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Parafoveal-on-foveal effects in normal reading

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Abstract

A corpus of eye movement data derived from 10 English and 10 French participants, each reading about 50,000 words, was examined for evidence that properties of a word in parafoveal vision have an immediate effect on foveal inspection time. When inspecting a short word, there is evidence that the lexical frequency of an adjacent word affects processing time. When inspecting a long word, there are small effects of lexical frequency, but larger effects of initial-letter constraint and orthographic familiarity. Interactions of this kind are incompatible with models of reading which appeal to the operation of a serial attention switch.

Keywords: Reading; Parafoveal-on-foveal effects; Eye movement control

1. Introduction

What properties of text influence eye movement control and when is this influence exerted? Since reading involves successive fixations, accurately located on text elements, it is obvious that some low-level control must take place (e.g. information about the physical location of target words). Indeed, possibly as much as 90% of the variance in fixation location can be accounted for by a combination of low-level visual processing and oculomotor constraints (Brysbaert & Vitu, 1998). Both the 'Strategy-Tactics' conjecture of O'Regan and co-workers (O'Regan, 1990, 1992; O'Regan & Lévy-Schoen, 1987; O'Regan, Vitu, Radach, & Kerr, 1994) and the *Mr. Chips* model of Legge, Klitz, and Tjan (1997) capitalised on this fact and attempted to provide a theory of eye movement control in reading couched in purely oculomotor terms. But both these approaches have proved inadequate. The '*where*?' of eye movement control in reading does appear to be substantially [1] under low-level control, but the '*when*?' is clearly not, and it is now beyond dispute that theoretical accounts of the complexities of temporal control in reading must make reference to cognitive factors. Both the number of fixations and their individual duration are tightly coupled to linguistic properties of the text, including orthographic, lexical, syntactic, pragmatic and discourse levels of description (see Rayner, 1998, for a comprehensive review).

Establishing that cognitive factors play a key role in eye movement control is several steps short of providing a comprehensive account of the processes involved. The first realistic computational model to attempt this is the *E-Z Reader* model of Reichle, Pollatsek, Fisher, and Rayner (1998); see also, Reichle, Rayner, and Pollatsek (2003). This model provides a good account of the effects of the lexical frequency, predictability and physical eccentricity of text items on fixation duration and

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[1] Although not completely (see Hyönä, 1995; Vonk, Radach, & van Rijn, 2000).

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refixation rate. It also elegantly accounts for a wide range of well-established outcomes, such as the size and direction of the preview effect in various contexts, the existence of short-duration fixations, word skipping and spillover effects. *E-Z Reader* is not simply a mathematical model designed to maximise the fit of a set of equations to a set of data. If it were, it might be seen as relatively 'expensive', given its number of free parameters (Jacobs, 2000). Rather, it is "psychologically committed". High among its basic design features is the aim to make the parameters of the model psychologically plausible. In this sense it is to be distinguished from its rivals, which either make no claims of this kind, are indifferent to the issue of psychological plausibility, or continue to one degree or another to deny the relevance of cognitive factors in eye movement control (see Reichle et al., 2003, for an even-handed comparison of current models).

The particular type of psychological theory to which *E-Z Reader* is committed accounts for the reader's behaviour in terms of the deployment of overt and covert attention. This distinction is an ancient one, but was first given significant empirical support by the work of Posner (1978, 1980) and was first applied to the task of reading by McConkie (1979) and then, in more detail, by Morrison (1984). Morrison proposed that the reader's covert attention shifts from word to word in a serial fashion as lexical access [2] is achieved for each successive fixated word (see Henderson, 1992, for a review). The dissociation between overt eye movements and covert shifts of attention provides a convincing explanation of the parafoveal preview advantage because for a period of time the reader will be fixating word$_n$, while actually processing word$_{n+1}$. For obvious reasons, theories of this kind are referred to as involving a 'serial attentional shift'. In Morrison's initial conception it was proposed that both covert and overt processes were triggered by the same cognitive event (e.g. word identification). This leads to the prediction that preview advantage is independent of foveal load (i.e. pre-processing of parafoveal words only takes place during the fixed time needed to prepare a saccade). It proved impossible to confirm this crucial prediction: Preview advantage varies quite substantially as a function of foveal load in normal reading (Henderson & Ferreira, 1990). The only successful method to date of accommodating these pre-processing effects in a serial model has been to postulate separate sources of cognitive control over overt and covert processes. In early versions of the *E-Z Reader* model, the covert shift of attention was linked to word identification, but overt eye movements were triggered by an earlier sub-lexical process referred to as a 'familiarity check'. Although this term was dropped in later versions, the model continues to identify two distinct stages of lexical processing and continues to link the first of these to the overt process of saccade programming and the second to the covert shift of attention.

A model proposing a serial attentional shift linked to the stages of lexical processing commits itself to the claim that properties of a parafoveal target cannot directly influence concurrent foveal processing time. An attentional shift is defined as a discrete process. Either attention is allocated to a parafoveal word, in which case that word's properties arrive too late to affect foveal processing, or it has not been allocated, in which case the properties are unavailable. It follows that because information from an extra-foveal source only becomes available after attention has been switched away from the fovea, strong parafoveal-on-foveal effects represent a serious challenge, not simply to *E-Z Reader*, but to any model committed to a psychological process termed 'attention-shifting'. The meaning of unfixated parafoveal words should not influence processing at the fovea because this would imply that lexical processing might occur in parallel, a claim which is simply incoherent in the context of any serial model. As Reichle et al. (2003) put it: "... if large consistent effects of the meaning of word$_{n+1}$ on the fixation duration of word$_n$ could be demonstrated, then such a demonstration would be problematic for the *E-Z Reader* model." (p. 67).

Until recently, this potential embarrassment has been avoided because parafoveal-on-foveal effects have, in general, been neither 'large' nor 'consistent'. Early attempts to provide evidence were negative (Carpenter & Just, 1983; Henderson & Ferreira, 1993; Rayner, Fischer, & Pollatsek, 1998; but see Kennedy, 2000, for a discussion. See also an interesting retrospective reanalysis of some early data by Rayner, 1975, discussed in Rayner, White, Kambe, Miller, & Liversedge, 2003). More recently, the situation has changed somewhat, with evidence from several laboratory studies, mostly involving the identification of short strings of isolated words, that properties of an uninspected parafoveal item can have an *immediate* effect on current foveal processing (Inhoff, Radach, Starr, & Greenberg, 2000; Inhoff, Starr, & Shindler, 2000; Kennedy, 1995, 1998, 2000; Kennedy, Murray, & Boissiere, 2004; Murray, 1998; Kennedy, Pynte, & Ducrot, 2002; Pynte, Kennedy, & Ducrot, 2004; Underwood, Binns, & Walker, 2000). Across this range of studies, parafoveal effects on foveal inspection time appear to implicate physical, orthographic, sub-lexical, lexical, and even pragmatic properties of an as-yet uninspected parafoveal word. Nonetheless, some important caveats need to be entered. There are as many reports of null effects as of significant effects (Altarriba, Kambe, Pollatsek, & Rayner, 2001; Rayner, Balota, & Pollatsek, 1986; Rayner, Pollatsek, & Reichle, 2003; Rayner, White, et al., 2003; Schroyens,

[2] Morrison did not use this term, but it is clear that the trigger event is seen as word identification.

Vitu, Brysbaert, & d'Ydewalle, 1999; White & Liversedge, 2004). In particular, Rayner and colleagues have pointed to the fact that the tasks where parafoveal-on-foveal effects appear most evident have borne little resemblance to normal reading (Rayner & Juhasz, 2004). Further, the absolute size of any obtained modulation of foveal inspection time is generally very small. Finally, the direction of obtained significant effects has proved inconsistent across studies, sometimes quite dramatically so, with significant reversals (Hyönä & Bertram, 2004). [3]

Kennedy et al. (2002) argued that a failure to control for the effects of foveal and parafoveal length explains many of the inconsistencies and apparent null effects. They showed that parafoveal-on-foveal effects vary systematically as a function of the length of the two words involved. When viewed from a position within a short word, some words in parafoveal vision may be visible enough to be identified and in this case effects are found that relate to the word frequency of a parafoveal target. [4] In contrast, if a parafoveal word cannot be identified, and in particular if its initial orthography is irregular or highly constrained, its presence may act as a target for an early inter-word saccade. This has the effect of shortening foveal inspection time, producing paradoxical 'inverted' effects relating to initial-letter familiarity or constraint. The situation is different when we consider long words. Acuity considerations alone mean that viewed from a relatively remote position in a long word, an adjacent word of average length can rarely be identified. This is particularly the case if a foveal word is fixated only once. But parafoveal initial letters are often visible and parafoveal-on-foveal effects arise, in this case driven solely by pre-lexical properties of word$_{n+1}$, such as its initial-letter constraint, or sub-lexical properties such as its orthographic familiarity. An additional complication with regard to long foveal words is that they are much more likely to be refixated. Properties of the parafoveal stimulus serve to change foveal refixation probability. Since Kennedy et al. (2002) provide evidence that parafoveal-on-foveal effects vary as function of foveal length, it is perhaps less surprising that inconsistencies arise when averages are taken over opposing underlying trends (for example, Hyönä & Bertram, 2004).

The objection that apparent violations of the assumption of serial processing arise only in tasks unrelated to normal reading is more difficult to refute. This claim (e.g. Rayner, Pollatsek, et al., 2003; Reichle et al., 2003) is plausible, given the highly artificial nature of some of the relevant laboratory studies. Serial sequential models of eye movement control in normal reading would clearly be preserved if parafoveal-on-foveal effects were shown to be real, but restricted to artificial laboratory tasks. [5] It is true that some studies reporting positive effects have actually employed tasks approximating normal reading (Inhoff, Radach, et al., 2000; Inhoff, Starr, et al., 2000; Kennedy et al., 2004), but it is these results in particular which have proved difficult to replicate (Rayner, White, et al., 2003). Robust effects obtainable in the laboratory are commonly attenuated or absent in normal reading and little is known about why such attenuation occurs (Radach, Kennedy, & Rayner, 2004). Until this question has been satisfactorily resolved, the only defensible way of meeting the objection of artificiality is to make use of reading tasks with demands that, as far as practicable, approximate those imposed on the normal reader. The present paper sets out to do this.

The theoretical background to the work is dealt with in detail Kennedy et al. (2002). We argue that an account in terms of a strictly serial allocation of attention is inadequate to account for lexical processing in reading. Properties, including relatively high-level properties such as lexical frequency, are available from at least two adjacent words in parallel. Information is processed in parallel and the combined foveal and parafoveal processing load is continually monitored. A process-monitoring mechanism, sensitive to the rate at which information can be acquired across the attentional span, modulates three distinct foveal responses. The first is a tendency for the eyes to remain at the current location (STAY) and process both foveal and parafoveal items. This typically arises when a foveal word is short and/or easy to identify and the next (parafoveal word) is also short and/or easy to identify. Foveal processing time in these circumstances is directly modulated by parafoveal lexical frequency (i.e. the presence of a low frequency parafoveal word will increase foveal processing time). The second response typically arises as a result of a particularly demanding parafoveal configuration (e.g. a highly constrained word with unfamiliar initial orthography). In this case, the reader may execute an early saccade (GO), possibly before complete identification of the foveal stimulus. 'Difficult' configurations of letters act as a target for this class of inter-word saccades, producing a process referred to by Hyönä and Bertram (2004) as 'magnetic attraction' (see also Pynte et al., 2004). It

[3] It might be argued that statistically significant reversals in the direction of an effect represent weak evidence that the effect does not exist. It is also possible that hidden interactions are present across the data sets.

[4] As discussed in Section 3.2, the possibility is entertained in the *E-Z Reader* model that words may be skipped as a consequence of attention shifts to word$_{n+1}$ if these yield its complete identification. If fixation duration is inflated prior to a skip, this would mimic an outcome that might otherwise be ascribed to a parafoveal-on-foveal effect. See also footnote 6.

[5] At least one made use of a corpus of data derived from a small group of participants reading sequences of naturalistic text in German (Kennedy, 1998), but the sample size was too small to show more than trends.

should be noted that parafoveal-on-foveal effects of this kind will appear to be paradoxically ‘inverted’, because the execution of an early exit saccade reduces foveal processing time. Finally, properties of a parafoveal word may lead the reader to refixate the foveal word (a SHIFT response). The majority of intra-word refixations arise from foveal difficulty associated with low frequency long words, or from initial fixations located at a sub-optimal viewing position, or from a combination of both. But foveal refixations are also modulated by properties of parafoveal words, serving to increase their visibility (virtually all intra-word refixations are in a left–right direction reading English). The additional time involved in executing such within-word refixations can thus be traded off against the possibility that the next word might be completely identified. Although it may appear puzzling that readers should refixate word$_n$ as a consequence of properties of word$_{n+1}$, rather than simply execute an inter-word saccade, it should be remembered that identification of word$_n$ itself represents the primary part of the combined processing load (see Kennedy et al., 2002, for further discussion).

In the present study, a large-scale corpus of eye movement data is explored with a view to identifying parafoveal-on-foveal effects. The data were obtained as participants read extracts from newspaper articles for comprehension, a task probably as close to ‘normal reading’ as can be achieved in a controlled laboratory environment. Three hypotheses were tested. First, the null hypothesis, derived from *E-Z Reader* and similar models postulating a serial attentional shift, that foveal inspection time should not be directly influenced by any property of an adjacent parafoveal word. A less severe hypothesis, possibly consistent with serial sequential models, is that *lexical* properties of an adjacent parafoveal word should not influence foveal processing, whereas sub-lexical properties might. [6] We tested two distinct experimental hypotheses, relating to short and long foveal words respectively: (1) That inspection time on short foveal words will be directly influenced by both lexical and sub-lexical properties of adjacent parafoveal words, particularly if these are also short; and (2) that inspection time on long foveal words will be either uninfluenced by properties of parafoveal words, or will show effect restricted to properties relating to its initial letters, such as informational constraint or orthographic familiarity. In the latter case, the specific prediction is that parafoveal-on-foveal effects will be driven primarily by modulation to refixation strategy (and its influence on the visibility of an adjacent parafoveal word). Taken together, the two experimental hypotheses predict significant interactions involving foveal and parafoveal length. In the present paper we do not address the question as to whether parafoveal-on-foveal effects at a supra-lexical level occur (Kennedy et al., 2004; Murray, 1998; Rayner et al., in press)

[6] For example, In *E-Z Reader* 7 pre-attentive processes sensitive to parafoveal word length might affect the probability that word$_{n+1}$ will be skipped.

2. Methods

2.1. English language corpus

Text was taken, with permission, from editorials in *The Independent* newspaper (a high-quality daily newspaper on sale throughout the UK). A series of 20 text files were prepared for display, each comprising about 2800 words, split into 40 five-line ‘screens’. The texts comprised 56,212 tokens and 9776 types in total. The materials were presented using a high-resolution (8×16) monopitch font (upper and lower case) in white-on-black polarity on a monochrome monitor with a high-speed phosphor, running at a frame rate of 100 Hz. Presentation of successive ‘screens’ began with a fixation marker three characters to the left of the position to be occupied by the initial word of the first line. Once inspected, the fixation marker was replaced after a delay of 150 ms by the display of the five lines of text, double-spaced. Line length was 80 characters.

Data were acquired from a sample of ten native English-speaking participants. Testing took place in Dundee. Participants were instructed to read the materials normally and to press a button when they had finished reading the display. They were told beforehand that each text (which comprised several ‘screens’) would be followed by a short multiple-choice comprehension test.

The display monitor was interfaced to a Control Systems Artist 1 graphics card mounted in an IBM compatible computer. At the selected viewing distance of 500 mm, one character subtended approximately 0.3° of visual angle. Eye movements were recorded from the right eye using a Dr. Bouis pupil-centre computation oculometer interfaced to a 12-bit A–D device sampling X and Y position every 1 ms. This eye tracker has a resolution of better than 0.25 characters over a 60-character calibrated range (Beauvillain & Beauvillain, 1995). A dental wax bite bar and chin rest were used to minimise head movements. The eye movement recording system was calibrated prior to the presentation of each set of three screens. Calibration involved fixating a series of five points presented in succession across the line located at the top, centre and bottom of the screen. For a given participant, testing took place over a period of between 8 and 10 days, depending on the ease with which calibration could be completed.

Measures of fixation duration, gaze duration, and initial landing position were computed off-line. The data reduction technique used an X–Y vector version of the standard X-only system employed in the Dundee laboratory. This uses statistical algorithms based on the resolution of the data for each individual participant with respect to the obtained noise in a given data set and involves the detection of periods of stability, rather than the detection of saccades. An initial pass through the data for one calibration trial arrives at an estimate of point-to-point variation. This value is then used to test the separation of successive clusters of stable data (in effect, running *t*-tests are conducted on successive clusters). Clusters which cannot be statistically separated in this way are aggregated. Finally the data are smoothed to aggregate potential within-letter saccades. The effective resolution of the eye-tracking system is considerably better than one character position. The English corpus comprises about 500,000 data points.

2.2. French language corpus

Text was taken, with permission, from editorials and other extended articles in *Le Monde* a high-quality daily newspaper on sale throughout France. A series of 20 text files were prepared for display, each comprising about 2600 words, split into 40 five-line 'screens'. The texts comprised 52,173 tokens and 11,321 types in total. Data were acquired from a sample of ten native French-speaking participants. Testing took place in Aix-en-Provence. [7] In all other respects, the procedure, including calibration technique and data reduction methods, were identical to those employed for the English data sets. The French corpus also comprises about 500,000 data points.

2.3. Eye movement measures

Cases were selected where two words of defined lengths were fixated in succession. Foveal and parafoveal "short" words were defined as 5 and 6 characters in length. "Long" words were 8–12 characters. To be counted, pairs of words had to occur on the same line of text and words associated with punctuation were excluded. Cases in French where the second of two words was preceded by a single letter and an apostrophe (e.g. ⟨d′⟩, ⟨s′⟩, ⟨l′⟩, etc.) were also excluded. [8] Apart from word length, three properties of parafoveal words were computed: (1) Word frequency, with reference to the Kuçera and Francis norms for English texts (Kuçera & Francis, 1967) and with reference to the Brulex norms for French (Content, Mousty, & Radeau, 1990). In both languages, cases where a given word was not present in the relevant norms were indexed using the overall frequency of occurrence of the item in the texts. [9] For words of 5, 6, 8, 9, 10, 11 and 12 characters in length, frequency of occurrence in the English corpus were 255, 90, 43, 33, 55, 14 and 9. The equivalent values for the French texts were 125, 74, 55, 58, 23, 24 and 37. (2) Its initial-letter constraint, or 'Informativeness', defined as the number of words in the relevant norms sharing its initial three letters. (3) The cumulative lexical frequency, or 'Familiarity', of the initial three letters, computed by adding the word frequencies of all the words of the same length, plus or minus 2 characters, sharing the given initial trigram (see Pynte, Kennedy, & Murray, 1991, and Pynte et al., 2004, for further discussion of the derivation of these measures). Values above or below the median for words of the same length were defined as 'High' and 'Low' respectively for each of these measures.

Three principal eye movement measures were computed: (1) initial gaze duration, defined as summed fixation duration up to the first exit for the first encounter with a given word (i.e. only the initial encounter with re-read words was included); (2) the probability of refixating a word; (3) average fixation duration for cases where a word was processed in a single fixation. Two lengths of foveal and parafoveal word, together with High and Low values of Frequency, Informativeness and Familiarity were treated as factors in an overall $2 \times 2 \times 2 \times 2 \times 2$ analysis of variance design. This quasi-experimental design raises three issues that need to be considered. First, we are adopting what Kliegl, Grabner, Rolfs, and Engbert (2004) refer to as an "experimental control approach" employing orthogonal sampling from a corpus of eye movement data. This was pioneered by Kliegl, Olson, and Davidson (1983; see also McConkie, Kerr, Reddix, & Zola, 1988) and is to be contrasted with a "statistical control approach" using repeated-measures multiple regression. Both approaches have advantages and disadvantages, but in the present context the quasi-experimental design allows for a more transparent comparison with the laboratory studies it is intended to illuminate and, in particular, with the study by Kennedy et al. (2002). Whichever approach is adopted the possibility must be conceded that a particular outcome may have been mediated by variables not included in the sampling scheme: The technique provides a useful exploratory tool in generating hypotheses which must be tested in controlled experiments. [10] Second, across the sample of word pairs, the number of cases in a given cell of the design inevitably reflects their incidence in the language as a whole and,

[7] Two French-speaking participants were tested in Dundee. The experiment was conducted in French throughout, using the French language versions of the control software.

[8] A referee has pointed out that in cases where the second word ended a line that word might be more visible. On the other hand, the cost of losing a large percentage of cases would be high and changes in relative visibility do not bear directly on the primary hypotheses.

[9] Local word frequency correlated $r = 0.96$ with the relevant norms.

[10] See Kliegl et al. (2004) for an interesting discussion of these issues and for an explicit comparison of the two approaches.

consequently, varied quite widely. For example, by definition there are many more high-frequency tokens than low. An inescapable consequence is some variability in the reliability of estimates of the mean in different cells and in the analyses that follow this has been addressed by reporting the number of cases on which the relevant means were based, by interpreting interactions with caution, and by not seeking to interpret high-order interactions, should any be found. The third issue relates to the fact that the number of words analysed is very large. It effectively exhausts, rather than samples, the reference population (i.e. words employed in journalistic prose). It follows that the by-Participants analyses reported generalise to this population of words. Nonetheless, we report supplementary $F2$ analyses, treating the 20 texts read by each participant as a random factor.

3. Results and discussion

3.1. All words

Scores in the Comprehension Tests were >95% for all participants. An overall analysis of variance was carried out on the measure of foveal gaze to test for interactions involving Foveal Length. There was a significant interaction between Foveal Length, Parafoveal Word Frequency and Parafoveal Familiarity, $F1(1,18) = 7.03$, $p = 0.02$, $F2(1,1216) = 6.03$, $p = 0.01$. Although we had a priori grounds for considering each foveal length separately, this outcome provides additional statistical justification.

3.2. Short foveal words

Average gaze duration on ‘short’ foveal words (i.e. 5 and 6 letters in length) is shown in Table 1 as a function of properties of the following (parafoveal) word. Analysis of variance of these data revealed a significant main effect of parafoveal word frequency. Gaze duration on short foveal words was 12 ms longer when the lexical frequency of the following parafoveal word was low (Low Frequency = 273 ms, 5204 cases; High Frequency = 261 ms, 18,093 cases), $F1(1,18) = 12.86$, $p = 0.002$, $F2(1,608) = 7.11$, $p = 0.007$. There was no interaction with the length of the parafoveal target and no interaction with Informativeness (all $F1$ and $F2 < 1$). The only other effect to achieve statistical significance in by-Participants and by-Items analyses was a main effect of Language and this is dealt with separately in Section 3.4 below.

The null hypothesis must be rejected: The lexical frequency of a parafoveal word plainly exerts an influence over foveal gaze duration. It is true that the size of the effect is relatively small, but it is highly reliable. The outcome is inconsistent with the operation of a serial attentional shift acting to render foveal processing immune from the effects of parafoveal information. It appears more consistent with the suggestion that processing of both foveal and parafoveal words, in this case up to the point of identification, occurs in parallel. It should be noted that the obtained parafoveal-on-foveal effect relates to the lexical frequency of the defined target and not some low-level property that might conceivably exert a pre-attentive effect.

In an attempt to discover whether the modulation in foveal gaze duration was a result of *more* or of *longer* fixations, further analyses were carried out on the probability of refixating the foveal word and on fixation duration for cases where the defined short foveal words were processed in a single fixation. The relevant data are also shown in Table 1. As is evident from the table, refixation probability was low overall and there was only very modest variation as a function of the identified properties of a parafoveal word. Overall, the average

Table 1
(i) Average gaze duration (ms) on ‘short’ words (5–6 characters) as function of the Length, Lexical Frequency, Initial Trigram Type Frequency (‘Informativeness’), and Initial Trigram Cumulative Lexical Frequency (‘Familiarity’) of the immediately succeeding parafoveal ‘target’ word; (ii) Average probability of a refixation on a given foveal word, as a function of the parafoveal properties defined in (a); (iii) Average single fixation duration on the foveal word

	Low frequency parafoveal word				High frequency parafoveal word			
	Low type freq		High type freq		Low type freq		High type freq	
	Lo CLF	Hi CLF	Lo CLF	Hi CLF	Lo CLF	Hi CLF	Lo CLF	Hi CLF
(i) Gaze								
Short target	286	262	289	268	268	260	264	264
Long target	270	268	273	271	265	261	246	264
(ii) Refix prob								
Short target	0.20	0.22	0.25	0.15	0.19	0.17	0.16	0.17
Long target	0.19	0.24	0.17	0.16	0.18	0.16	0.16	0.20
(iii) Single fix								
Short target	254	231	242	246	239	236	248	234
Long target	240	241	253	241	238	239	219	238

probability of refixating a short foveal word was 0.18 with exactly the same value for short and long targets. Nonetheless, even for relatively short words, where refixation was presumably not necessary for foveal identification, refixation rate was higher when the parafoveal word was of low frequency (Low Frequency = 0.19, 1354 cases; High Frequency = 0.17, 4023 cases), $F1(1,18) = 4.50$, $p = 0.04$, $F2 < 1$. Although not consistent across texts, this analysis suggests that a proportion of the obtained variation in gaze duration, even for short foveal words, may be directly attributable to modulation of refixation rate.

The effect of properties of a parafoveal target on fixation duration itself was examined by an analysis of cases restricted to cases where the defined short foveal words were processed in a single fixation. Although the size of the effect of Parafoveal Lexical Frequency was reduced (8 ms compared to the 12 ms effect in the gaze measure), it was also highly significant (Low Frequency = 244 ms, 3850 cases; High Frequency = 236 ms, 14,070 cases), $F1(1,18) = 9.62$, $p = 0.007$, $F2(1,608) = 9.68$, $p = 0.002$.

Setting aside differences between the two languages, which are dealt with later in the paper, the results of the analysis of short foveal words can be summarised as follows: (1) there is a parafoveal-on-foveal effect relating to lexical frequency; (2) the effect is mediated to some degree by changes in refixation rate on the foveal word, although this is not the case for all texts; but (3) it is clearly also present as a direct influence on fixation duration. Since the direction of the effect is in an orthodox direction, with low frequency parafoveal items increasing foveal inspection time, it appears that successful identification of an adjacent word is not simply a source of preview benefit. It is hard to see how the *E-Z Reader* model could accommodate to this outcome, but there are possibly two escape routes available. The first is to claim that the occasional occurrence of mis-located fixations would be enough to drive the (admittedly small) effect (Rayner, Pollatsek, et al., 2003; Rayner, White, et al., 2003). From time to time a saccade will fall short of its target and data will be allocated to word$_n$ when, in reality, it is word$_{n+1}$ that is being processed (i.e. attention has shifted to the parafoveal word). It is true that this would rescue a strictly serial process, but it is inconsistent with the fact that, even for these short words, part of the effect relates to intra- rather than inter-word saccades (it is difficult to see why the reader should refixate a word that has been inaccurately located). In any case, the effect of Word Frequency is significant in both by-Participant and by-Item analyses for the measure of single fixation duration. We shall return to these points in more detail in Section 4. Alternatively, reference might be made to the fact that, in one specific respect, word-encoding is not strictly serial in the *E-Z Reader* model. That is, words may be skipped as a consequence of attention shifts to word$_{n+1}$ if these yield its complete identification. If (and only if) the ancillary argument is accepted that fixation duration is inflated prior to a skip, this fact might account for a (small) proportion of apparent parafoveal-on-foveal effects. However, skipping is generally associated with short high-frequency parafoveal words, whereas we observe inflated gaze associated with low-frequency targets. The evidence on these issues remains contentious (Radach & Heller, 2002; Rayner, 1998) and has recently been further complicated by the results of Kliegl and Engbert (in press), who claim that inflated fixation duration prior to a skip might actually be restricted to cases where the parafoveal word is of low frequency. They observed *shorter* fixation duration prior to a high-frequency skipped word. [11] Finally, neither escape route can satisfactorily deal with the apparent 'inverted' effects that are discussed in Sections 3.3 and 3.4 dealing with long foveal words.

3.3. Long foveal words

Average gaze duration on 'long' foveal words (8–12 letters in length) is shown in Table 2, also as a function of properties of the following, parafoveal, word. It will be recalled that the prediction in this case was attenuated (or absent) effects of the parafoveal word's lexical frequency, but effects relating to properties of its initial-letter Informativeness and/or Familiarity. The results conform to this pattern. In contrast to the results for short foveal words, there was no main effect of parafoveal word frequency on foveal gaze duration. The obtained 5 ms difference, although far from significant, actually runs in an unorthodox, or 'inverted' direction (Low Frequency = 319 ms, 6404 cases; High Frequency = 324 ms, 18,845 cases), $F1 < 1$, $F2 = 1.26$. There was, however, a significant interaction between Parafoveal Target Length and Word Frequency, $F1(1,18) = 8.39$, $p = 0.01$, $F2(1,304) = 3.51$, $p = 0.06$. There was no evidence of a frequency effect for long targets viewed from within a long word, even accepting that the measure of gaze included cases where the foveal word would have been refixated (Low Frequency = 328 ms, 4402 cases; High Frequency = 319 ms, 10,082 cases), $F1(1,18) = 2.30$, $F2(1,304) = 1.54$. When the parafoveal target word was short, its lexical frequency did exert an effect. However, gaze duration was *shorter* in the presence of low frequency parafoveal targets, and the difference approached significance (Low Frequency = 310 ms, 2002 cases; High Frequency = 328 ms, 8763 cases), $F1(1,18) = 3.17$, $p = 0.08$, $F2(1,304) = 2.08$. One possible interpretation of this

[11] We are grateful to Keith Rayner for drawing our attention to this study.

Table 2
(i) Average gaze duration (ms) on 'long' foveal (8–12 characters) words as function of the Length, Lexical Frequency, Initial Trigram Type Frequency ('Informativeness'), and Initial Trigram Cumulative Lexical Frequency ('Familiarity') of the immediately succeeding parafoveal 'target' word; (ii) Average probability of a refixation on a given foveal word, as a function of the parafoveal properties defined in (a); (iii) Average single fixation duration on the foveal word

	Low frequency parafoveal word				High frequency parafoveal word			
	Low type freq		High type freq		Low type freq		High type freq	
	Lo CLF	Hi CLF	Lo CLF	Hi CLF	Lo CLF	Hi CLF	Lo CLF	Hi CLF
(i) Gaze								
Short target	324	286	309	321	315	325	345	328
Long target	340	345	308	318	316	333	301	327
(ii) Refix prob								
Short target	0.36	0.24	0.32	0.30	0.33	0.34	0.37	0.37
Long target	0.39	0.39	0.30	0.35	0.35	0.37	0.32	0.37
(iii) Single fix								
Short target	257	248	245	262	245	252	241	253
Long target	253	280	252	244	249	253	241	253

outcome is that short targets may occasionally have been identified, even from a viewing position within a long foveal word. But this would hardly account for the inverted direction of the induced 'frequency effect', which is more consistent with an early GO response, triggered by an unusual stimulus configuration in the parafovea.

In contrast to the rather fugitive effects of parafoveal lexical frequency on gaze duration, the predicted parafoveal-on-foveal effect exerted by the target's initial-letter Informativeness was clearly reliable. This, too, interacted with Target Length, $F1(1,18) = 5.11$, $p = 0.03$, $F2(1,608) = 7.05$, $p = 0.01$. For short targets (where, it will be recalled, there was an inverted effect of parafoveal frequency), gaze duration was 13 ms shorter in the presence of Informative (or more constrained) parafoveal words, although the difference was not significant (Informative = 313 ms, 5963 cases; Uninformative = 326ms, 4802 cases), $F1(1,18) = 2.03$, $F2(1,304) = 2.92$, $p = 0.08$. For long targets (where, it will be recalled, there was no significant effect of parafoveal frequency), foveal gaze duration was 21 ms longer when the initial trigram of the parafoveal target was Informative, and this effect was highly significant (Informative = 334 ms, 8889 cases; Uninformative = 313 ms, 5595 cases), $F1(1,18) = 21.03$, $p < 0.001$, $F2(1,304) = 4.13$, $p = 0.04$. By definition, the Informativeness of a parafoveal target relates to the number of other words (we will employ the term "competitor" to avoid the theoretical assumptions associated with the concept "neighbour") sharing its initial letters, but this is to leave out of account the properties of these activated competitor words. Low frequency words are likely to activate higher frequency competitors and, equally, competitors activated by a high-frequency word will, on average, be of lower frequency. To examine this, a subsidiary analysis was carried out in which the "Competitor Status" of the parafoveal word was a factor (i.e. parafoveal words were categorised as either having a more frequent competitor or not). Other factors were Foveal Length and Language. In the analysis of short foveal words, the manipulated parafoveal properties did not exert any influence and did not interact with either Length or Language, all $F1$ and $F2 < 1$. In contrast, foveal gaze on long words was significantly shorter when the parafoveal word had a more frequent competitors, $F1(1,18) = 10.42$, $p < 0.01$, $F2(1,152) = 4.06$, $p = 0.04$. Since this manipulated parafoveal property is confounded with frequency (e.g. words with a more frequent competitor are generally less frequent than words whose competitors are not more frequent) our purpose in presenting the analysis is simply to indicate a possible mechanism to account for the *combined* effects of Frequency and Informativeness. A low frequency word with a more frequent competitor may be perceived as 'ambiguous' in the sense that the physical stimulus in the parafovea differs from properties recovered from the lexicon. In other words, readers 'see' something different from what their lexicon tells them they are looking at.

Returning to the treatment of measured gaze, the interactions with Target Length are consistent with the proposition raised in Section 1 that the visibility of the target plays an important role in parafoveal-on-foveal cross-talk. Long targets, viewed from a position within a long foveal word, will only rarely be identified, and it is unsurprising that their lexical frequency plays little role in foveal processing time. On the other hand, sub-lexical, or more accurately pre-lexical, information, in the form of the relative constraint of a parafoveal target's initial letters, does influence foveal processing time. We interpret the effects of Informativeness (i.e. initial-letter constraint) as pre-lexical, but it is difficult to see how they can be characterised as 'pre-attentive'. Since orthographic familiarity was controlled in the design, the effect of Informativeness relates to the number of lexical candidates activated by a particular set of initial letters. This is certainly an 'early' effect in lexical processing, but is not the kind of low-level information that that Reichle et al. (2003) argue might be compatible with the operation of a serial attentional mechanism governing word skipping.

Gaze duration offers rather a weak attack on the effects of parafoveal information on foveal processing because the measure includes cases where a word was refixated. The vast majority of within-word refixations have the effect of bringing the eyes closer to the next word and, for this reason, foveal refixation rate can be seen as a useful index of parafoveal visibility. As noted in the Introduction, there is a processing trade-off between the advantage of being closer to an intended saccadic target, and the fact the necessary additional within-word saccade to bring this about incurs a time penalty (Kennison & Clifton, 1995). The prediction that the pattern found in the analysis of gaze on long foveal words results from modulation to refixation rate (something which is hinted at even for short foveal words) can be readily tested. If correct, the pattern of effects in the analysis of gaze should be present in analyses of refixation rate, but absent, or at least attenuated, in analyses of cases where foveal words were processed with a single fixation.

Average refixation probability is shown in Table 2. Overall, the probability of refixating a long foveal word was 0.34. The interaction between Target Length and Word Frequency found in the gaze duration data was echoed in the analysis of refixation probability, $F1(1,18) = 3.41$, $p = 0.07$, $F2(1.608) = 1.33$. Sub-analyses restricted to the data from short target words demonstrate that the obtained 'inverted' frequency effect arises from a paradoxically *higher* foveal refixation rate when the parafoveal target was of high frequency and this was significant by participants, albeit not consistent over texts (Low Frequency = 0.30, 928 cases; High Frequency = 0.35, 3628 cases), $F1(1,18) = 4.06$, $p = 0.05$, $F2(1,304) = 1.28$. There was no effect of parafoveal frequency on foveal refixation rate in the case of long target words (Low Frequency = 0.33, 2091 cases; High Frequency = 0.34, 4246 cases), $F1$ and $F2 < 1$.

Although non-significant, the pattern of means relating to the interaction between Target Length and Target Informativeness also echoes that evident in the measure of gaze duration, $F1(1,18) = 2.78$, $p = 0.1$, $F2(1,608) = 3.92$, $p = 0.04$. There was no effect of Informativeness of short targets on foveal refixation rate (Informative = 0.32, 2539 cases; Uninformative = 0.34, 2017 cases), $F1 < 1$, $F2(1,304) = 1.15$. It will be recalled that for long targets there was a significant increase in foveal gaze duration when a parafoveal word was Informative. This effect is to a large extent explained by an increased tendency to refixate the foveal stimulus in this case: (Informative = 0.37, 4005 cases; Uninformative = 0.34, 2332 cases), $F1(1,18) = 3.91$, $p = 0.06$, $F2(1,304) = 2.96$, $p = 0.08$.

Since long foveal words were almost twice as likely to be refixated as short, it is possible that, when a word was processed in a single fixation, the initial fixation location might have been a-typical. It follows that the interpretation of analyses of single fixation duration is less straightforward for long foveal words than for short, because of greater uncertainty regarding the location of fixations. This should be borne in mind when considering analyses of single fixation duration. Dealing first with the paradoxical 'inverted' effects of parafoveal word frequency found in the analyses of foveal gaze, the interaction between Target Length and Target Frequency was completely absent in the case of single fixation duration, $F1$ and $F2 < 1$. In its place, there was a modest (7 ms) parafoveal-on-foveal main effect of Target Frequency on foveal single fixation duration, in an orthodox direction (Low Frequency = 255 ms, 3385 cases; High Frequency = 248 ms, 10,970 cases), $F1(1,18) = 4.48$, $p = 0.04$, $F2(1,608) = 2.29$.

As predicted, the interaction between Target Length and Target Informativeness was greatly attenuated, although the pattern of means was similar to that found in the analysis of gaze duration, $F1 = 2.37$, $F2 = 2.01$. For short targets, there was no effect of parafoveal Informativeness on foveal single fixation duration (Informative = 251 ms, 3424 cases; Uninformative = 251 ms, 2785 cases). For long targets, the effect was much smaller (11 ms rather than 21 ms), although Informative parafoveal targets still acted to slow the processing of a foveal word significantly (Informative = 259 ms, 4884 cases, Uninformative = 248 ms, 3263 cases), $F1(1,18) = 7.87$, $p = 0.01$, $F2(1,304) = 2.54$, $p = 0.10$.

The pattern of results for long foveal words supports the experimental hypothesis. It is inconsistent with the operation of a serial attentional shift, and the presence of 'inverted' effects effectively rules out an account in terms of mis-located fixations or saccadic under-shoots. The process of parafoveal 'candidate selection' appears to influence the probability of executing intra-word refixations (which, in turn, have the effect of increasing parafoveal visibility). Further experimental work will be needed to examine the possibility that parafoveal lexical frequency and Informativeness might be subsumed under a single 'competitor status' effect.

3.4. Language differences

Although the exploration of differences between the two languages was not a primary aim of this paper, there were several important differences in the way English and French texts were processed and since these bear directly on the question of parafoveal-on-foveal effects they will be considered here. Although there were no interactions involving Language and either Target Frequency or Target Informativeness, and there were no main effects of Familiarity, there were a number of significant interactions involving Language and Parafoveal Target Familiarity. In this section we briefly report on the nature of the main effects of Language, [12] and then consider parafoveal-on-foveal orthographic effects separately for the two languages.

For short foveal words, gaze duration was significantly longer reading French than English (English = 245 ms, 13,138 cases, French = 290 ms, 10,159 cases), $F1(1,18) = 10.90$, $p = 0.004$, $F2(1,608) = 407.05$, $p < 0.001$. The probability of refixating short foveal words was slightly higher for readers of French (English = 0.17, 2515 cases; French = 0.20, 2862 cases), but this was not reliable in the by-Participants analysis, $F1 < 1$, $F2(1,608) = 60.70$, $p < 0.001$. Single fixation duration was significantly longer reading French (English = 221 ms, 10,623 cases; French = 259 ms, 7297 cases), $F1(1,18) = 14.44$, $p = 0.001$, $F2(1,608) = 437.36$, $p < 0.001$ and comparing this 38 ms difference with the 45 ms difference in gaze duration, it is clear that differences in refixation rate were not primarily responsible for the longer gaze durations.

Gaze duration was also much longer reading long words in French than in English (English = 280 ms, 13,079 cases, French = 362 ms, 12,170 cases), $F1(1,18) = 17.05$, $p < 0.01$, $F2(1,608) = 300.07$, $p < 0.01$. However, in this case, refixation probability was also significantly higher. In fact, long French words were 40% more likely to be refixated than English (English = 0.28, 4852 cases; French = 0.40, 6129 cases), ($F1(1,18) = 4.70$, $p = 0.04$, $F2(1,608) = 122.82$, $p < 0.001$). Although single fixation duration was reliably longer in French, (English = 228 ms, 8227 cases, French = 276 ms, 6129 cases), $F1(1,18) = 21.52$, $p < 0.01$, $F2(1,608) = 485.23$, $p < 0.01$, it appears that about half of the 81 ms difference in gaze duration can be attributed to the fact that refixation is globally more common reading French.

In the case of short foveal words, there was an interaction between Language and the Cumulative Lexical Frequency of the parafoveal target in both measured gaze, $F1(1,18) = 5.35$, $p = 0.03$, $F2(1,608) = 2.31$, $p = 0.13$, and single fixation duration, $F1(1,18) = 12.55$, $p < 0.001$, $F2(1,608) = 5.55$, $p = 0.02$. When a short foveal word is processed in English, the presence of a parafoveal word with unfamiliar initial letters serves to increase foveal gaze duration in an orthodox direction by 16 ms (Unfamiliar initial trigram = 253 ms, 3581 cases, Familiar = 237 ms, 9557 cases), $F1(1,9) = 6.11$, $p = 0.03$, $F2(1,304) = 5.22$, $p = 0.02$, and single fixation duration by 14 ms (Unfamiliar = 228 ms, 2847 cases; Familiar = 214 ms, 7776 cases), $F1(1,9) = 7.14$, $p = 0.02$, $F2(1,304) = 7.48$, $p = 0.01$. This is consistent with the results of Inhoff, Radach, and et al. (2000), Inhoff, Starr, and et al. (2000) and Underwood et al. (2000). However, when a short foveal word is processed in French, the presence of a parafoveal word defined as 'unfamiliar' paradoxically appears to *decrease* foveal processing time. The 5 ms difference in gaze was not significant (Unfamiliar initial trigram = 288 ms, 5780 cases, Familiar = 293 ms, 4379 cases), $F1$ and $F2 < 1$, but the 6 ms 'inverted' effect on single fixation duration achieved significance in the by-Participants analysis, (Unfamiliar = 256 ms, 4164 cases; Familiar = 262, ms, 3133 cases) $F1(1,9) = 6.38$, $p = 0.03$, $F2(1,304) = 1.00$.

The equivalent interaction between Language and Target Familiarity was not significant in the analysis of gaze on long foveal targets, $F1(1,18) = 2.53$, $F2(1,608) = 4.17$, $p = 0.04$, but was present in the measure of single fixation, $F1(1,18) = 5.97$, $p = 0.02$, $F2(1,608) = 16.87$, $p < 0.001$. When a long foveal word is processed in English there is no effect of parafoveal Familiarity on single fixation duration (Unfamiliar = 228 ms, 2163 cases; Familiar = 228 ms, 6064 cases). In French, single fixation duration time again appears paradoxically 15 ms *shorter* in the presence of targets with unfamiliar initial trigrams (Unfamiliar = 268 ms, 3870 cases; Familiar = 283 ms, 2259 cases). This 'inverted' effect was highly significant, $F1(1,18) = 10.83$, $p = 0.01$, $F2(1,304) = 15.13$, $p < 0.001$.

Although English and French data were collected in different laboratories, it is unlikely that the differences in processing time, refixation rate, and sensitivity to parafoveal Familiarity arose as a result of some trivial procedural artifact, if only because completely identical equipment and control software were used to collect the data, which were then subsequently analysed using identical data-reduction software. There are several possible explanations for the outcome. First, although length was controlled in the analyses, average word length in French is approximately one character longer than in English. This could lead French readers to adopt a slightly different global reading strategy, but it is very unlikely to do so because there were, in fact, relatively more short words in the French texts. For example, the fact that the definite article in French is a two-letter word means that two-letter words comprised 19.7% of words in the French texts and only 17.2% in English. A more plausible explanation lies in the distribution of information across the letters of a given words. This differs between French and English. In particular, terminal accents, case markers, and marks of gender and tense all convey important morphological information in French. There is little systematic evidence on this question, but it is possible that global differences in sensitivity to parafoveal orthography exist in the two languages and that

[12] A referee has pointed out that we cannot exclude the possibility that main effects of Language relate individual differences between readers rather than to text properties. We accept this point, although it is worth noting that effects of Language are generally restricted to measures of token familiarity.

Table 3
(i) Average launch position (in characters) from English 'long' (8–12 characters) foveal words as function of the length and Initial Trigram Cumulative Lexical Frequency ('Familiarity') of the immediately succeeding parafoveal 'target' word; (ii) The equivalent data for French 'long' foveal words

	All cases		Single fix	
	Lo CLF	Hi CLF	Lo CLF	Hi CLF
(*i*) *English*				
Short target	5.79 (0.27)	5.54 (0.25)	6.26	5.97
Long target	5.47 (0.29)	5.29 (0.31)	6.02	5.73
(*ii*) *French*				
Short target	5.38 (0.41)	5.93 (0.38)	5.90	6.27
Long target	5.52 (0.39)	5.17 (0.43)	5.87	5.65

Launch position is the distance, in characters, between the point in the foveal word from which the right-going saccade was launched and the left boundary of the defined parafoveal target word. The figure in brackets for the 'all cases' data is the average refixation probability for that cell in the design (see text for further discussion).

these are responsible, in part, for the differences in refixation rates (see Pynte & Kennedy, 1993, for a discussion of the influence of terminal accents in French on eye movements).

Examination of the complete set of data, for both short and long words, suggests that parafoveal items with unfamiliar initial orthography act to increase foveal processing time for short English words, i.e. a parafoveal-on-foveal effect in an orthodox direction. The visibility of the target word plays an important role, because there were no effects even approaching significance for long foveal words. On the other hand, although not always statistically significant, the pattern of results in French takes the form of an apparently counter-intuitive 'inverted' effect on foveal processing. French readers appear globally more sensitive to parafoveal orthography than readers of English, in the sense there are more significant effects relating to parafoveal Familiarity in the French data set than in the English.[13] Rather than interpret the French data in terms of a paradoxical processing penalty exacted by parafoveal familiarity, it seems more likely that unfamiliar parafoveal orthography triggered an early saccade (or GO response) in the case of French. This is consistent with the demonstration by Pynte et al. (2004), in an experiment conducted in French, that orthographic illegality induces an 'inverted' effect on single fixation duration (Experiments 2 and 3) and affects skipping probability (Experiment 1). It is also incidentally consistent with the fact that White and Liversedge (2004) found no significant difference in an equivalent experiment conducted in English.

The most striking difference between the two languages relates to refixation rate, and it would be surprising if this did not have significant consequences. Refixation obviously has processing consequences for a fixated word, but it also acts to change the visibility of the next word. In the context of models appealing to a serial attentional shift this may not be of great consequence. At most it would influence the size of preview effects. But assuming that parafoveal-on-foveal effects of target orthography are real, more important consequences follow. Since the data show that French readers shift foveal fixation position more readily than English, the question arises as to whether this tendency can be linked to properties of the parafoveal word. The most direct way of examining this is to examine at launch position as a function of parafoveal familiarity and the relevant data are shown in Table 3.

There were no main effects or interactions involving Language on measured launch position from short foveal words (all $F1$ and $F2 < 1$). The analysis of data from long foveal words did, however, reveal a significant interaction involving Familiarity, Target Length and Language. This was significant for the measure involving all cases, $F1(1,18) = 6.05$, $p = 0.02$, $F2(1,608) = 8.39$, $p < 0.01$ and although not significant in the measure restricted to single fixations, the pattern of means was similar, $F1(1,18) = 2.40$, $F2 < 1$. Separate analyses were conducted for each Language.

When reading English, saccades were launched from a more remote position when the parafoveal target's initial letters were unfamiliar. This was true for the measure including all cases, (Familiar = 5.42 characters, 9637 cases; Unfamiliar = 5.63 characters, 3442 cases), $F1(1,9) = 6.53$, $p = 0.03$, $F2 < 1$, and for single fixation cases (Familiar = 5.85 characters, 6064 cases; Unfamiliar = 6.14 characters, 2163 cases), $F1(1,9) = 11.58$, $p < 0.01$, $F2(1,304) = 2.18$, although in both instances the effect was not consistent across texts.

The effect of Target Familiarity on launch position when reading French was strongly conditioned by the length of the parafoveal target, with a Target Length × Familiarity interaction present in measures involving all cases, $F1(1,9) = 10.23$, $p = 0.01$, $F2(1,608) = 12.01$, $p < 0.01$, and in measures restricted

[13] It should be recalled that the "competitor" analyses (dealing with the combined effects of lexical constraint and frequency) reported in Section 3.2 show absolutely no differences between languages. The locus of language differences appear to be at a lower level.

to single fixations, $F1(1,9) = 6.29$, $p = 0.03$, $F2(1,304) = 4.66$, $p = 0.03$. As noted above, readers of French spend more time processing words, primarily because they are more likely to refixate them. Table 3 gives average refixation probability values for the 'all cases' measures and it is worth noting that the (non-significant) relationship between refixation probability and parafoveal familiarity echoes the (significant) relationship with launch position, but only in the French data set: the higher the probability of refixation, the closer the launch position. Separate analyses at each target length revealed no significant effects for short targets, but a tendency for launch position to long targets to be more remote when their initial letters were unfamiliar (for 'all cases', Familiar = 5.17 characters, 2424 cases; Unfamiliar = 5.52 characters, 5262 cases, $F1(1,9) = 23.03$, $p < 0.01$, $F2(1,152) = 4.72$, $p = 0.03$; and for single fixation cases, Familiar = 5.63 characters, 1181 cases; Unfamiliar = 5.87 characters, 2698 cases, $F1(1,9) = 8.18$, $p = 0.02$, $F2(1,152) = 1.53$.)

3.5. Short-range processing

Since parafoveal Familiarity appears to modulate foveal launch position, it is worthwhile re-examining the parafoveal-on-foveal effects found for long foveal words in the data set for both languages in circumstances where launch position was relatively close to the target word. One way of securing this is to employ a variant of the 'sub-gaze' technique developed by Kennedy et al. (2002). Single fixation duration on long foveal words was computed for cases where the launch position was closer than 5 characters from the target (i.e. the fixation position prior to leaving the foveal word was to the right of the word's centre). This measure allows for a direct comparison between short and long foveal words. Since the purpose of the analysis was to examine parafoveal visibility, measurements were restricted to short parafoveal targets (5–6 characters in length) and, to maximise the number of cases, foveal words of *any* length (less than 20 characters) were analysed. Although non-significant, the effect of Target Informativeness was in the same direction as obtained in the analyses of single fixation duration involving all cases (Informative = 251 ms, 4231 cases; Uninformative = 246 ms, 2971 cases), $F1(1,18) = 2.77$, $p = 0.1$, $F2(1,304) = 2.54$, $p = 0.1$. However, given the complete absence of any effect of Target Word Frequency in analyses involving all cases, it is worth noting that, in cases where the target was within 5 characters, a modest (and orthodox) effect of Target Word Frequency emerges (Low Frequency = 253 ms, 1654 cases; High Frequency = 244 ms, 5548 cases), $F1(1,18) = 3.04$, $p = 0.1$, $F2(1,304) = 3.07$, $p = 0.1$.

The interaction involving Language and the cumulative lexical frequency of the target's initial letters was even more marked in this restricted set of cases, $F1(1,18) = 16.24$, $p < 0.001$, $F2(1,608) = 13.84$, $p < 001$. For English texts, when launch position was relatively close to the target, parafoveal Familiarity had little effect on inspection time (Unfamiliar = 234 ms, 1104 cases; Familiar = 223 ms, 2934 cases) $F1(1,9) = 2.21$, $F2(1,152) = 1.61$, an outcome which mirrors that for short foveal stimuli. In contrast, the French data offer compelling evidence of an 'inverted' effect—an early saccade (or GO response) triggered by the presence of unfamiliar parafoveal orthography. Foveal single fixation duration (which is, in this case, equivalent to saccade latency) was 25 ms shorter when the target's initial letters were unfamiliar (Unfamiliar = 256 ms, 2038 cases; Familiar = 281, 1126 cases), $F1(1,9) = 26.68$, $p < 0.001$, $F2(1,152) = 16.54$, $p < 001$.

4. General discussion

In this section we will first briefly discuss the issue of laboratory findings vs. 'real-world' testing. We will then consider possible alternative explanations for our findings, and finally, the implications of the data for serial attention shift models and *E-Z Reader* in particular.

There is little doubt that some of the tasks that purported to demonstrate apparent parafoveal-on-foveal effects could hardly be described as 'normal reading'. This was perhaps particularly true of the first demonstration (Kennedy, 1995, 1998), in which participants were exposed to repeated presentations of the same foveal word throughout the experiment. More recent studies have provided closer approximations to normal reading, but few have escaped this criticism and none have provided evidence clear-cut enough to incur serious damage to the canonical serial attention shift model. The present data remedy this situation by showing a predictable pattern of effects in a normal reading task. Furthermore, taken at face value, they are incompatible with the assumption of serial processing which is a central part of the processing engine in the *E-Z Reader* model.

In general, the pattern of effects confirms our experimental hypotheses. The effects for short foveal words reflect lexical properties of words in the parafovea, whereas effects obtained for long words reflect pre-lexical or sub-lexical properties. An exception is the special case where short targets are viewed from a position close to the boundary of a long word. In that case, modest parafoveal-on-foveal effects of lexical frequency appear even for long foveal words. In the set of short foveal words, refixation rate may have been too low to show a very strong relationship between modulations in gaze duration and refixation rate, but the evidence points in that direction. The relationship is clearly present in the set of long foveal words. The 'inverted' effects on gaze in the case of long foveal words with a short parafoveal target are also in the predicted direction, although the fact that they are not echoed in measured single fixation duration is puzzling. In contrast, the 'inverted' effects on single fixation durations relating to orthographic familiarity in French are consistent with the notion of a particularly irregular initial-letter sequence triggering an early exit saccade.

The question arises, nonetheless, as to whether the pattern of results reported here can be accepted at face value. Two, somewhat related, escape routes remain open to proponents of serial processing. The first rests on the claim that dependencies in the language could result in what might be termed "proxy" effects. For example, if words with a particular property generally co-occur in text, apparent effects of the properties of word$_{n+1}$ on n will be found, but need not be interpreted as implying parallel processing. In part, this is an empirical question, and we know of no evidence suggesting that such local dependencies exist. But, in any case, an explanation in such terms cannot account for the present pattern of results, where sub-lexical effects are associated with long words and lexical effects with short words. However, the most obvious counter to an account in terms of hidden dependencies of this kind is the fact that parafoveal-on-foveal effects have been demonstrated in laboratory studies with complete control over text properties.

Another account in terms of "proxy" effects is somewhat harder to dismiss. This rests on the notion of "mis-located" fixations briefly raised in Section 3.2. Rayner, Warren, Juhasz, and Liversedge (in press) examined possible parafoveal-on-foveal effects of sentential anomaly and pragmatic plausibility. Although the obtained effects were small and not reliable in all measures, they obtained a pattern of results somewhat similar to that obtained by Murray (1998) and Kennedy et al. (2004), in that implausible or anomalous information appeared to exert an effect before the critical word had been directly inspected. Rayner et al. do not see this outcome as offering particularly strong support for parallel processing. Rather, they point to the fact that the effect is restricted to fixations located very close to the critical word. They refer to these fixations as "mis-located". There is a commendable simplicity to this explanation: the effects of word$_{n+1}$ manifest themselves precisely because it is word$_{n+1}$ which is being examined, the allocation of the associated data to word$_n$ being an error.

Target "mis-location" can be interpreted in two ways and Rayner et al. (in press) offer both possibilities. The first interpretation relates to poor calibration or to an inaccurate tracker. It is possible that a reader may be processing word$_{n+1}$ when the tracker (or subsequent off-line analysis) allocates the data to word$_n$. As noted in Section 2, the present data were collected using a Dr. Bouis oculometer. The claim might be made that this instrument is less accurate than, for example, the Dual Purkinje tracker, which arguably has a higher spatial resolution. A tracker with lower spatial resolution should undoubtedly lead to more incorrectly allocated fixations. We have two responses to this claim. The first is to note that at least one study allows for direct comparison of these two trackers (Kennedy, Brysbaert, & Murray, 1998). Both instruments were able reliably to detect an extremely small effect (substantially less than 0.5 characters). The second involves a re-examination of the present data sets. As noted in Section 2.1, the algorithm used to determine eye movements in the present study was based on the detection of the end of fixations rather than the beginning of saccades. Running statistical tests using the distribution of point-to-point variation in the data stream were used to group or separate clusters of data (putative fixations). The 90th percentile of this point-to-point distribution (an indication of effective resolution) is generated as part of the output stream and analysis of these data shows no evidence that the effects obtained relate to systematic variation in resolution, whether caused by machine "noise" or by movements of the participant's head (which was, of course, fixed using a bite-bar). Effective resolution did not differ in between the two sets of participants (the criterion values were English = 0.11 and French = 0.12, $t < 1$). Correlations were computed between measured resolution and the size of the single fixation Word Frequency effect and the single fixation Informativeness effect across the data set as a whole for each participant. None of the correlations approached significance (for short words $r = -0.13$ for Word Frequency and $r = -0.23$ for Informativeness; for long words, $r = +0.11$ for Word Frequency and $r = -0.15$ for Informativeness) and three out of the four are actually negative. Our conclusion is that, while machine error is always present, there is no support for the idea that it had systematic effects on the present data.

The second interpretation of the notion of "mis-location" involves consideration of participants' targeting behaviour. Having processed word$_n$, readers may intend to saccade to word$_{n+1}$, but actually land on word$_n$. Undershoots of this kind mean that processing associated with word$_{n+1}$ will be allocated to word$_n$ (in this case correctly allocated, because that is where the participant is looking). It is worth setting out in detail what such a mechanism involves in the context of a serial model. The reader, having switched attention to word$_{n+1}$ and started processing it, executes a saccade which *erroneously* lands on the currently fixated word. The interaction we find with Target Length for long foveal words is compatible with this account. Since longer saccades are typically planned towards longer words, it follows that fewer mis-locations should occur with long targets, and this is what we find. On the other hand, in all other respects mis-location of this kind is quite incompatible with the pattern of obtained results. Why are effects obtained for single fixations (the explanation demands at least two fixations on word$_n$)? How are the various "reversed" effects to be explained? Why should there be systematic differences in mis-location in French and English and why should these differences have opposing consequences? Finally, although not significant in the case of short words, the overall pattern of results suggests that parafoveal-on-foveal effects are, at least to some degree, modulated by within-word refixation. If a saccade planned towards word$_{n+1}$ lands erroneously on word$_n$, why is that word re-fixated, rather than a saccade executed to the word already identified as the correct target?

It is, of course, always possible that artefacts or hidden variables correlated with manipulated factors might explain a given outcome, but there is paradox in searching for explanation in the present case in terms of machine or participant error. This is because it leads to the conclusion that, far from being restricted to laboratory tasks, parafoveal-on-foveal effects might only be found in studies of normal reading, where somewhat poorer experimental control is inevitable. Arguments based on machine error or on occasional saccadic under-shoot are much less likely to have force in the context of small-scale laboratory studies.

We believe that the present data pose particular problems for those who wish to claim that parallel processing of two successive words does not occur in normal reading. In fact, the most natural interpretation of the data is that such parallel processing is relatively ubiquitous. Clearly, the pattern of results must now be examined in the context of further controlled experimental work. Our data are helpful in this regard because they point to the size and direction of effects, the required power of an experimental design to demonstrate them, and some of the factors which must be controlled. If the apparent effects of parafoveal length, lexical frequency, lexical constraint and orthographic regularity can be further confirmed, the outcome would be particularly damaging to the *E-Z Reader* model, largely because it is explicit enough to allow refutation on the grounds of psychological implausibility. But, in fact, no model proposing a serial attentional shift can deal with the obtained pattern of effects. For example, current models suggesting that processing occurs over a *gradient* of attention (e.g. the SWIFT model of Engbert, Longtin, & Kliegl, 2002) fare equally badly. The unexpectedly significant role played by within-word refixation and the presence of 'inverted' effects at all levels of processing, from orthographic to lexical, cannot be accommodated. Early GO responses, triggered by parafoveal difficulty, suggest the operation of a targeting mechanism that has access to more than the kind of low-level information that feeds a pre-attentive process. Finally, and perhaps most significantly, although the broad pattern of effects relating to Word Frequency and Informativeness is strikingly similar in the two languages examined, the pattern of parafoveal-on-foveal orthographic effects differs markedly in English and French. At a trivial level this helps reconcile some of the apparent inconsistencies in the literature, because comparisons have been made between different languages (and, with hindsight, inappropriately). In the context of a strictly serial attentional shift, variation in the attentional span induced by a particular orthography (something which has been understood for many years) had no particularly important processing consequences. However, this is not the case if properties of successive words interact in different ways in different languages. Obviously, language differences can be patched post-hoc to connectionist models such as Glenmore (Reilly & Radach, 2003). But it is much less obvious that our understanding of the role played by differences in the distribution of information across words in different languages (or by consequential differences in reading strategy) is exact enough for the pattern of language differences found here to be an emergent property of a process model. A successful model of the reading process must be informed by an understanding of the mechanisms at work. *E-Z Reader* has the clear advantage over all its competitors, in that it is explicitly committed to specific psychological processes and, in particular, to the assumption of a serial attentional shift. But our conclusion is that the investment in models predicated on this assumption may be premature, given that the underlying processes appear considerably more complex than was initially imagined.

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