the possibility that orthographic parafoveal-on-foveal effects may vary with the relative frequency of target and parafoveal words. A tendency for differential effects of orthographic relatedness with word frequency was indeed observed at least in the measures of gaze duration and single fixation duration, but this proved to be nonsignificant in most cases, and the picture was made more complex, as the effects also varied with the position of the critical letter in the words. A pattern of data still came out significantly in both gaze duration, and single fixation duration (i.e., the three-way interaction), which basically revealed a tendency for greater facilitation with either low- or high-frequency target words depending, respectively, on whether the critical letter corresponded to an external or an internal letter.

A priori, these results may not allow us to distinguish between alternative views for the processing of adjacent words. First, the observation of an overall facilitation due to orthographic relatedness, which is in line with previous reports of visual, and orthographic parafoveal influences (Inhoff et al., 2000b), only tells us that the processing of two adjacent words can occur in parallel at least up to the letter level. It is therefore compatible with either pure parallel or distributed processing views. It is also not completely opposed to a sequential view, as the possibility that attention may not be perfectly focused on the foveal word at the very beginning of a fixation can be envisaged in sequential processing models. On the other hand, the unexpected combined influence of target frequency and critical letter position on the likelihood of parafoveal-on-foveal effects does not unambiguously indicate that parallel processing extends beyond the letter level. Indeed, the possibility that the pattern of data may be due to perceptual rather than lexical processes cannot be completely excluded. In particular, since both four-, and five-letter words were mixed in the reported analysis, data selection may have resulted in more data from a given word length in some conditions.

The observation that parafoveal-on-foveal effects were not present across all dependent variables, and particularly that these failed to come out significant in the measure of refixation likelihood, and first fixation duration may however, constitute one case against sequential processing models. If parafoveal-on-foveal effects were due to attention being not perfectly focused on the foveal word at the very beginning of an eye fixation, or before selective processing occurs, then these effects should emerge relatively early in the time course of an eye fixation. They should therefore be more likely to occur in the measure of refixation likelihood, and first fixation duration, as these may correspond to earlier indicators of ongoing processing than single fixation or gaze durations. In line with this assumption, previous studies indicate that the duration of first fixations in instances where the word receives two consecutive fixations is relatively short, and shorter on average than the duration of single fixations (see Vitu, McConkie, Kerr, & O'Regan, 2001; Vitu & O'Regan, 1995). This suggests first that the programming of a within-word refixation arises relatively early, and second, that the duration of first fixations when averaged over one and several fixation cases is biased towards shorter time ranges than single fixation or gaze duration.

To examine in more detail the time course of parafoveal-on-foveal effects, a quartile analysis of the gaze duration in the different conditions was conducted. For this analysis, only five-letter target words were considered, since controlling for the length of the words may help by reducing the range of possible interpretations for the observed phenomena. Results presented in Figure 4 reveal that a facilitation effect due to orthographic similarity emerges over time for low-frequency targets in the case of outer letters, and for high-frequency targets in the case of inner letters. It is only for gaze durations in the range of 350–400 ms (around the third quartile) that the outer-letter curves differentiate between high- and low-frequency targets, and at about 320 ms (median) that a difference starts emerging between high- and low-frequency targets for the case of inner letters. An analysis of variance run separately on each quartile actually revealed that the three-way interaction involving orthographic relatedness, target frequency, and critical letter position (with two levels) was significant only for the third quartile, $F_1(1, 47) = 4.76$, $p < .05$. These results confirm the notion that orthographic parafoveal-on-foveal influences may be only lately determined, which suggests that our failure to report significant effects with first fixation duration resulted from the time course of the effects in relation with the characteristics of the dependent variable. Given the time range of first fixation durations, which averaged at about 272 ms for five-letter words, only a hint of an effect could be captured with this dependent variable.

The present observation that orthographic influences from the parafovea take time to develop, and actually do not emerge earlier than 320–350 ms from the beginning of an eye fixation, leads us to reject the hypothesis that sequential processing was at the origin of the reported effects. In addition, the similarity in the pattern of data between instances where four- and five-letter words were mixed, and instances where only five-letter words were considered (see for comparison, Figure 1b and Figure 4c, e–f) suggests that the combined influence of target frequency, and critical letter position on the likelihood of parafoveal-on-foveal effects does not result from a confounding with word length, and it cannot therefore be solely attributed to perceptual factors. The question however remains as to whether pure parallel processing or distributed processing best accounts for the observed effects, and in a

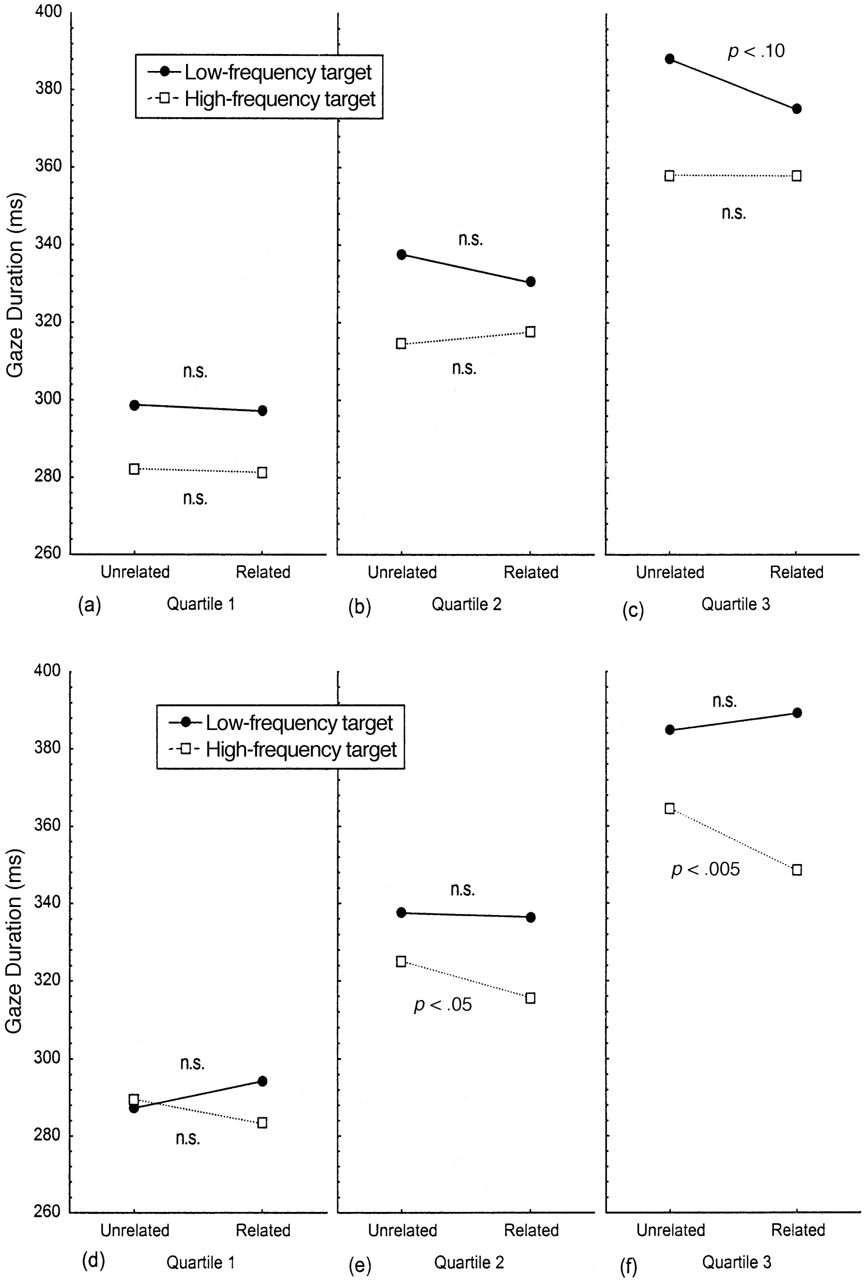

Figure 4. First, second, and third quartile of the gaze duration on five-letter target words of high and low frequency as a function of orthographic relatedness, and separately for outer (a–c) and inner (d–f) critical letter positions.

relative manner, which processes underlie the role of the critical letter position. We have at present no definitive explanation for the obtained pattern of data, although we could not find a way to account for it in the framework of distributed processing models (see Inhoff et al., 2000a, 2000b). The assumption that more resources would be allocated to the foveal word when it is difficult to process cannot account for the fact that parafoveal-on-foveal effects tend to be larger with low- than high-frequency targets when the words differ by their first or last letter.

A pure parallel processing view may be a better candidate at accounting for the present set of findings. This makes no recourse to the notion of attention, and envisages the processing of two adjacent words in terms of a competition between the lexical candidates that become activated on the basis of both foveal and parafoveal letter information. In this view, all letters are extracted simultaneously, and the primary constraint is that visual information is sampled with a higher resolution, and therefore faster from the centre of the foveal region than from the parafoveal region (see Schiepers, 1980; Schroyens et al., 1999). An additional constraint relates to the respective properties of the foveal and parafoveal words, which affect the rate of ongoing processing associated with each word, and therefore determine the presence or absence of parafoveal-on-foveal effects. As suggested by previous studies, word frequency may be one of those critical factors. First, the frequency of the fixated word directly influences the gaze duration on the word, which in turn determines the amount of parafoveal processing (Schroyens et al., 1999). Second, the frequency of a parafoveal word largely influences the rate of parafoveal processing (Inhoff & Rayner, 1986; Vitu, 1991). Third, when both foveal and parafoveal words are orthographically similar, their respective frequency determines which word gets activated first, and therefore whether the parafoveal word can compete with the foveal word (see Segui & Grainger, 1990).

Starting from this, we may expect that in the present experiment, parafoveal preview was more efficient when low-frequency targets were paired with high-frequency parafoveal words than in the opposite condition. However, whether this resulted in the former case in greater facilitation or in inhibition (or a null effect) did not only depend on the respective frequency of foveal and parafoveal words, or their level of competitiveness, but also on the position of the critical letter that distinguished both words, or the ease with which this letter could be detected (Bouma, 1973). First, when the critical letter corresponded to the first or last letter of the word, its visibility was enhanced, and the possibility of noticing where both words differed was increased. This helped in the rejection as a candidate for the foveal location, one competing candidate (i.e., a higher frequency neighbour) that was quickly activated from the parafovea. As a result, facilitation was favoured when low-frequency targets were paired with a high-frequency parafoveal word. In a reverse manner, the condition where a high-frequency target was associated with a lower frequency parafoveal word tended to produce no effect, probably because rapid identification of the foveal word coupled with the possibility of detecting the critical letter resulted in an inhibition of the parafoveal word unit, neutralising the facilitation that would normally arise from having two sets of similar features/letters in foveal and parafoveal vision respectively.

On the other hand, when the critical letter corresponded to an inner letter, its visibility was reduced due to lateral masking. This first allowed facilitation due to feature/letter similarity to arise when high-frequency targets were paired with low-frequency parafoveal words. In opposition, this produced no facilitation, or a tendency for an inhibition in the condition where a high-frequency parafoveal word accompanied a low-frequency target. Indeed, the parafoveal word was processed faster than the foveal word, and it acted as a strong competing candidate. As suggested by Segui and Grainger's (1990) masked priming study, when a candidate gets more likely, inhibition of its lower frequency neighbours including the target word may develop interfering with the identification of the target. The reason why our results failed to reveal a significant inhibition is not clear at present, although this may be related to timing constraints or the fact that inhibitory effects take more time to emerge than facilitation effects. Indeed, in another experiment (unpublished data using the same paradigm) we succeeded in obtaining inhibitory effects in conditions where the words were read at a lower pace than in the present experiment. In the same manner, Perea (1998) reported inhibitory priming effects for the case of inner letters, but in a perceptual identification study where participants' responses were not time-constrained.

It is clear that the above set of assumptions will need to be tested further, and that the present work was only an initial approach in trying to distinguish between alternative views for the processing of adjacent words. Further research may benefit from trying to replicate the present study with more observations, and also from attempting to determine whether the effects suggested in the present paper generalise to normal reading situations. At the same time, we think that the present results may not be specific to the recognition of pairs of isolated words. Our experimental situation although corresponding to an over-simplified reading task that involves none of the syntactic or semantic high-level processes specific to natural reading, was relatively successful in reproducing the dynamics of oculomotor scanning that characterise reading. The gaze durations observed in our experiment were on average about 50 ms longer than the gaze durations observed in normal reading, indicating that the two RT distributions have considerable overlap. In addition, the effect still prevailed when the analysis was limited to single fixations, which had an average duration very similar to the gaze durations reported by Schilling et al. (1998).

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