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Parafoveal-on-foveal effects on eye movements in text reading: Does an extra space make a difference?

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Abstract

Schiepers [Schiepers (1980). Response latency and accuracy in visual word recognition. *Perception & Psychophysics, 27*, 71–81] proposed that in text reading, the currently fixated word and the next word are processed in parallel but with a time delay of 90 ms per degree of eccentricity. In his model, the benefit of seeing the upcoming word is due to the fact that the parafoveal information from fixation n is combined with the foveal information from fixation $n + 1$ to boost word recognition, at least when the fixation on word n is of an optimal duration (between 210 and 270 ms). We tested this assumption by adding an extra blank space between the foveal and the parafoveal word. According to the model, this should result in a 30 ms longer processing time for the foveal word. However, reading time was shorter for a word followed by a double space than for a word followed by a single space. An effect of parafoveal word length was also observed with a longer word in the parafovea leading to shorter fixation times on the foveal word. Implications of these low-level parafoveal-on-foveal effects are discussed.

Keywords: Reading; Parafoveal-on-foveal effects

1. Introduction

When people are reading, their eye movements are characterized by a sequence of saccades and fixations. The main purpose of the saccades is to bring new information into the center of the visual field, where visual acuity is highest. However, there is a large body of evidence that, in addition to foveal word processing, information from the word to the right of the fixation is extracted and used in reading as well (see Rayner, 1998; for a review). Two of the most important findings in this respect are the phenomenon of word skipping and the so-called parafoveal preview benefit. About one third of the words in a text are skipped during first-pass reading. This is particularly so for short words and words that lie close to the previous fixation location (i.e., when the saccade is launched from the second half of the word prior to the target word). There is also a smaller influence of the difficulty of the target word (see Brysbaert, Drieghe, & Vitu, 2005; Brysbaert & Vitu, 1998, for a meta-analysis of the data). The parafoveal preview benefit refers to the finding that reading is slower when the letters of the word to the right of the currently fixated word are not visible than when they are visible (e.g. Blanchard, Pollatsek, & Rayner, 1989; Morris, Rayner, & Pollatsek, 1990; Rayner, 1975; Rayner, Well, Pollatsek, & Bertera, 1982). From these findings, it is clear that processing of parafoveal information plays a role in normal reading. There is, however, much more controversy over the question to what extent

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parafoveal information concerning word $n+1$ influences the fixation duration and gaze duration[2] of the currently fixated word *n*. This latter possibility is referred to as parafoveal-on-foveal effects and several suggestions of such effects have been made.

A first way in which parafoveal processing of word $n+1$ might influence the gaze duration on word *n*, was proposed by Pollatsek, Rayner, and Balota (1986). They reported that the fixation duration was longer before a saccade that skipped the next word than before a saccade that was targeted at the next word. They interpreted this finding as evidence for the hypothesis that words were skipped as a result of a two-stage process. First, a saccade was programmed to word $n+1$, but if this word was recognized (or was likely to be recognized) before the saccade was initiated, the program could be cancelled and replaced by a new program for a saccade towards word $n+2$ (see Reichle, Rayner, & Pollatsek, 2003; for the latest update of this model of eye movement control). The cancellation of the original program and the replacement by a new one were the origin of the longer fixation duration on word *n*. Unfortunately, this finding is a bit controversial with some studies finding the effect and others that do not (e.g., Drieghe, Brysbaert, Desmet, & Debaecke, 2004; but see Drieghe, Rayner, & Pollatsek, submitted). A recent study suggests that longer fixations before a skipping saccade are observed only when long and difficult words are being skipped (Kliegl & Engbert, in press). When short and easy words are skipped, fixation durations actually tend to be shorter than when these words are fixated. Although the latter finding is a problem for most theories of eye movement control in reading, if it can be replicated it still is an example of how processing word $n+1$ may influence the gaze durations on word *n*.

Another suggestion of how parafoveal word $n+1$ might affect the gaze duration on word *n* was made by Kennedy and colleagues (e.g., Kennedy, 1998; Kennedy, Murray, & Boissiere, 2004; Kennedy & Pynte, 2005). Kennedy (1998) reported that the gaze durations on word *n* were shorter when word $n+1$ was a low-frequency word and when it was a long word. He interpreted this paradoxical parafoveal-on-foveal effect as evidence for a model of eye movement control (which has been referred to as the process monitoring hypothesis) in which word *n* and word $n+1$ are processed in parallel (with some time delay depending on the length of word *n*) and in which the resources are allocated as a function of the difficulty of both words. The harder word $n+1$ is to process, the stronger it pulls the eyes towards it, in order to optimize the extraction of visual information from the page of text. Again, however, the evidence for this parafoveal-on-foveal effect is not unequivocal, with some studies failing to report an effect of the difficulty of word $n+1$ on the gaze duration for word *n* (e.g., White & Liversedge, 2004), and others reporting a lengthening of the gaze duration for difficult parafoveal words (e.g., Hyönä & Bertram, 2004, Experiment 2; see Rayner & Juhasz, 2004; for a critical review of the evidence).

A final suggestion about how processing of word $n+1$ might affect the reading time of word *n* was made by Schiepers (1980). Schiepers started from the observation that in a perceptual identification task it takes on average 90 ms longer per degree of eccentricity to identify a word, arguably because it takes that much time for the stimulus to activate the relevant letter and word representations in the brain. Given that one degree of visual angle roughly coincides with three letter positions[3] and that saccades usually are 7–9 letters long, Schiepers hypothesized that if word $n+1$ was presented in foveal vision 210–270 ms after it had been presented in parafoveal vision, the parafoveal information from fixation *n* could be merged with the foveal information on fixation $n+1$. By combining both sources of information, the activation of the word representation could be faster than if it were based on the foveal information alone. This, argued Schiepers, could be the origin of the typical fixation durations of some 250 ms seen in text reading. When fixations are shorter or longer, part of the parafoveal preview benefit is lost, because the synchrony in the arrival of parafoveal and foveal information is less than optimal.

The ideas of Schiepers (1980) were utilized by Schroyens, Vitu, Brysbaert, and d'Ydewalle (1999) to provide a neat explanation of a puzzling finding. In their experiment, Schroyens et al. presented three alphabetic stimuli. The first one was a boundary stimulus, which either was a high-frequency word, a low frequency-word, or a homogeneous string of the letter z. There were two lengths of these boundary stimuli: 3 letters long (e.g., *now*, *tic*, *zzz*) and 5 letters long (e.g., *first*, *vaunt*, *zzzzz*). The second word was the target word and was a high-frequency or a low-frequency word of 7 letters (e.g., *because*, *judaism*). Finally, there was a third word with a length ranging from 4 to 8 letters. The task of the participants was to read the three stimuli and to indicate whether one of the words referred to an article of clothing (e.g., *cap*, *skirt*, *trousers*). The intriguing finding was that participants looked more than 20 ms longer at a *zzzzz* string than at a *zzz* string, even though there was no more information to be obtained from a 5-letter z-string than from a 3-letter z-string. Sch-

[2] The gaze duration is the sum of the fixations from the moment the eyes land on word n to the moment they move off again.

[3] Nowadays we know that in reading the numbers of letters are a more appropriate metric to use than degrees of eccentricity. The number of letters crossed by saccades is relatively stable, independent of the visual angle (Morrison & Rayner, 1981).

royens et al. ventured that the only reason for the longer gaze durations on *zzzzz* than on *zzz* was that in the former case the parafoveal word was on average one letter position further away from the fixation location. If fixation durations are partly determined by the need to synchronize the parafoveal information from the current fixation with the foveal information from the next fixation, then the oculomotor system had some 30 ms longer to wait before initiating the saccade.

Strong influences of word length on eye movement parameters have also been reported in studies that looked at the factors that govern eye movement control in text reading. Increases in word length are known to increase the probability of fixating a word (Brysbaert & Vitu, 1998; Rayner & McConkie, 1976) and of making a second fixation on that word (Vitu, O'Regan, Inhoff, & Topolski, 1995). Word length is also positively correlated with gaze duration, partly because of the increased tendency to refixate long words, but also partly due to increased fixation durations on long words (Calvo & Meseguer, 2002; Rayner & Fischer, 1996; Rayner, Sereno, & Raney, 1996). Interestingly, the issue of word length has never received much attention from researchers investigating visual word recognition with lexical decision and word naming. The prevailing wisdom (e.g., Balota, 1994, pp. 308–309; Harley, 2001, p. 148) seems to be that word length does not have a strong effect on lexical decision and naming, as long as words are controlled for frequency and lexical neighborhood, and as long as the nonwords in the lexical decision task are properly chosen (Hudson & Bergman, 1985)[4]. Because of these divergent views on the impact of word length, it seemed worthwhile to us to explicitly test whether part of the word length effect in text reading could be a result of the need to synchronize the arrival of parafoveal and foveal information, as claimed by Schiepers (1980) and recently endorsed by Schroyens et al. (1999) and Kennedy, Pynte, and Ducrot (2002).

There is a very simple test of Schiepers's conjecture. If the retinal distance between the parafoveal and the foveal word affects the reading time of the foveal word, then adding an extra space between both words should result in a longer gaze duration on the foveal word. This extra time should be in the order of 30 ms (as the parafoveal information has been shifted by one third of a degree of visual angle). Prior studies using manipulations of the spacing between words have concentrated primarily on the effects of denying space information. This line of research has shown that reading unspaced text is detrimental for the reading rate (for a review see Rayner & Pollatsek, 1996) hence demonstrating the importance of the word boundaries. Only a few studies have looked at the effects of double spacing, and those that did so mostly used a letter search task (e.g. Jacobs, 1987; Jacobs & O'Regan, 1987). The study that comes closest to the current experiment is a study by Rayner, Fischer, and Pollatsek (1998). In their second experiment they used a so-called wide space condition. It consisted of a blocked presentation of three blank spaces between the words. The task was normal reading. The comparison between this spaced condition and normal reading showed no significant differences, but the means strongly suggested, contrary to the prediction from the Schiepers model, a reduction of the viewing times in the case of wide spacing. The only other studies we are aware of that used double spacing in normal or close to normal reading are Kolers, Duchnicky, and Ferguson (1981) and Heller and Müller (1983). Kolers and colleagues directly compared single and double spacing and reported no effects on individual fixations but a slightly lower number of fixations in the condition with the double spacing. In the study by Heller and Müller the distance between the words was varied between 1° and 7°. A larger distance between the pre-target and the target word resulted in longer saccades and prolonged fixation durations on the target, presumably because of a reduced parafoveal preview benefit.

2. Experiment 1

Whereas Rayner et al., Kolers et al., and Heller and Müller used a blocked presentation of the wide spacing, in our experiment we worked with normally spaced text that had an occasional extra blank space after target words of 5 letters. We chose this word length because we wanted to increase our chances of observing a single fixation on the target word (words that are shorter, are skipped too often; and words that are longer, are refixated too often). To ensure that the extra blank space would not draw too much attention, we used a large number of filler texts in the experiment.

2.1. Method

2.1.1. Participants

Participants were 40 first-year students at Ghent University, who participated for course credits. They all had normal, uncorrected vision and were native Dutch speakers.

2.1.2. Apparatus

Eye movements were recorded with a Senso-Motoric Instruments (SMI Eyelink) video-based pupil tracking system. Viewing was binocular but eye movements were recorded from the right eye only. A high speed video camera was used for recording. It was positioned

[4] The missing word length effect in visual word recognition is present even up to 9 letter words but is limited to skilled readers. Impaired and beginning readers show a word length effect in smaller words (Nazir, 2000).

underneath the monitored eye and held in place by head-mounted gear. The system had a visual resolution of 20 s of arc. Fixation locations were sampled every 4 ms and these raw data were used to determine the different measures of oculomotor activity during reading. The display was placed at a distance of 69 cm from the participant's eye, so that three characters coincided with 1° of visual angle. A chin rest was used to reduce head movements during the experiment.

2.1.3. Materials

We used the 36 text fragments created for the Drieghe et al. (2004) study.[5] Each text fragment consisted of five lines of text. The original purpose of this stimulus set was to examine combined effects of word length (2 and 4 letter words) and predictability on word skipping, but this has no further relevance for the present study. The 5-letter words in the stimulus set served as the target words of the present experiment. All the targets were located in the middle portion of a line of a text and none was the last or penultimate word of a sentence. For each text, two variants were made according to a latin-square design, with half of the targets followed by one blank space, and the other half followed by two blank spaces. To increase the number of observations we allowed for two 5-letter words to serve as targets within the same text fragment. When this was the case, one variant always had one blank space after the first target and a double after the second target; for the other variant, the order was reversed. In total, there were 35 cases of words followed by a double space and 35 matched cases of words followed by a single space.

2.1.4. Procedure

Before the experiment started, participants were informed that the study was about the comprehension of short texts that were displayed on a computer screen. Text administration was self-paced. Participants stopped text presentation by pressing on a button. Each passage of text was presented as a whole. Participants were asked to read at their normal speed, and to answer any comprehension question that would follow the passage. On average, questions followed on one fourth of the trials. The participants had no difficulty answering these questions, which were simple true–false statements. They were correct 87% of the time. The initial calibration of the eye-tracking system generally took approximately 10 min and consisted of a standard nine-point grid. Following the initial calibration the participant was given 10 practice trials to become familiar with the procedure before reading the experimental text fragments. The 36 experimental text fragments were embedded in a pseudo-random order in 108 filler texts. Each participant was presented with one of the two possible variants of the critical text fragments according to a Latin square design. Participants completed a single session lasting about 1 h, containing 144 text fragments to read.

2.2. Results

Our primary dependent variable of interest is the single fixation duration on the target word. We will also report the gaze duration[6] on the target word as well as the number of fixations on the target word. For the word after the target word, we will report the first fixation duration and gaze duration, as well as the properties of the saccade originating from the target word and landing on the following word. These latter measurements are reported to look at the effects the extra blank space has after the eyes have left the target word. 5.4% of the data were removed from the analyses because of track loss or because the fixation was shorter than 100 ms (see Morrison, 1984; Rayner, Sereno, Morris, Schmauder, & Clifton, 1989; for justification). From this data set, the gaze duration and number of fixations on the target word were calculated. After these analyses, a supplementary reduction of the data set was done for calculating the other measurements, by selecting only those trials in which there was a single fixation on the target word followed by a forward saccade. All in all, 1473 observations (of a total of 2800) were included in this reduced data set. All analyses were run over participants ($F1$-analyses) and items ($F2$-analyses).

2.2.1. Fixation times on the target

A repeated measures ANOVA was carried out on the gaze durations on the target word, which are shown in Table 1. The gaze duration on the target word followed by a double blank space was shorter than when it was followed by a single blank space. This 8 ms effect was marginally significant by participants [$F1(1,39) = 3.39$, $p < 0.10$] and was significant by items [$F2(1,69) = 2.95$, $p = 0.05$].

The single fixation times on the target also revealed an effect opposite to what was expected. Instead of increasing the fixation duration, an extra blank space reduced the single fixation duration on the target word. A repeated measures ANOVA revealed that this 10 ms effect was significant both by participants [$F1(1,39) = 5.61$, $p < 0.05$] and by items [$F2(1,69) = 7.84$, $p < 0.01$]. The effect was not due to the fact that the target word was skipped less often in the two blank spaces condition than in the single blank space condition or to the fact

[5] All materials are available from the first author upon request, denis.drieghe@ugent.be.

[6] First fixation duration on the target word will not be reported because the target word was in the vast majority of the cases fixated only once (see analysis of fixation probability and number of fixations).

Table 1
Fixation time measures (in ms), number of fixations and fixation probability as a function of number of blank spaces after the target

	Number of blank spaces after the target word	
	1 space	2 spaces
Gaze duration word *N*	236	228
Single fixation duration word *N*	228	218
Number of fixations word *N*	0.77	0.75
Fixation probability word *N*	0.72	0.70
First fixation duration word *N* + 1	218	212
Gaze duration word *N* + 1	241	240

that the target word was refixated more often in one of the conditions. This can be seen from the number of fixations on the target word (0.77 fixations single blank space vs. 0.75 fixations in the double blank space condition, all *F*'s < 1) and the fixation probability of the target word (0.72 in the single blank space condition vs. a fixation probability of 0.70 in the double blank space condition, $F1(1,39) = 1.23$, $p > 0.20$; $F2(1,69) = 2.17$, $p < 0.10$), both shown in Table 1.

In our search for variables that moderated the reduction of the single fixation duration when the target word was followed by two blank spaces, we noticed that the reduction correlated with the length of word $n + 1$ [$t(68) = 2.05$, $p < 0.05$, explaining 24% of the variance]. The reduction was larger for long parafoveal words than for short parafoveal words. For instance, it was 17 ms for a 4-letter word in the parafovea, whereas it amounted to 38 ms for an 8-letter word.

2.2.2. Fixation times on the word following the target

As soon as the eyes landed on the word after the target word, the extra blank space manipulation no longer exerted an effect on the fixation times. The 6 ms difference in the first fixation duration was not significant [$F1 < 1$; $F2(1,61) = 3.39$, $p > 0.05$], nor was there any difference in the gaze duration [$F1 < 1$; $F2(1,61) = 1.45$, $p > 0.20$].

2.2.3. Characteristics of the saccade originating from the target

As can be seen from Fig. 1, the extra blank space caused a lengthening of the saccade out of the target word by 1.2 letter positions. This effect was significant both by participants [$F1(1,39) = 40.87$, $p < 0.001$] and by items [$F2(1,61) = 50.30$, $p < 0.001$]. Because the lengthening fully compensated for the extra blank space, the average landing position on word $n + 1$ was exactly the same in both conditions, regardless of the manipulation.

2.3. Discussion

According to Schiepers's (1980) model, foveal and parafoveal words are processed in parallel but with a time delay of 90 ms per degree of eccentricity. We hypothesized that adding an extra blank space to a word would result in the eyes staying for an extra 30 ms on this word before the synchrony became jeopardized. Therefore, inflated fixation durations on the word were predicted. What we found, however, was the complete opposite: Inserting an extra blank space after a target word did not result in longer fixations on the word, but in shorter fixations. This effect was marginally significant in the gaze durations on the target word, but was significant in the single fixation times. The direction of the effect and its size are highly comparable to the results obtained in a related study by Rayner et al. (1998). They reported on average 12 ms shorter fixation durations in their wide spacing condition. While there are some clear differences between both studies (Rayner et al. used a blocked presentation and three blank

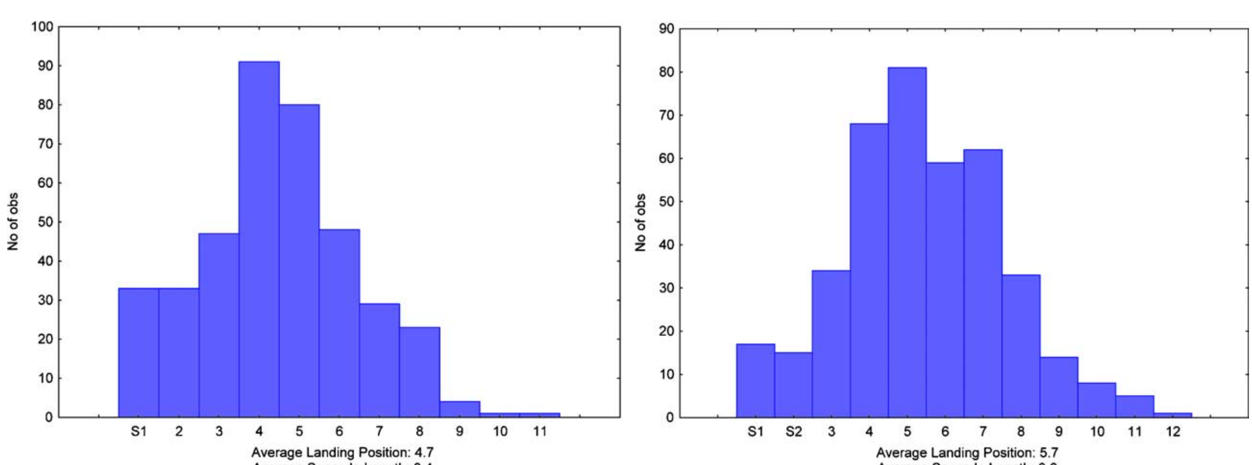

Fig. 1. Landing distribution of the saccade originating from the target word (in letter positions). The letter S indicates a blank space. Left-hand curve is the one blank space condition, right-hand curve is the two blank spaces condition.

spaces), it is reasonable to assume that the trend of an effect observed by Rayner et al. is the same effect we observe in the present experiment. Inserting an extra blank space between the words n and $n + 1$ causes (a) a reduction of the viewing time on word n, (b) a lengthening of the saccade from word n to word $n + 1$ by one character position to compensate for the extra blank space, and (c) no spill-over effects when the eyes land on word $n + 1$. We shall return to these findings in the general discussion.

A further (serendipitous) finding of the present experiment was that the reduction of the viewing times in the double blank space condition seemed to be modulated by the length of the parafoveal word. The difference between a single and a double blank space was larger for long words in the parafovea than for short words. However, before we speculate about the origin of this effect, it seemed appropriate to first try to replicate it in a proper experiment. After all, in Experiment 1 the length of the parafoveal word was not manipulated and, therefore, the parafoveal word lengths were unequally distributed.[7]

3. Experiment 2

Experiment 2 replicated the first experiment but manipulated the parafoveal word length. Short parafoveal words were 4-letter words; long words were 8-letter words. In addition, we created mindless reading trials in which the words were replaced by z-strings. These meaningless stimuli allowed us to assess to what extent the effect of parafoveal word was due to language processing or to low-level oculomotor control processes.

The task of z-reading, in which participants are asked to "fake" reading z-strings, is not new. In a study by Vitu et al. (1995) the task was used to compare the oculomotor behavior of readers reading normal text and readers scanning meaningless materials. Based on the similarity of the eye movement patterns in both conditions, they concluded that predetermined oculomotor strategies are an important determinant of eye movement control in reading. This conclusion was questioned by subsequent research. Rayner and Fischer (1996) reported many differences between text- and z-reading at a finer level of analysis, which they took as evidence for the hypothesis that eye movement control in reading is under immediate language control. Among the differences reported were increased fixation times and skipping rates in the z-string condition.

A comparison of text-reading and z-reading allowed us to determine whether the shorter fixation durations on a target word followed by a double blank space are due to the readability of the word (as a consequence of reduced lateral inhibition), or a low-level variable related to the lay-out of the different word blobs within the sentence. In addition, a comparison of text-reading and z-reading allowed us to see whether the effect of the length of the parafoveal word is language-inspired or whether it is due to a greater pulling of long word blobs (such as the global effect, proposed by Vitu, 1991).

3.1. Method

3.1.1. Participants

Thirty-two members of the Ghent University community participated in this experiment. All participants were native speakers of Dutch and had normal or corrected vision. They were paid 10€ for their participation.

3.1.2. Apparatus

The apparatus was the same as in Experiment 1.

3.1.3. Materials

We selected 30 text fragments from the 36 used in Experiment 1.[8] These text fragments were altered to ensure that every text fragment featured four 5-letter words, two of which were followed by a 4-letter word, and two by an 8-letter word. The 5-letter words served as the target words of the present experiment. All the target words were located in the middle part of a line of text and none was the last or penultimate word of a sentence. For each text fragment, two variants were made according to a latin-square design. Each variant had two instances of a double blank space, equally distributed over the short and long parafoveal words. In the alternate version, the single and double spaces were swapped. After the creation of the text fragments, we doubled the stimulus set by replacing all letters in the text fragments with the letter z, hence creating an extra 30 text fragments with two versions that mirrored all the properties of the original text fragments, with the exception of the letter identities. Overall, 120 text fragments were created.

3.1.4. Procedure

The procedure was the same as in Experiment 1 with a few exceptions. Participants were notified that 30 random trials would consist of z-strings and that they were

[7] From the 70 target words, 15 were followed by a 2-letter word, 16 by a 3-letter word, 12 by a 4-letter word, three by a 5-letter word, six by a 6-letter word, five by a 7-letter word, six by an 8-letter word, two by a 9-letter word, two by a 10-letter word, two by an 11-letter word and one by a 16-letter word.

[8] All materials are available from the first author upon request, denis.drieghe@UGent.be.

to “fake” normal reading behavior. Z-string trials were also inserted in the practice trials. The 60 experimental fragments were embedded in a pseudo-random order in 82 filler fragments, which were all meaningful texts. On average, questions followed on one fourth of the text fragments. Participants had no trouble answering these questions. They were correct 96% of the time. Participants completed a single session lasting about 50 min, containing 142 fragments to read (112 texts and 30 z-strings).

3.2. Results

Again, our primary dependent variable of interest was the single fixation duration on the target word. We will also report the gaze duration on the target word as well as the number of fixations on the target word and the fixation probability of the target word. To examine the effects of the extra blank space in the various conditions after the eyes left the target word, the first fixation and gaze duration on the following word will also be reported, together with the characteristics of the saccade originating from the target word. 3.0% of the data were removed due to track loss or because the fixation was shorter than 100 ms. After the analyses of the gaze duration and the number of fixations on the target, an additional reduction of the data set was carried out, selecting those trials on which there was a single fixation on the target word followed by a forward saccade. For these analyses, 3906 observations of a total of 7680 were included in the data set. All analyses were run over participants ($F1$-analyses) and items ($F2$- analyses).

3.2.1. Fixation times on the target

In a repeated measures ANOVA of the gaze durations on the target word with letter identity (normal vs. z-strings), parafoveal word length (4 vs. 8-letter words) and the number of blank spaces after the target (1 vs. 2) as independent variables, there was a main effect of letter identity [$F1(1,31) = 9.57$, $p < 0.01$; $F2(1,58) = 238.63$, $p < 0.001$]. The gaze durations in the z-string condition were clearly longer than in the text condition (by 58 ms on average; see Table 2).

When the analysis was restricted to the z-strings, there were no further significant effects: There was no main effect of word length [all Fs < 1], no main effect of the number of blank spaces [$F1 < 1$; $F2(1,58) = 1.13$, $p > 0.20$], nor an interaction between these two factors [all Fs < 1]. The situation was different in the normal reading condition. There we obtained a clear main effect both of parafoveal word length [$F1(1,31) = 13.20$, $p < 0.01$; $F2(1,59) = 5.76$, $p < 0.05$] and of number of blank spaces [$F1(1,31) = 15.09$, $p < 0.001$; $F2(1,59) = 16.94$, $p < 0.001$]. Gaze duration was on average 12 ms shorter when the target word was followed by a long word and it was also shorter when it was followed by a double blank space (on average 13 ms). There was no interaction between these two factors [all Fs < 1].

A similar picture emerged in the analyses of single fixation durations. The fixations were substantially longer in the z-string condition than in the text reading condition (on average 47 ms; $F1(1,31) = 11.56$, $p < 0.01$; $F2(1,58) = 122.74$, $p < 0.001$), but when we restricted the analyses to the z-string data no further significant effects were observed: no main effect of word length [$F1(1,31) = 1.83$, $p > 0.10$; $F2 < 1$], no main effect of the number of blank spaces [all Fs < 1], nor an interaction between these two variables [$F1(1,31) = 1.43$, $p > 0.20$; $F2 < 1$]. In contrast, for text reading there was a significant effect of parafoveal word length [$F1(1,31) = 14.67$, $p < 0.001$; $F2(1,59) = 6.90$, $p < 0.05$] and a significant effect of the number of spaces on the single fixation data [$F1(1,31) = 26.72$, $p < 0.001$; $F2(1,59) = 28.97$, $p < 0.001$]. Contrary to the gaze duration data, the interaction between these two factors was significant by participants [$F1(1,31) = 4.42$, $p < 0.05$] and marginally significant by items [$F2(1,59) = 3.97$, $p = 0.051$]. As in Experiment 1 single fixation durations were shorter before a double blank space and this effect was larger when the target word was followed by an 8-letter word (21 ms) than when it was followed by a 4-letter word (8 ms). Single fixation times were shorter when the target word was followed by a long word, and although this effect in the single space condition was rather small (4 ms), contrasts showed that it was

Table 2
Fixation time measures (in ms) and number of fixations as a function of letter identity, parafoveal word length and number of blank spaces after the target

	Letters				z-strings			
	4-letter word in parafovea		8-letter word in parafovea		4-letter word in parafovea		8-letter word in parafovea	
	1 space	2 spaces	1 space	2 spaces	1 space	2 spaces	1 space	2 spaces
Gaze duration	240	228	231	214	286	283	289	285
Single fixation duration	225	217	221	200	256	262	268	264
Number of fixations	0.78	0.74	0.71	0.69	0.48	0.58	0.49	0.59
Fixation probability	0.69	0.67	0.63	0.62	0.41	0.50	0.42	0.52

significant by participants [$t1(32) = 2.20$, $p < 0.05$] and marginally significant by items [$t2(60) = 1.89$, $p > 0.05$].

3.2.2. Number of fixations on the target and fixation probability of the target

In the analysis of the number of fixations on the target, a repeated measures ANOVA on all three factors showed a significant main effect of letter identity [$F1(1,31) = 13.34$, $p < 0.001$; $F2(1,59) = 147.16$, $p < 0.001$]. As shown in Table 2, the number of fixations were clearly lower for the z-string conditions (0.53 vs. 0.73 fixations). When analyzed separately, the z-string data showed no effect of parafoveal word length [all F's < 1], but did show a significant effect of the number of blank spaces after the target word [$F1(1,31) = 12.99$, $p < 0.01$; $F2(1,59) = 27.56$, $p < 0.001$]. An extra blank space caused the z-string target word to have a higher number of fixations, with an average increase of 0.10 fixations. The interaction between the parafoveal word length and number of blank spaces was not significant [all F's < 1]. The analysis of the data on normal reading showed a significant effect of parafoveal word length [$F1(1,31) = 10.01$, $p < 0.01$; $F2(1,59) = 6.14$, $p < 0.05$]. When the following word was an 8-letter word, the number of fixations on the target word was on average 0.06 lower. In normal reading there was no effect of the number of blank spaces after the target word [$F1(1,31) = 2.15$, $p > 0.10$; $F2(1,59) = 1.39$, $p > 0.20$] and there was no interaction between these two factors [all F's < 1].

The fixation probabilities of the target, as shown in Table 2, show the exact same patterns as observed in the data on the number of fixations on the target. A repeated measures ANOVA on all three factors showed a significant main effect of letter identity [$F1(1,31) = 25.76$, $p < 0.001$; $F2(1,59) = 201.68$, $p < 0.001$]. The probability of fixating the target word was lower for the z-strings (0.46 vs. 0.65). When analyzed separately, there was no effect of parafoveal word length [$F1(1,31) = 2.27$, $p > 0.10$; $F2(1,59) < 1$], but there was an effect of the number of blank spaces after the target word [$F1(1,31) = 17.38$, $p < 0.001$; $F2(1,59) = 40.13$, $p < 0.001$]. An extra blank space caused the z-string target word to be fixated more often, with an average increase of 0.10 in fixation probability. The interaction between these 2 factors was not significant [all F's < 1]. In the normal reading data there was a significant effect of parafoveal word length [$F1(1,31) = 11.10$, $p < 0.01$; $F2(1,59) = 7.52$, $p < 0.01$]. When the following word was an 8-letter word, the probability of making a fixation on the target word was on average 0.06 lower. There was no effect of the number of blank spaces after the target word [$F1(1,31) = 1.76$, $p > 0.10$; $F2(1,59) = 1.05$, $p > 0.20$] and there was no interaction between these two factors [all F's < 1].

3.2.3. Fixation times on the word following the target

When we restricted the data set to those cases in which a single fixation on the target word was followed by a fixation on the following word, we ended up with a large number of empty cells for the z-strings. A fixation on the next word followed in 20% of the trials only. Therefore we did not further analyze the data of the z-strings. A repeated measures ANOVA was carried out on the first fixation data in the normal reading condition, as shown in Table 3. The main effect of word length was marginally significant by participants [$F1(1,28) = 3.45$, $p < 0.10$] but not by items [$F2 < 1$]. The effect of the number of blank spaces was marginally significant by participants [$F1(1,28) = 3.01$, $p < 0.10$] and was significant by items [$F2(1,50) = 4.44$, $p < 0.05$]. This was due to a significant difference between an 8-letter word that followed a single blank space and an 8-letter word that followed a double blank space [$t1(31) = -2.25$, $p < 0.05$; $t2(58) = -2.14$, $p < 0.05$], the latter showing a longer first fixation duration. The overall interaction between word length and the number of blank spaces was not significant [$F1(1,28) = 1.62$, $p > 0.20$; $F2 < 1$].

For the gaze duration data, there was a significant effect of word length by participants [$F1(1,28) = 6.13$, $p < 0.05$; $F2(1,50) = 2.73$, $p > 0.10$]. If the parafoveal word was an 8-letter word gaze duration was on average 15 ms longer. There was no significant main effect of the number of blank spaces by participants [$F1(1,28) = 1.99$, $p > 0.10$] but there was by items [$F2(1,50) = 5.33$, $p < 0.05$]. After a double blank space gaze duration was on average 8 ms longer. There was no interaction between word length and the number of blank spaces [all F's < 1].

3.2.4. Characteristics of the saccade originating from the target

The data on the characteristics of the saccade originating from the target word and landing on the following word are shown in Fig. 2. There was a significant effect of parafoveal word length on the saccade length [$F1(1,28) = 48.28$, $p < 0.001$; $F2(1,50) = 56.64$, $p < 0.001$]: the saccade was 1.4 character positions longer when landing into an 8-letter word. The main effect of the number of blank spaces was also significant

Table 3
Fixation time measures (in ms) on the word following the target word as a function of parafoveal word length and number of blank spaces after the target

	4-letter word in parafovea		8-letter word in parafovea	
	1 space	2 spaces	1 space	2 spaces
First fixation duration	212	215	212	228
Gaze duration	221	226	231	246

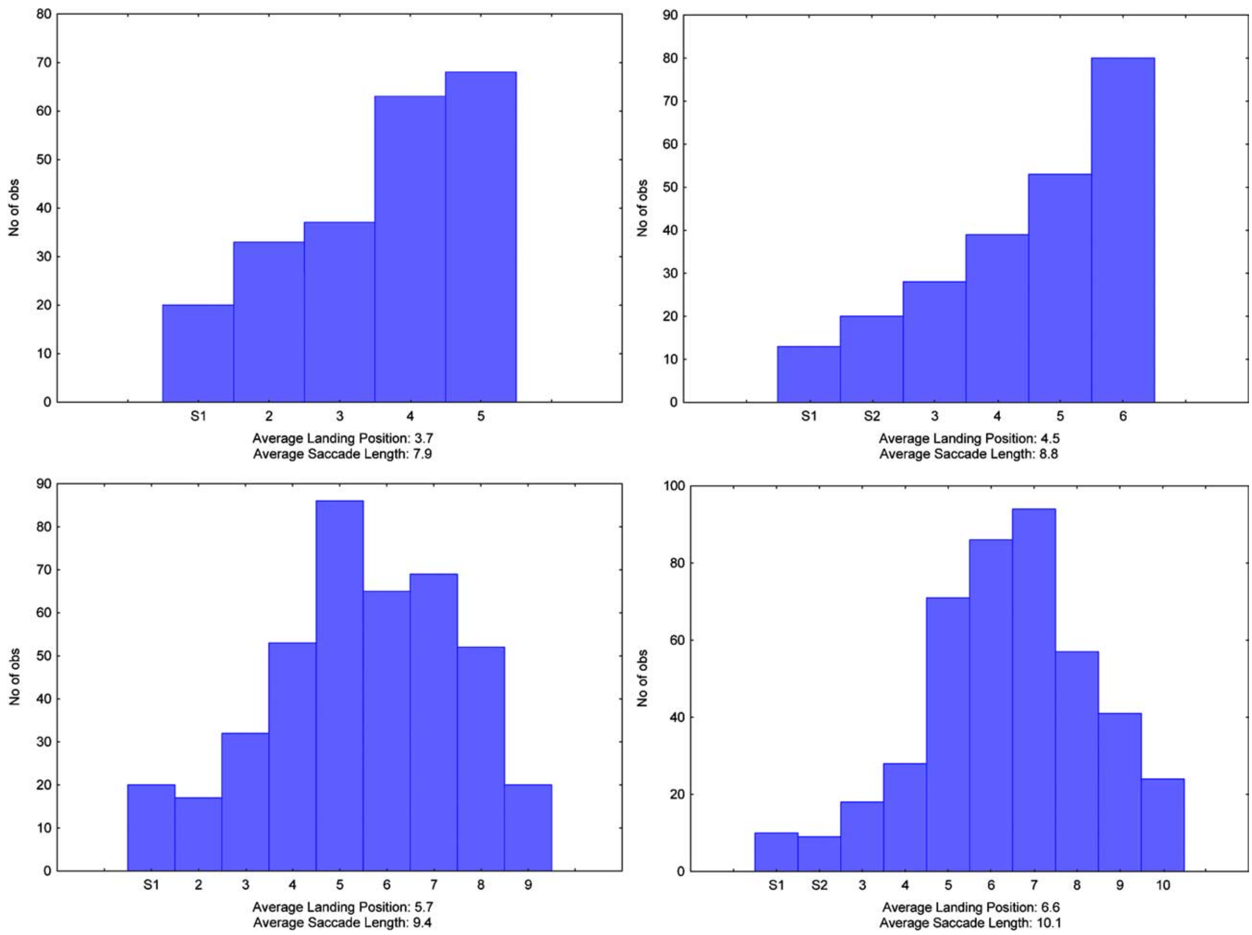

Fig. 2. Landing distribution of the saccade originating from the target word (in letter positions) on the following word. The letter S indicates a blank space. The top curves are for the conditions with a 4-letter word following the target word, the bottom curves are for the conditions with an 8-letter word following the target word. Left-hand curves are the one blank space conditions, right-hand curve are the two blank spaces conditions.

[$F1(1, 28) = 29.31$, $p < 0.001$; $F2(1, 50) = 56.32$, $p < 0.001$]. An extra blank space caused a lengthening of the saccade by 0.84 character positions. As in Experiment 1, the lengthening compensated for the extra blank space, making the average landing position on word $n + 1$ almost identical. There was no interaction between parafoveal word length and the number of blank spaces after the target [all F's < 1].

3.3. Discussion

Experiment 2 replicated the finding of Experiment 1 that in text reading fixation durations on target words are shorter when the word is followed by a double blank space than when it is followed by a single blank space. This effect was present both in the single fixation durations and in the gaze durations. Shorter fixation times were not observed in z-string reading, a finding that seems to support a reduced lateral masking interpretation. The z-string data replicated the basic findings that were reported for these materials before: longer fixation times and more word skipping were observed than in normal text reading (e.g., Vitu et al., 1995; Rayner & Fischer, 1996).

The data on the number of fixations on the target word and the fixation probability of the target word were also in line with those observed in Experiment 1: Adding a blank space between two words did not increase the probability of the first word being fixated. This contradicts predictions one of the authors previously made in the Extended Optimal Viewing Position model of word skipping (Brysbaert & Vitu, 1998). According to this model, word skipping for word $n + 1$ depends on the length of word $n + 1$ and the distance of word $n + 2$ from the fixation location. Adding a space between word $n + 1$ and word $n + 2$ should increase the probability of fixating word $n + 1$ (because word $n + 2$ is farther away). Interestingly, this effect was observed when participants were reading meaningless z-strings: Chances of fixating a target word were 10% higher when there were two blank spaces after the word than when there was only one (see Table 2). So, whereas a double blank space had a significant influence on skipping rates obtained in the z-string data, in normal reading this manipulation had no effect on the skipping data. In short, this is a strong indication that not all word skipping in text reading is due to oculomotor factors.

Another dissociation between z-reading and text reading was found in the effect of the length of the parafoveal word. Whereas a long parafoveal word $n + 1$ decreased the gaze duration on a 5-letter foveal word n and increased the likelihood of skipping the word n, no such effect was observed for z-reading. This is a very interesting observation, because one of the interpretations of the parafoveal length effect has been that a long parafoveal word pulls the landing position towards its center of gravity (i.e., the so-called global effect; Vitu, 1991; Gautier, O'Regan, & Le Gargasson, 2000). However, in that case we should have observed a similar effect in z-reading. The fact that the effect was not observed in z-reading is more in line with Kennedy's (1998) conjecture that in text reading the eyes are pulled towards the region with the highest information (assuming that long words on average are more informative than short words). An alternative interpretation could be that z-reading, because of its longer fixations and saccades, is less influenced by the global effect than normal text reading.

The fixation times on the word after the target word showed the standard word length effect (Calvo & Meseguer, 2002; Rayner & Fischer, 1996; Rayner et al., 1996), and an effect of the number of blank spaces, mostly due to a longer fixation time on an 8-letter word preceded by a double blank space. The latter effect could be expected based on the reduced processing (shorter fixation durations, more skipping) of the previous word in the double-space condition. Both of these factors contribute to reducing the parafoveal preview benefit.

Finally, the data on the saccade originating from the target word and landing on the following word are also highly compatible with the data obtained in Experiment 1. The extra blank space was fully compensated by lengthening the saccade by approximately one character position, hence landing on the same site. The landing distributions in Fig. 2 also show that it is not very meaningful to compare the average landing position for short and long parafoveal words, because in the former condition we clearly got a truncated distribution, with many saccades aimed at the word after the short parafoveal word.

4. General discussion

The possibility of parafoveal-on-foveal effects in eye movement control has become a major issue in recent research on eye movements in reading, because researchers see it as the critical test to determine whether the words in a line of text are processed one by one, or whether two or more words are being processed in parallel. According to the first view, the human visual attention system is able to limit word processing in text reading to one word at a time (i.e., there is an early selection of information). The most elaborate and detailed model of this type is the E-Z Reader model (Pollatsek, Reichle, & Rayner, 2003; Rayner, Reichle, & Pollatsek, 1998; Reichle, Pollatsek, Fisher, & Rayner, 1998; Reichle, Rayner, & Pollatsek, 1999, 2003). One of the core assumptions of the model is that attention covertly shifts from word to word. Only the word within the attentional beam is being processed, and the beam does not shift to the next word until full identification (or close to full identification) of the currently fixated word has been obtained. Words are processed serially because it is important for readers to keep the word order straight (Pollatsek & Rayner, 1999). The "leave-on-completion" assumption of the model can account for foveal-on-parafoveal effects (as reported by Henderson & Ferreira, 1990; Kennison & Clifton, 1995; Schroyens et al., 1999), but does not predict parafoveal-on-foveal effects other than the extra time needed to replace a cancelled forward saccade to word $n + 1$ by a new saccade to word $n + 2$ (see Section 1).

However, as discussed in the introduction, in recent years a number of parafoveal-on-foveal effects have been published that seem to raise the possibility of parallel word processing in reading (Hyönä & Bertram, 2004; Inhoff, Radach, Starr, & Greenberg, 2000; Inhoff, Starr, & Shindler, 2000; Kennedy, 1998, 2000; Kennedy et al., 2002; Schroyens et al., 1999; Starr & Inhoff, 2004; Underwood, Binns, & Walker, 2000; Vitu, Brysbaert, & Lancelin, 2004). According to some (Radach & Kennedy, 2004), the evidence now is so strong that we no longer have to question whether such effects exist but how we can understand them, whereas others remain more cautious (Rayner & Juhasz, 2004; Rayner, White, Kambe, Miller, & Liversedge, 2003).

The discovery of parafoveal-on-foveal effects has been accompanied by the development of alternative models of eye movement control, all embracing a parallel view on foveal and parafoveal word processing (with late selection of information). The SWIFT model (Engbert, Longtin, & Kliegl, 2002; Kliegl & Engbert, 2003), for instance, adopts many of the architectural features of the E–Z Reader model, but departs from it by assuming a parallel, spatially distributed lexical processing. The Glenmore model (Reilly & Radach, 2003) is an even more radical departure from the attention based, sequential processing models by replacing the entire concept of attention by a saliency map, based on the highly influential model by Findlay and Walker (1999). A similar view is defended in Yang and McConkie's (2001) competition-inhibition model, which is also based on the Findlay and Walker model and which puts a very strong emphasis on non-cognitive factors to explain eye movements in reading.

A weakness of the available evidence on parafoveal-on-foveal effects, however, is that it has not yet been framed within a coherent model that allows researchers to predict which effect will be obtained when and why (Rayner & Juhasz, 2004). This is even more a problem because the effects are not always pointing in the same direction (see e.g., Hyönä & Bertram, 2004). In this paper, we set out to directly test a basic assumption of one coherent set of ideas that has been put forward and that recently has been referred to a number of times. According to Schiepers's (1980) model, foveal and parafoveal words are processed in parallel but with a time delay of 90 ms per degree of eccentricity. In this model, the parafoveal preview benefit is not due to the fact that the attentional system already partly processed the parafoveal word by the time the eyes reach this word (as defended by E–Z Reader), but to the fact that the activation of word representations is boosted when the foveal information from fixation n can be combined with the parafoveal information from fixation $n - 1$. This combination of information from different fixations critically depends on the synchrony with which the activation arrives in the relevant brain centers. Based on this assumption, we hypothesized that adding an extra blank space to a word would allow the eyes to stay for an extra 30 ms on this word before the synchrony became jeopardized. Therefore, an inflated fixation duration on the word was predicted. What we found, however, was the complete opposite: Inserting an extra blank space after a target word did not result in longer fixations on the word, but in shorter fixations.

Although we failed to find direct evidence for the Schiepers model, we did obtain evidence for parafoveal-on-foveal influences. There were three such influences. First, the fixation durations on the target words were not similar in the two-space condition as in the single-space condition; they were significantly shorter. Second, we found an effect of parafoveal word length with a longer word in the parafovea leading to shorter fixation durations and slightly less fixations on the prior word. And third, the effect of the double blank space was modulated by the length of the parafoveal word; the reduction in the single fixation time on the target due to the double blank space tended to be larger when the following word was an 8-letter word than when it was a 4-letter word. Interestingly, none of these effects were observed when we asked participants to mimic reading behavior when presented with z-strings. This strongly suggests that the effects we observed are not due to low-level oculomotor variables related to the length and the lay-out of the word blobs, otherwise we would have found the same effects in the z-scanning task.

We will start our discussion with the first finding, the reduced fixation duration prior to a double space and the slightly lower probability of fixating this word. The fact that there was no similar effect in z-reading indicates that the origin of the effect is likely to be language related. The simplest explanation probably is reduced lateral masking of the letters in the double space condition, a phenomenon that would have no repercussions on the task of scanning z-strings. This processing advantage leads to faster word recognition with hardly any repercussions for the fixation on the next word. This explanation is compatible with the findings reported by Rayner et al. (1998) who found similar data in a blocked presentation of wide spacing.

Our second finding concerns the effect of parafoveal word length on viewing times: A long word $n + 1$ in the parafovea leads to a shorter viewing time on word n. The effect of parafoveal word length was first reported by Kennedy (1998). In his experiment participants first viewed a fixation marker after which three words were presented on the screen. The first word was either the word *looks* or the word *means*. In the *looks* case participants had to indicate whether the two following words had the same spelling, in the *means* case participants had to indicate whether they had the same meaning. Kennedy concluded from his results that parafoveal word length acted to modify foveal inspection time, resulting in a shorter foveal fixation time in the case of a longer second word. A replication of the experiment using a task closer to normal reading (Kennedy, 2000, Experiment 2) also found this effect of parafoveal word length. In this task participants had to read strings of unrelated words, looking for rare occurrences of an article of clothing (see also Schroyens et al., 1999). Although this task was clearly closer to normal reading as compared to the previously used looks-means task, the generalizibility of the results to normal reading is still somewhat disputed (Rayner et al., 2003). An effect of parafoveal word length was also observed in a large data corpus of normal reading containing the eye movements of four German-speaking students reading the first two parts of *Gulliver Travels* (Radach, 1996). Kennedy (1998) further reported in this corpus an effect of parafoveal word length on the fixation durations of the foveal word: a long parafoveal word was associated with shorter single fixation durations on the foveal word. For a 5- to 8-letter foveal word for instance, the single fixation duration ranged from an average of 287 ms in the case of a 4-letter parafoveal word to an average of 274 ms in the case of 7- to 10-letter parafoveal word. Also in normal reading Hyönä and Bertram (2004, Experiment 2) reported a similar effect of parafoveal word length in Finnish. The parafoveal words they used consisted of a set of short (7–9 letters) and long (12–15 letters) compound words. In their experiment the targets preceding long compounds received a shorter gaze duration than those preceding short compounds. Hyönä and Bertram also interpreted this finding in terms of long parafoveal words attracting an early saccade towards them, but they were unable to replicate the finding in a follow-up experiment (2004, Experiment 4).

In a parallel processing model such as the one proposed by Kennedy (1998) the harder the word $n + 1$ is to process, the stronger it pulls the eyes towards it, in order to optimize the extraction of visual information from the page of text. Such a mechanism could explain the effect parafoveal word length had on our fixation times on the target. The question remains however whether the attraction that the longer word in the parafovea exerts, finds it origin in processing difficulties associated with longer words. An alternative hypothesis comes to mind. The attraction of parafoveal word length could just be a consequence of a strategy that tries to distribute the fixation locations in the most efficient way, landing more on long words and skipping shorter words. If such a strategy exists, it is not inconceivable that it results in an attraction, a pulling force, if a very suitable candidate is close-by. An extra blank space prior to it could make the candidate stand out more, which would explain our third finding, why the parafoveal word length effect was larger in the double space condition than in the single space condition. The major difference between the mechanism described in the alternative hypothesis and the one proposed by Kennedy is that the alternative hypothesis does not assume that the parafoveal attraction is based on word processing in the parafovea. The only variable it requires is word length.

At this point, it is important to note that we see the explanation for the observed patterns in the data of the current study as a combination of two effects. The shorter fixation duration prior to a double blank space is due to a reduction of lateral inhibition, increasing the readability of the following word. The effect of parafoveal word length is explained by an attraction exerted by long words resulting in a pulling force closely related to the ideas proposed by Kennedy (1998), although the present proposition downplays the original assumptions. Neither of these two influences can individually account for all the effects observed in the present study. A reduced fixation duration prior to a longer word can not be expected solely based on an reduced lateral inhibition hypothesis. Likewise, there is no reason to predict a reduced fixation duration prior to a double blank space based on the pulling force account. However, a double blank space could boost the saliency of a long word, resulting in the observed interaction between the double blank space manipulation and the effect of parafoveal word length.

Finally, it has to be acknowledged that the parafoveal-on-foveal effects unraveled in the present experiments, do not look very damaging for the serial assumption of the E–Z Reader model either. A distinction has to be made between the rather low-level parafoveal-on-foveal effects reported here and effects such as for instance the meaning of the word to the right of the fixation influencing the current fixation. Better visibility of a word due to less lateral interference is not incompatible with the principles underlying E–Z Reader. The same may be true for the effect of the length of the parafoveal word. Although E–Z Reader in our view underestimates the effect of word length in interword eye movement control (Brysbaert & Drieghe, 2003), in the latest version of the model (Reichle et al., 2003) a pre-attention stage of processing has been incorporated allowing information about word length to be extracted prior to the shift of attention. While this recent adaptation was not specifically constructed for accounting for the effects reported above, it might offer an explanation for them (Rayner et al., 2003).

Indeed, one of the most striking results of the present experiment is the apparent ease with which the participants dealt with the breach in the spacing protocol. With the exception of the shortened fixation durations, the double blank space caused hardly any noticeable signs of changed eye movement behavior. Only in the condition in which a double blank space preceded a long word did a clear effect of reduced parafoveal preview emerge. There was a swift adaptation of the outgoing saccade so that the landing position on the parafoveal word was the same in the double space condition as in the single space condition. This, incidentally, is a very clear demonstration of the fact that eye movements are determined by the visual lay-out of the text to be read, and are not selected at random from a distribution of possible saccade sizes (as has recently been suggested by McConkie (personal communication) whilst reviewing Brysbaert et al., 2005). The participants were not aware of the space manipulation. About one-third of them were asked after the experiments whether they had noticed anything unusual about the text fragments they had read, and none reported the occasional double spacing. A potential reason for not noticing the manipulation could be that it is altogether not such an uncommon phenomenon. We are not aware of any study reporting the frequency of unintended double spaces in normal texts, but from personal experience we can say that once one starts to pay attention to the phenomenon, an unintended double spacing in for instance e-mails does appear quite often. Another argument for the flexibility of readers to deal with changed spacing could be the common use of justified fonts, an option in most modern text editors, which also requires a swift adaptation from the reader in terms of adjusting to different letter sizes and spacing.

All in all, in what started as a direct test of a core assumption of the Schiepers (1980) model, our main conclusion must be that the model failed to make the correct prediction. On the basis of the present evidence, we cannot conclude that the fixation (and the gaze) duration on a word is the result of two forces: (1) the need to process the foveal word, and (2) the need to synchronize the parafoveal information from the current fixation with the foveal information from the next fixation. As a matter of fact, our results went reliably in the opposite direction. Therefore, we feel that Schiepers's ideas can no longer be used as the basis for a parallel model of eye movement control in reading. What we did find was that an extra blank space speeds up the reading process, presumably due to a reduced lateral masking. An effect of parafoveal word length was also reported, a long word leading to shorter fixation times and a fewer number of fixations on the previous word. This latter finding has been interpreted as a pulling force exerted by longer words, possibly resulting from a strategy to distribute fixations in text in the most efficient manner.

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