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Linguistic and nonlinguistic influences on the eyes' landing positions during reading

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Two eye tracking experiments show that, for near launch sites, the eyes land nearer to the beginning of words with orthographically irregular than with regular initial letter sequences. In addition, the characteristics of words, at least at the level of orthography, influence the direction and length of within-word saccades. Importantly, these effects hold both for lower case and for visually less distinctive upper case text. Furthermore, contrary to previous evidence (Tinker & Paterson, 1939), there is little effect of type case on reading times. Additional analyses of oculomotor behaviour suggest that there is an inverted optimal viewing position for single fixation durations on words. Both the supplementary analyses and the effects of orthography on fixation positions are relevant to current models of eye movements in reading.

Eye movement control in reading is influenced by both the visual and the linguistic characteristics of the text, as well as by the nature of the oculomotor control system. The present study investigates four important issues related to these factors: (a) Are there linguistic influences on where words are first fixated and refixated? (b) Do linguistic factors influence where words are fixated in the absence of visually distinctive ascenders and descenders—that is, for upper case text? (c) Does type case influence when and where the eyes move? (d) Does the fixation position within words influence fixation durations? Each of these issues are described in the Introduction, and their implications for developing comprehensive accounts of eye movement control in reading are considered in the General Discussion.

Linguistic influences on fixation positions within words

Preprocessing of text allows selection of the next saccade target and programming of the next eye movement (for a review, see Rayner, 1998; see also Liversedge & Findlay, 2000). Preprocessing of word length information, as marked by the spaces between words, is used to influence where the eyes first land on a word (McConkie & Rayner, 1975; Morris, Rayner, & Pollatsek, 1990; O'Regan, 1979, 1980; Pollatsek & Rayner,

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1982; Rayner, Fischer, & Pollatsek, 1998). Consequently, first fixations are most likely to land on the preferred viewing position (Rayner, 1979), which is between the beginning and the middle of words (Deutsch & Rayner, 1999; Dunn-Rankin, 1978; McConkie, Kerr, Reddix, & Zola, 1988). Refixation saccades might also be programmed on the basis of word length. For example, O'Regan (1990) argued that the locations of refixations are determined by the position of the first fixation on a word in relation to the word length. A number of studies have shown that linguistic information can influence which words are fixated, shown by the probability of skipping and refixating words on first pass (e.g., Rayner, Sereno, & Raney, 1996). However, a critical issue concerns whether linguistic information can also be preprocessed and influence saccade targeting within words as shown by initial fixation positions and the targeting of refixation saccades.

There is little evidence to suggest that nonfoveal lexical preprocessing influences where words are first fixated (for a review, see White & Liversedge, 2004). However some studies do suggest that nonfoveal orthographic preprocessing can influence saccade programming such that fixations land nearer to the beginning of orthographically irregular than regular beginning words. Hyönä (1995) presented words in sentences with orthographically regular or very irregular word beginnings. The irregular word beginnings specifically included letters that rarely occur in Finnish. Hyönä found that fixations landed nearer to the beginning of the orthographically irregular words, especially on the space before the word. However, because the irregular word beginnings included very infrequent letters, it is unclear whether the landing position effect was produced by individual letters that are linguistically infrequent and perhaps visually unfamiliar, or by infrequent letter sequences. Other experiments have examined the effect of orthography on fixation positions on letter strings in isolated word tasks. Typically, participants successively fixate two letter strings presented adjacently and then make some form of categorical decision on the basis of the strings that they have fixated. These experiments provide a greater degree of control over the location from which saccades are launched. Advocates of such tasks usually argue that they are intended to be generalized to reading, although clearly the tasks do not demand sentence comprehension or even, in some cases, word recognition processes. Experiments using such techniques have shown that word initial infrequent letter sequences produce first fixation positions nearer the beginning of words than do words with frequent initial letter sequences (Beauvillain & Doré, 1998; Beauvillain, Doré, & Baudouin, 1996; Doré & Beauvillain, 1997). Recently, similar results have been shown in sentence reading in Dutch (Vonk, Radach, & van Rijn, 2000) and German (Radach, Inhoff, & Heller, 2004). Radach et al. showed a graded influence of orthography on landing positions such that fixations landed nearer to the beginning of words with low than with medium, and with medium than with high, initial letter sequence frequency. A recent study by White and Liversedge (2004) also found that first fixation positions were nearer the beginning of misspelled than correctly spelled words in English.

Nevertheless, a number of studies have failed to find an effect of initial letter sequence frequency on first fixation positions in isolated word tasks (Kennedy, 1998, 2000), short passage reading tasks (Inhoff, Starr, & Shindler, 2000; Liversedge & Underwood, 1998; Pynte, Kennedy, & Ducrot, 2004), and corpus reading studies (Radach & Kempe, 1993; Radach, Krummenacher, Heller, & Hofmeister, 1995; Radach & McConkie, 1998). It is possible that these studies showed no effect of orthography on fixation positions due to (a) the use of insufficiently strong manipulations of word initial letter sequence frequency, (b) the use of passages rather than single sentences, which might have influenced reading strategy and therefore perhaps eye movement control, or (c) the lack of precise analyses of trials on which prior fixations provided a better than average preview of the critical word (i.e., near launch sites).

As with the literature for initial fixation positions on words, evidence also suggests that more complex information than word length can influence targeting of refixation saccades. Evidence from isolated word tasks (Pynte, 1996, 2000; Pynte, Kennedy, & Murray, 1991) and sentence reading studies (Bertram & Hyönä, 2003; Hyönä, 1995; Hyönä & Pollatsek, 1998; White & Liversedge, 2004) suggest that the location of refixations can be influenced by the linguistic characteristics of the word.

While previous studies that have suggested that preprocessing of orthography can influence where words are fixated have used isolated word tasks or languages other than English, the present study tests whether the effects shown in these studies also generalize to reading English sentences. Previous studies have not controlled for individual letter frequency or have specifically included infrequent letters (Hyönä, 1995). Also, other experiments have used English misspellings to produce orthographically irregular words (White & Liversedge, 2004). In contrast, the present study uses correctly spelled words in which individual letter frequency for the word initial letters is carefully controlled. Experiment 1 tests the hypothesis that the orthographic regularity[1] of word initial letter sequences influences fixation positions on words in correctly spelled English sentences. In order to provide a rigorous test of this hypothesis, the present study uses strong manipulations of word initial letter sequence frequency. Additionally, precise analyses were undertaken to specifically examine cases in which there was a good preview of the critical word (for saccades launched from near to the critical word).

It is impossible to strongly manipulate orthographic regularity whilst also controlling for word frequency and for the number of lexical candidates that can be generated from the word initial letter sequence (type frequency) in English. However, previous studies have shown no evidence of an influence of either type (White & Liversedge, 2004) or word (Rayner et al., 1996) frequency on initial fixation positions. In light of these studies we consider it unlikely that lexical differences between orthographically regular and irregular beginning words might influence saccade targeting. Importantly, the present study provides a strong test of whether any kind of nonfoveal linguistic processing, at least at the level of letter sequences, can influence where words are fixated. Crucially, if any kind of nonfoveal linguistic preprocessing is shown to influence where words are first fixated, then this would show that visual word length is not the only type of nonfoveal information to influence saccade targeting. We refer to any effects of orthographic regularity as being orthographic simply because any differences between the conditions must be explained by processing at or beyond the level of letter sequence processing. Therefore in Experiment 1, if preprocessing at or beyond the level of orthography can influence saccade programming then first fixations and refixations may be influenced by orthographic regularity. In contrast if preprocessing of exclusively visual word length information influences saccade programming then there should be no effect of orthographic regularity on fixation positions.

Linguistic influences on fixation positions for upper case text

Doré and Beauvillain (1997) and Beauvillain and Doré (1998) showed that the frequency of word initial letter sequences influences where upper case words are first fixated in isolated word tasks. However it is possible that with the added variables and different demands on processing resources in natural reading situations, it might only be possible to process nonfoveal letter sequence frequencies in visually distinctive lower case text. Therefore it is important to test whether orthography influences initial fixation positions on upper case text in sentence reading.

[1] Informativeness (type frequency) is the number of words that contain a particular letter sequence. In contrast, orthographic familiarity (token frequency) is the sum of the frequencies of the words that contain a particular letter sequence. In the present experiment, there are differences in both type and token frequency, and so we refer to “orthographically regular” (frequent) and “orthographically irregular” (infrequent) initial letter sequences.

Lower case letters have visually distinctive ascenders or descenders, or neutral shapes (Paap, Newsome, & Noel, 1984). Reichle, Rayner, and Pollatsek (2003) suggested that low spatial frequency information, such as the presence or absence of ascenders and descenders, might influence saccade programming. Reichle et al. do not specify exactly what influence this information would have on where words are fixated (Liversedge & White, 2003). Nevertheless, it is possible that the source of any orthographic influences on landing positions may be due to differences in the low spatial frequency visual characteristics of lower case text, such as the presence of ascenders or descenders. Alternatively, such visually distinctive features might be crucial to enable accurate nonfoveal preprocessing of abstract letter information. Previous research shows that abstract letter information can be extracted from nonfoveal text (McConkie & Zola, 1979; Rayner, McConkie, & Zola, 1980). The oculomotor control system may use such abstract letter processing to modulate landing positions according to orthography.

An additional issue is whether orthographic influences on fixation positions are determined by visual pattern familiarity or abstract linguistic familiarity. For example, the visual pattern for "pne" is unfamiliar compared to the visual pattern "pri". However, the abstract orthographic letter sequence of "PNE" is also less familiar than that of "PRI". If both lower and upper case text are equally visually familiar then it is possible that the influence of orthography on fixation positions is determined by visual pattern familiarity for both types of case. However, if upper case text is less familiar than lower case text (due to reduced exposure), and if the influence of orthography on fixation positions is determined by differences in visual pattern familiarity, then orthography might influence fixation positions for lower, but not upper, case text. That is, upper case text may not be sufficiently visually familiar to produce the necessary differences in visual pattern familiarity for different letter sequences. In contrast, if the influence of orthography on fixation positions is determined by abstract orthographic processing then there should be no difference in the effect of orthography on landing positions for upper compared to lower case text, because the underlying abstract codes are the same despite the different visual information.

Experiment 2 therefore examines whether orthographic regularity influences fixation positions when visually distinctive letter shape cues, which are available in lower case text, are removed. If orthographic regularity does influence saccade programming for upper case text then this would demonstrate that preprocessing of letter sequence frequencies does not depend on the highly visually distinctive low spatial frequency letter shape features that are unique to lower case text. Such a result would also be consistent with the notion that abstract preprocessing of orthography influences fixation positions.

Effects of type case on eye movements in reading

As well as examining whether type case influences orthographic effects on fixation positions, it is also important to establish whether any reduced visual distinctiveness or familiarity of upper, compared to lower, case text has any effect on oculomotor behaviour as indexed by general reading measures. Although some studies have recorded eye movements during the reading of upper case text (e.g., Trueswell, Tanenhaus, & Garnsey, 1994), to our knowledge, the only study to examine eye movements in the reading of sentences presented in lower compared to upper case text was undertaken by Tinker and Paterson in 1939 (for a discussion of this work, see also Morrison & Inhoff, 1981; Paterson & Tinker, 1946, 1947). Tinker and Paterson used a photographic technique to record eye movements whilst participants read paragraphs of text in either lower or upper case. Total reading times were 7% longer for upper than for lower case text. However, this result is confounded by differences in the size of the text: The upper case text covered a 35% larger area than did the lower case text. Consequently in Tinker and Paterson's experiment, the overall longer reading times may reflect greater processing difficulty due to acuity (text size) of upper case text rather than reduced visual distinctiveness or familiarity of upper compared to lower case text. To our knowledge, Experiment 2 therefore provides a first unconfounded test of whether the visual distinctiveness or familiarity of upper, compared to lower, case text influences eye movement control in reading.

Effects of fixation position on fixation duration

The present study provides an ideal opportunity to test a further issue related to eye movement control in reading—that is, whether the fixation position within a word influences fixation durations. A number of previous studies have investigated this issue, and these are discussed directly in relation to our findings following our presentation of the main results from Experiments 1 and 2 (in the section "Experiments 1 and 2, further analyses").

Overall, the present study provides four areas of investigation into eye movement control in reading. The experiments test whether preprocessing of orthographic information can influence where words are first fixated and refixated and whether such effects hold for both lower and upper case text. Experiment 2 also examines whether eye movement behaviour is influenced by type case. In addition, the combined data from the two experiments provide an opportunity to test whether fixation position within words influences fixation durations.

EXPERIMENT 1

Experiment 1 was designed to provide a strong test of whether the frequency of word initial letter sequences influences landing positions in the reading of correctly spelled English sentences. Fixation positions on orthographically regular beginning words (e.g., *miniature*) were compared to those on orthographically irregular beginning words (e.g., *ergonomic*). Importantly, there were no differences in the individual letter frequency of the initial three letters of the critical words, and the sentence frames up until the word after the critical word were identical except for the critical word. Given these constraints, the stimuli were designed to provide the strongest possible test of whether linguistic factors influence where words are first fixated.

Method

Participants

A total of 44 native English speakers at the University of Durham were paid to participate in the experiment. The participants all had normal or corrected-to-normal vision and were naïve in relation to the purpose of the experiment.

Materials

The critical words had orthographically regular or irregular word beginnings, and these two conditions were manipulated within participants and items. Word frequencies and *n*-gram frequencies were calculated in counts per million using the CELEX English word form corpus (Baayen, Piepenbrock, & Gulikers, 1995).

The initial trigram type and token position-specific frequencies were significantly higher for the orthographically regular condition (type, $M = 105$, $SD = 61$; token, $M = 2{,}400$, $SD = 3{,}661$) than for the orthographically irregular condition (type, $M = 3$, $SD = 2$; token, $M = 8$, $SD = 8$), ts > 3.2, ps $< .01$. The initial trigram token frequencies were within the 1st to the 5th deciles for the orthographically irregular condition and the 9th to the 10th deciles for the orthographically regular condition. The initial (first and second letter) and second (second and third letter) bigram type and token frequencies were also significantly higher for the orthographically regular than for the irregular condition, ts > 2.5, ps $< .05$. The visual familiarity of individual letters was also controlled using nonposition-specific frequency counts;[2] there were

[2] There was also no difference in position-specific token frequency monogram frequency counts (ts < 1.1). There were some differences in position-specific type frequency monogram frequency counts. However, most importantly, the absence of any differences in token frequency for both position-specific and nonposition-specific counts shows that there is no difference in the familiarity of the monograms between the orthographically regular and irregular word beginning conditions.

no significant differences in type or token monogram frequency between the two conditions for the first, second, or third letters of the critical words (*t*s < 1.2).

In order to produce an extremely strong manipulation of orthographic regularity there necessarily has to be a difference in the lexical characteristics of words between the conditions. Although the primary factor to be investigated was letter sequence familiarity (token frequency), these strong manipulations also produced differences in the number of lexical candidates that include those letter sequences (type frequency). In addition, critical words in the regular condition had, on average, higher word frequency in counts per million ($M = 24$, $SD = 29$) than did the critical words in the irregular condition ($M = 1$, $SD = 2$). Importantly, as noted in the Introduction, any differences between the conditions must be explained by processing at or beyond the level of letter sequence processing.

There were 24 critical words in each condition; all were either 9 or 10 letters long, and they were matched for length across the two conditions with a mean word length of 9.4 characters ($SD = 0.5$). Each pair of critical words was embedded roughly in the middle of the same sentential frame up to and including the word after the critical word. Each of the sentences was no longer than one line of text (78 characters). The words before and after the critical word were either five or six letters long and had medium to high frequencies. The critical words were not predictable from the prior sentential context. Twelve participants were given sentence fragments up to the position of the critical word, and they were asked to write down what they thought the next word might be. None of the participants guessed any of the critical words. See Appendix for a list of experimental sentences and critical words.

Two lists of 72 sentences were constructed, and 22 participants were randomly allocated to each list. Filler sentences were included in order to provide a wider variety of sentence structures. Each list included all 48 experimental sentences and 24 filler sentences. Within each list the sentences were presented in a fixed pseudorandom order with four filler sentences at the beginning. For each condition, 12 experimental sentences were presented in the first half of one list and in the second half of the other list. Sixteen experimental sentences and 8 filler sentences were followed by a comprehension question.

Procedure

Eye movements were monitored using a Dual Purkinje Generation 5.5 eye tracker. Viewing was binocular but only the movements of the right eye were monitored. The sentences were presented on a ViewSonic 17GS monitor with characters presented in Courier font. The letters were presented in light cyan (by mixing the green and blue input signals on the monitor) on a black background. The viewing distance was 70 cm, and three and a half characters subtended one degree of the visual angle. The resolution of the eye tracker was 10 min of arc, and the sampling rate was every millisecond.

Participants were instructed to understand the sentences to the best of their ability. A bite bar and head restraint were used to minimize head movements. The participant completed a calibration procedure, which included the presentation of six successive calibration points; the software calculated the position of eye fixation on this basis. The calibration accuracy was checked after every few trials during the experiment. After reading each sentence the participants pressed a button to continue and used a button box to respond "yes" or "no" to comprehension questions. The entire experiment lasted approximately 30 minutes, and participants were given one break.

Analyses

Fixations shorter than 80 ms that were within one character of the next or previous fixation were incorporated into that fixation. Any remaining fixations shorter than 80 ms and longer than 1,200 ms were discarded. A total of 4.4% of trials were excluded due to either no first-pass fixations on the sentence prior to word $n - 1$ or tracker loss or blinks on first-pass reading of word $n - 1$ or the critical word.

Table 1. *Mean gaze durations on and probability of refixating the critical word, and length and landing position of rightward refixation saccades for each condition for Experiments 1 and 2*

		Gaze duration[a]				Rightward refixation			
						Length[b]		Position[b]	
Exp.	*Condition*	*M*	*SD*	*≥Two FP fixes*	*Left refix*	*M*	*SD*	*M*	*SD*
1	Regular	393	162	.35	.26	5.1	2	6.8	1.6
	Irregular	521	272	.48	.39	4.6	1.8	6.6	1.7
2	Regular, lower	366	163	.27	.23	5.3	1.9	7.1	1.6
	Regular, upper	378	189	.27	.22	5.2	1.8	7	1.7
	Irregular, lower	498	302	.4	.31	4.6	1.9	6.7	1.6
	Irregular, upper	490	297	.38	.39	4.9	1.8	6.8	2

Note: ≥Two FP fixes: frequency of making two or more first-pass fixations on the critical word. Left refix: frequency of first refixating to the left of the initial fixation on the critical word. Frequency of making two or more first-pass fixations is based on those cases (98–99%) in which the critical word was fixated on first pass. Frequency of first refixating to the left is based only on multiple first-pass fixation cases.
[a]In ms. [b]In number of characters.

Results

Paired samples t tests were undertaken with participants (t_1) and items (t_2) as random variables. Gaze duration (the sum of fixation durations before leaving the word on first pass) and refixation probability were calculated for the critical word. The most crucial measures were: initial landing positions on the critical word; saccade extent into the word; launch site before first fixating the word; and the saccade length and position of refixations on the critical word (measured in characters). Launch sites were calculated from the end of word $n - 1$ such that saccades launched from the final letter of word $n - 1$ were said to be launched one character from the critical word. The mean error rate on the comprehension questions was 9%, indicating that participants properly read and understood the sentences.

Reading time and refixation probability

Table 1 shows the mean gaze durations on and the probability of refixating the critical word. Gaze durations were significantly longer on irregular than on regular beginning words, $t_1(43) = 8.08$, $p < .01$; $t_2(23) = 9.25$, $p < .01$, and the irregular words were significantly more likely to be refixated on first pass than were the regular beginning words, $t_1(43) = 6.27$, $p < .01$; $t_2(23) = 6.06$, $p < .01$. These results support those of Vonk et al. (2000), and they correspond to Lima and Inhoff's (1985) finding that fixations are longer on words with constraining (infrequent) than with less constraining (frequent) initial trigrams. The results might also reflect the standard word frequency effect, that fixations are longer, and refixations are more likely, on infrequent (orthographically irregular beginning) than on frequent (orthographically regular beginning) words (e.g., Inhoff & Rayner, 1986).[3]

[3] There were no significant effects of the orthography of the critical word on the duration of the fixation prior to first fixating the critical word for all of the data, for fixations located on word $n - 1$ and for fixations located three or fewer characters from the critical word for both Experiments 1 (ts < 1) and 2 (Fs < 1.2). Therefore the word initial letter sequences of the critical word did not influence fixation durations until the critical words were directly fixated. That is, there was no evidence to suggest that nonfoveal preprocessing of words can influence the duration of the fixation directly before they are first fixated: so-called "parafoveal-on-foveal effects" (for a review, see Rayner, White, Kambe, Miller, & Liversedge, 2003). The fact that orthography influenced saccade programming, but not the duration of the fixations, whilst this programming took place supports previous claims that the factors that drive when and where the eyes move are quite different (Rayner & McConkie, 1976; Rayner & Pollatsek, 1981).

Table 2. *Experiment 1. Mean landing positions on the critical word and lengths and launch sites of saccades into the critical word*

		Landing position		*Saccade length*		*Launch site*	
Data set	*Orthography*	*M*	*SD*	*M*	*SD*	*M*	*SD*
All data	Regular	3.7	2.1	8.3	2.6	4.6	3
	Irregular	3.6	2	8.2	2.8	4.7	2.9
	Difference	0.1		0.1		−0.1	
Launch word $n - 1$	Regular	4	1.9	7.6	1.7	3.6	1.7
	Irregular	3.8	1.8	7.5	1.7	3.7	1.6
	Difference	0.2		0.1		−0.1	
Launch ≤3 characters	Regular	4.9	1.5	7.1	1.5	2.1	0.8
	Irregular	4.6	1.5	6.9	1.5	2.2	0.8
	Difference	0.3		0.2		−0.1	

Note: Results are shown in number of characters for all of the data, for saccades launched from word $n - 1$, and for saccades launched from three or fewer characters from the beginning of the critical word.

Landing position

Table 2 shows the mean first fixation positions on the critical word for Experiment 1. The mean first fixation position on the critical word was 0.1 characters nearer the word beginning for irregular than for regular beginning words, but this difference was not significant, $t_1(43) = 1.44$, $p = .16$; $t_2(23) = 1.25$, $p = .22$. Since text that is further from fixation is visually degraded relative to that nearer to fixation, studies frequently analyse nonfoveal text processing as a function of launch site (e.g., Kennison & Clifton, 1995; Lavigne, Vitu, & d'Ydewalle, 2000; Rayner, 1975; Rayner, Binder, Ashby, & Pollatsek, 2001; see also McConkie et al., 1988). Saccades launched from further away might be less likely to be influenced by the characteristics of the critical word. When the analyses were restricted to the 84% of saccades launched from word $n - 1$, the mean first fixation position was 0.2 characters significantly nearer the word beginning for irregular than for regular beginning words, $t_1(43) = 2.12$, $p = .04$; $t_2(23) = 2.3$, $p = .03$. Figure 1 shows the distribution of landing positions for each condition for saccades launched from the previous word. The landing position distribution for the irregular beginning words is shifted to the left compared to that for the regular beginning words. Similarly, when the analyses were restricted to the 41% of saccades launched from three or fewer characters before the critical word, the mean first fixation position was 0.3 characters significantly nearer the word beginning for irregular than for regular beginning words, $t_1(43) = 2.52$, $p = .02$; $t_2(23) = 2.91$, $p = .01$. The results therefore provide clear evidence that nonfoveal preprocessing, at least at the level of orthography, influences where words are first fixated for saccades launched from near launch sites. Note that orthography may influence where words are first fixated only for saccades launched from near, but not from far, launch sites.[4]

Fixations prior to the critical word

Table 2 also shows the mean saccade lengths and launch sites corresponding to the analyses of landing positions above. For all of the data and for saccades launched from the previous word there were no effects of orthographic regularity

[4] In the present paper the landing position data are analysed as a function of specific launch site regions. An alternative technique is to categorize near and far launch sites using a median split for each subject and for each condition. Using this method, Experiment 1 produced an interaction between orthographic regularity and launch site, $F_1(1, 43) = 10.06, p < .01$; $F_2(1, 23) = 7.99, p = .01$, such that there was an effect of orthography on landing positions for saccades launched from near, $t_1(43) = 2.87, p < .01$; $t_2(23) = 3.88$, $p < .01$, but not from far (ts < 1.1) launch sites. However, the corresponding analysis for Experiment 2 produced no significant interaction between orthographic regularity and launch site (Fs < 1).

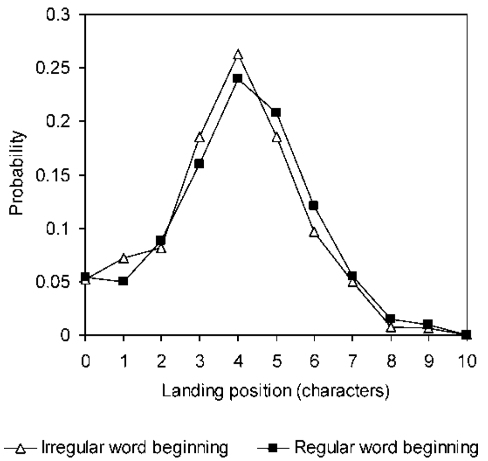

Figure 1. *Experiment 1: First fixation positions on the critical word for saccades launched from the previous word. Landing Position 0 is the space before the word, and Landing Position 1 is the first letter of the word.*

on launch site (ts < 1.2) or saccade length into the critical word (ts < 1.5). For saccades launched from three characters from the beginning of the critical word there were marginal, but not reliable, effects of orthographic regularity on launch site, $t_1(43) = 1.72$, $p = .09$; $t_2(23) = 2.04$, $p = .05$, and saccade length, $t_1(43) = 1.07$, $p = .29$; $t_2(23) = 1.77$, $p = .09$.

Refixations

For those trials in which multiple first-pass fixations occurred on the critical word, Table 1 shows the probability of making a first refixation to the left of the initial fixation and the mean length and position of initial rightward refixation saccades. First refixations were significantly more likely to be to the left of the initial fixation position if the word had an irregular, rather than a regular, word beginning, $t_1(43) = 3.96$, $p < .01$; $t_2(23) = 3.48$, $p < .01$. Rightward refixation saccades were significantly shorter on orthographically irregular words,[5] $t_1(41) = 3.05$, $p < .01$; $t_2(23) = 2.44$, $p = .02$. Rightward refixation saccades also tended to land nearer the word beginning for irregular than for regular beginning words but the difference was not significant, $t_1(41) = 1.85$, $p = .07$; $t_2(23) = 1.02$, $p = .32$. The results show that processing of the fixated word, at or beyond the level of orthography, also influences the direction and length of refixation saccades.

Discussion

The orthographically irregular words were more difficult to process than the orthographically regular beginning words, shown by the longer reading times and greater probability of refixating the irregular words. The irregular words were more difficult to process than the regular words due to differences in either orthography or word frequency, or both.

More importantly, the results support previous evidence from languages other than English (Beauvillain & Doré, 1998; Beauvillain et al., 1996; Doré & Beauvillain, 1997; Hyönä, 1995; Radach et al., 2004; Vonk et al., 2000) and from an experiment using misspellings (White & Liversedge, 2004), which suggest that first fixation positions land significantly nearer to the beginning of orthographically irregular than regular beginning words for saccades launched from the previous word. Individual letter frequency was carefully controlled in this experiment, and so the effects must be explained by preprocessing at least at the level of letter sequence frequencies rather than individual letter familiarity. Note that the influence of such linguistic preprocessing on fixation positions in this study has been shown only with quite long words (9–10 letters long), and therefore these findings can be generalized only to other long words. The importance of this finding should not be underestimated. To be clear, it indicates that the oculomotor control system is sensitive to linguistic, as well as visual,

[5] In Experiment 1, the participants' analyses for rightward refixation saccade lengths and positions were based on the data of 42 readers because two participants did not make rightward refixations on the critical word in both conditions. There were insufficient data to undertake similar analyses for leftward refixations.

nonfoveal information when targeting saccades to words. Although there were no reliable effects of orthographic regularity on either saccade length or launch site, differences in both these measures must have contributed to the difference in first fixation position.

Note that Figure 1 shows that the difference in orthographic regularity produces an overall small shift in the preferred viewing position, rather than a specific change in the saccade target. It is possible that very infrequent individual letters may be so visually unfamiliar (rather than just linguistically infrequent) that they draw saccades directly towards them. This may have been the case in Hyönä's (1995) study, and it is similar to an attraction account of saccade programming (Hyönä, 1993). However, when individual letter frequency (and therefore individual letter visual familiarity) is carefully controlled, as in the present experiment, the effect of orthography is to produce a small shift in the preferred viewing position. Perhaps orthography modifies the word length based saccade computation (Beauvillain & Doré, 1998).

Linguistic processing also influenced the direction and length of refixation saccades. The findings support evidence from previous sentence reading studies showing that the location of refixations is influenced by the linguistic characteristics of words (Bertram & Hyönä, 2003; Hyönä, 1995; Hyönä & Pollatsek, 1998; White & Liversedge, 2004). It is possible that there were differences in the regularity of letter sequences within the words, and these could have attracted refixation saccades such that they were shorter in orthographically irregular than in regular beginning words. The results might also be explained by differences in general processing difficulty, such as word frequency, influencing targeting of refixation saccades (Hyönä & Pollatsek, 1998, 2000). However note that the effect of orthographic regularity on refixation saccade lengths might be qualitatively different from that on refixation directions. The former may involve a small adjustment in the saccade amplitude whereas the latter might involve cancelling or initiating saccade programmes (see Becker & Jürgens, 1979).

EXPERIMENT 2

Experiment 1, and all other sentence reading studies of the effects of orthography on fixation positions, presented text primarily in lower case. Experiment 2 examined whether the visually distinctive nature of lower case text is necessary for preprocessing of nonfoveal letter sequences and subsequent modulation of fixation positions by those letter sequences. In order to do this, Experiment 2 used the same stimuli as those in Experiment 1 but half of the sentences were presented in lower case (other than the first letter of the first word) and half entirely in upper case.

If the more visually distinctive nature of lower case letters is necessary to enable nonfoveal processing at least at the level of orthographic regularity, then there should be an interaction between orthography and case on fixation positions (initial fixations and refixations) on the critical word. That is, there should be effects of orthography on fixation positions for lower case text, because the lower case text provides visually distinctive letter shapes, but there should be no effects of orthography on fixation positions for upper case text, because the upper case letters are not so visually distinctive. In contrast, if the more visually distinctive nature of lower case letters is not necessary to enable nonfoveal processing of orthographic regularity in natural sentence reading, then there should be a main effect of orthography. That is, orthography should influence fixation positions to the same extent for both lower and upper case text.

In addition, Experiment 2 provides an opportunity to examine whether eye movement patterns are generally different for lower and upper case text. In contrast to Tinker and Paterson's (1939) original study, in the present experiment viewing distance was controlled, and lower and upper case characters subtended the same degrees of visual angle. If eye movement patterns differ between lower and upper case text in the present experiment then this will indicate that the visual distinctiveness, or familiarity, of type case influences reading behaviour.

Method

Participants

Sixty native English speakers at the University of Durham were paid to participate in the experiment. The participants all had normal or corrected-to-normal vision, none had participated in Experiment 1, and all were naïve in relation to the purpose of the experiment.

Materials and design

The stimuli were identical to those in Experiment 1 except that half were presented in lower case (except for the first letter of the first word) or entirely in upper case. The variables of orthography (regular, irregular) and case (lower, upper) were manipulated within participants and items.

Four lists of 72 sentences were constructed, and 15 participants were randomly allocated to each list. Each list included all 48 experimental sentences and 24 filler sentences. Lower and upper case experimental and filler sentences were intermingled throughout the lists. Case and orthography were manipulated across the four lists following a Latin square design. Within each list the sentences were presented in a fixed pseudo-random order with four filler sentences at the beginning. Sixteen experimental sentences and 8 filler sentences were followed by a comprehension question.

Procedure

The procedure was the same as that in Experiment 1.

Analyses

The analyses were the same as those in Experiment 1. A total of 5% of trials were excluded due to either no first-pass fixations on the sentence prior to word $n-1$ or tracker loss or blinks on first-pass reading of word $n-1$ or the critical word.

Results

Reading measures were calculated as in Experiment 1 with additional measures (total sentence reading time, number of fixations, mean forward and regressive fixation durations, number of regressions, mean forward and regressive saccade lengths) for the analyses of case. Paired samples t tests were undertaken in order to examine the effects of case on general reading measures with participants (t_1) and items (t_2) as random variables. For analyses related to the critical word, repeated measures analyses of variance (ANOVAs) were undertaken for the variables of orthography (regular, irregular) and case (upper, lower) with participants (F_1) and items (F_2) as random variables. The mean error rate on the comprehension questions was 7%, indicating that participants properly understood the sentences.

Effects of case

Tinker and Paterson (1939) found that total sentence reading times were 7% longer for upper case text than for lower case text. However in the present experiment total sentence reading times (including both fixations and saccades) were just 2% longer for upper (M = 3,870, SD = 1,555) than lower (M = 3,791, SD = 1,506) case text, and this difference was almost significant,[6] $t_1(59) = 1.88$, $p = .07$; $t_2(23) = 2.02$, $p = .06$. Whereas Tinker and Paterson found that upper case text produced 12% more fixations than did lower case text, there was no difference in the number of fixations between upper ($M = 12.8$, $SD = 4.4$) and lower ($M = 12.6$, $SD = 4.3$) case text (ts < 1.5, ps $> .16$) in the present experiment. Furthermore, in contrast

[6] An additional analysis was undertaken for the sentence reading times on the initial five experimental trials in Experiment 2. For these five items, whole sentence reading times were 3% longer when the text was presented in upper case (M = 4,395, SD = 1,578) than when it was presented in lower case (M = 4,257, SD = 1,646), and this difference was not significant, $t_1(58) = 1.33$, $p = .19$; $t_2 < 1$. The analyses across participants were based on 59 participants because 1 participant did not produce data for one of the conditions. These results suggest that the lack of difference between eye movement behaviour when upper and lower case text is read can not be due to practice effects that occurred during the experiment.

to Tinker and Paterson, who found that average fixation durations were 20 ms shorter for upper than for lower case text, in the current experiment there were no differences in either fixation durations preceded by a progressive (upper case, $M = 259$, $SD = 53$; lower case, $M = 256$, $SD = 53$), $t_1(59) = 1.93$, $p = .06$; $t_2(23) = 1.68$, $p = .11$, or a regressive (upper case, $M = 250$, $SD = 90$; lower case, $M = 255$, $SD = 100$), ts < 1.4, ps $> .19$, saccade. Although Tinker and Paterson found no effects of case on regression frequency, in this experiment there tended to be slightly more regressions for upper ($M = 2.4$, $SD = 2.2$) than for lower ($M = 2.3$, $SD = 2.1$) case text, $t_1(59) = 2.3$, $p = .03$; $t_2(23) = 2$, $p = .06$. Also, in contrast to Paterson and Tinker (1947) there were no differences in either forward (upper case, $M = 8.3$, $SD = 1.9$; lower case, $M = 8.3$, $SD = 1.9$; ts < 1) or regressive (upper case, $M = 10.4$, $SD = 9.5$; lower case, $M = 10$, $SD = 10$; ts < 1) saccade lengths. Overall, these data are inconsistent with the findings of Tinker and Paterson; the results indicate that there was little difference in eye movement behaviour when participants read text in upper compared to lower case.

Reading times and refixation probability

Table 1 shows the mean gaze durations and refixation probabilities on the critical word for each condition. Mean gaze durations were significantly longer on irregular than regular beginning words, $F_1(1, 59) = 75.58$, $p < .01$; $F_2(1, 23) = 53.33$, $p < .01$, and there were no effects of case (Fs < 1) and no interaction between orthography and case, $F_1(1, 59) = 1.45$, $p = .23$; $F_2 < 1$. For those cases in which a first-pass fixation was made on the critical word, the irregular beginning words were more likely to be refixated on first pass than were the regular beginning words, $F_1(1, 59) = 46.18$, $p < .01$; $F_2(1, 23) = 27.48$, $p < .01$, and there were no effects of case and no interaction between orthography and case (Fs < 1). Therefore, as in Experiment 1, reading times were longer, and there were more first-pass fixations on the orthographically irregular than on the regular words, due to differences in either orthography or word frequency.

Landing position

Table 3 shows the mean landing positions on the critical word for Experiment 2. For all of the data, mean first fixation positions on the critical word were numerically nearer the word beginning for irregular than for regular beginning words for both lower and upper case text, but the effect was not significant, $F_1(1, 59) = 2.74$, $p = .1$; $F_2(1, 23) = 2.7$, $p = .11$. There were also no

Table 3. *Experiment 2. Mean landing positions on the critical word and lengths and launch sites of saccades into the critical word*

		Landing position				*Saccade length*				*Launch site*			
		Lower case		*Upper case*		*Lower case*		*Upper case*		*Lower case*		*Upper case*	
Data set	*Orthography*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
All data	Regular	3.9	2.1	3.9	2.1	8.4	2.5	8.5	2.7	4.5	2.8	4.7	3.0
	Irregular	3.7	2	3.8	2.1	8.2	2.1	8.3	2.5	4.4	2.4	4.5	2.8
	Difference	0.2		0.1		0.2		0.2		0.1		0.2	
Launch word $n - 1$	Regular	4.3	1.8	4.2	1.9	7.9	1.7	7.9	1.7	3.5	1.6	3.7	1.6
	Irregular	4.1	1.8	4.2	1.9	7.8	1.6	7.8	1.8	3.7	1.6	3.6	1.6
	Difference	0.2		0		0.1		0.1		−0.2		0.1	
Launch ≤3 characters	Regular	5.2	1.5	5.2	1.5	7.3	1.5	7.3	1.5	2.1	0.8	2.2	0.8
	Irregular	5.0	1.4	4.9	1.6	7.2	1.4	7.1	1.6	2.2	0.8	2.2	0.8
	Difference	0.2		0.3		0.1		0.2		−0.1		0	

Note: Results are shown in number of characters for all of the data, for saccades launched from word $n - 1$, and for saccades launched from three or fewer characters from the beginning of the critical word.

significant effects of case (Fs < 1) and no interaction between orthography and case, $F_1(1, 59) = 1.5, p = .23$; $F_2(1, 23) = 1.77, p = .2$.

As in Experiment 1, the landing position effects were analysed as a function of launch site because saccades launched from distant launch sites might not be influenced by nonfoveal orthography due to degradations in visual acuity. When the analyses were restricted to the 84% of saccades launched from word $n-1$, the mean first fixation position was significantly nearer the word beginning for irregular than for regular beginning words, $F_1(1, 59) = 5.94, p = .02$; $F_2(1, 23) = 4.64, p = .04$, and there was no significant effect of case (Fs < 1) and no significant interaction between orthography and case, $F_1(1, 59) = 2.7, p = .11$; $F_2(1, 23) = 2.35, p = .14$. Although there was no significant interaction, the mean landing positions for saccades launched from word $n-1$ do suggest a larger difference in fixation positions for lower (0.2) than upper (0.04) case text. However, when the analyses were restricted to the 40% of saccades launched from three characters before the critical word, mean first fixation positions were 0.2 characters significantly nearer the beginning of irregular beginning words for lower case text and 0.3 characters significantly nearer the beginning for upper case text, $F_1(1, 59) = 3.89, p = .05$; $F_2(1, 23) = 19.5, p < .01$. There were no effects of case (Fs < 1), and there was no interaction between orthography and case (Fs < 1). Figure 2 shows that the landing position distributions are shifted to the left for orthographically irregular, compared to regular, beginning words for both lower (Panel A) and upper (Panel B) case text.

As in Experiment 1, the results show that, for near launch sites, first fixation positions land nearer to the beginning of lower case orthographically irregular than regular beginning words. Importantly, the same effect was found for upper case text, at least for saccades launched three or fewer characters from the critical word. Consequently the use of nonfoveal orthography to modulate first fixation positions on words does not depend on the greater visual distinctiveness of lower case text compared to upper case text. Also, there was no effect of case on landing positions, suggesting that any differences between lower and upper case text (such as visual distinctiveness or familiarity) did not influence fixation positions.

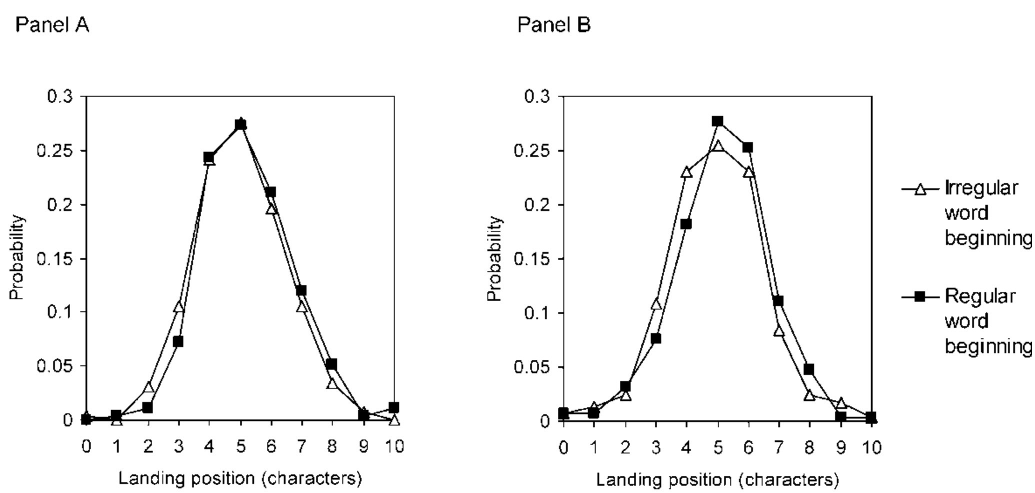

Figure 2. *Experiment 2: First fixation positions on the critical word for saccades launched from three or fewer characters before the critical word. Landing Position 0 is the space before the word, and Landing Position 1 is the first letter of the word. Panel A shows the landing position distributions for lower case text, and Panel B shows the landing position distributions for upper case text.*

Fixations prior to the critical word

Table 3 shows the mean launch sites prior to and saccade lengths into the critical word. For all the data, there were no effects of orthography, $F_1 < 1$; $F_2(1, 23) = 1.46$, $p = .24$, case, $F_1(1, 59) = 1.69$, $p = .2$; $F_2(1, 23) = 1.26$, $p = .27$, and no interaction between orthography and case (Fs < 1) on the mean launch site prior to fixating the critical word. Mean saccade lengths into the critical word were significantly shorter for irregular than for regular beginning words, $F_1(1, 59) = 6.43$, $p = .01$; $F_2(1, 23) = 6.69$, $p = .02$. There were no effects of case, $F_1(1, 59) = 2.76$, $p = .1$; $F_2(1, 23) = 1.49$, $p = .24$, and no interaction between orthography and case (Fs < 1). For saccades launched from word $n - 1$, there were no effects of orthography (Fs $<$ 1.3) or case (Fs < 1) and no interaction between orthography and case, $F_1(1, 59) = 3.43$, $p = .07$; $F_2(1, 23) = 2.49$, $p = .13$, on the mean launch site prior to fixating the critical word. Mean saccade lengths into the critical word tended to be shorter for irregular than for regular beginning words, $F_1(1, 59) = 1.85$, $p = .18$; $F_2(1, 23) = 3.54$, $p = .07$, and there were no effects of case (Fs < 1) and no interaction between orthography and case (Fs < 1). For saccades launched from three or fewer characters from the beginning of the critical word, there were no effects of orthography, $F_1 <$ 1; $F_2(1, 23) = 2.07$, $p = .16$, or case, $F_1(1, 59) = 1.53$, $p = .22$; $F_2 < 1$, and no interaction between orthography and case, $F_1(1, 59) = 3.58$, $p = .06$; $F_2 < 1$, on the mean launch site prior to fixating the critical word. Mean saccade lengths into the critical word tended to be shorter for irregular than for regular beginning words; the effect was significant across items, $F_2(1, 23) = 5.21$, $p = .03$, but not participants, $F_1(1, 59) = 1.77$, $p = .19$. There were no effects of case (Fs < 1) and no interaction between orthography and case (Fs < 1).

For all of the data saccades into the critical word are shorter for orthographically irregular words, regardless of case. A similar pattern holds for saccades launched from word $n-1$ and from three or fewer characters from the beginning of word n, although these results are not reliable. The results suggest that the more visually distinctive characteristics of lower case text, compared to upper case text, are not necessary in order for nonfoveal orthography to influence saccade extent. In contrast there were no significant effects of launch site and no consistent pattern in the direction of the means for each of the launch site analyses.

Refixations

Table 1 shows refixation saccade lengths and positions on the critical word. Refixations tended to be more likely to be to the left of the initial fixation position for irregular than for regular beginning words;[7] the effect was significant across items, $F_2(1, 23) = 7.65$, $p = .01$, but not participants, $F_1(1, 50) = 3.12$, $p = .08$. There were no effects of case (Fs < 1) and no interactions between orthography and case, $F_1(1, 50) = 3.67$, $p = .06$; $F_2(1, 23) = 1.62$, $p = .22$. Mean rightward refixation saccade lengths were significantly shorter in the irregular than in the regular word beginning conditions,[8] $F_1(1, 36) = 4.8$, $p = .04$; $F_2(1, 23) = 8.76$, $p < .01$. There were no effects of case (Fs < 1.8) and no interaction between orthography and case (Fs < 1). Mean rightward refixation landing positions were numerically nearer the word beginning for irregular than for regular beginning words but these differences were not significant, $F_1(1, 36) = 1.5$, $p = .23$; $F_2(1, 23) = 3.37$, $p = .08$; there were no effects of case and no interactions between orthography and case (Fs < 1). These analyses show that for both upper and lower case text, processing at least at the level of orthography influences the direction and length of refixation saccades.

[7] In Experiment 2, the participants' analyses for refixation probabilities were based on the data of 51 readers because 9 readers did not make refixations on the critical word in all four of the conditions.

[8] In Experiment 2, the participants' analyses for rightward refixation saccade lengths and positions were based on the data of 37 readers because 23 participants did not make rightward refixations on the critical word in all four of the conditions.

Discussion

The effects of case found in this experiment are quite different to those of Tinker and Paterson (1939). Tinker and Paterson found longer overall reading times for upper than for lower case text due to a greater number of fixations for upper case text; average fixation durations were actually shorter for upper than for lower case text. In contrast, although overall reading times were marginally longer for upper case text in the present experiment, this might be explained by numerically longer average forward fixation durations and a marginally higher number of regressions for the upper than for lower case text. The differences in results might be explained by the fact that the upper case text covered a larger area than did the lower case text in Tinker and Paterson's experiment. Perhaps the larger text reduced the number of characters and words that could be processed on each fixation in the upper case text, and participants may have compensated for this by increasing the number of fixations whilst shortening the average fixation durations (due to the reduced linguistic input). In the present experiment, the marginally longer reading times and similar fixation position effects for upper and lower case text suggest that while lower case text might be slightly easier to read because it is more visually distinctive or familiar, eye movement behaviour is largely the same regardless of type case.

For both upper and lower case text, first fixation positions were nearer the beginning of orthographically irregular beginning words for saccades launched from near launch sites. Beauvillain and Doré (1998) and Doré and Beauvillain (1997) found similar results for initial fixation positions using isolated word tasks. Saccade lengths were shorter into irregular than into regular beginning words. Note that for saccades launched from the previous word, the influence of orthography on initial fixation positions is numerically smaller for upper than for lower case text. This result may suggest that the effect of orthography on initial fixation positions is attenuated for upper case text such that orthography influences fixation positions from more distant launch sites for lower than for upper case text. However, as there were no significant interactions between orthography and case, we focus on the statistically reliable main effect of orthography on fixation positions. Refixation directions and positions were also influenced by the orthography of the fixated word for both upper and lower case text. The main effects of orthography and the absence of an interaction between orthography and case for fixation positions support the findings of Experiment 1 and show that processing at or beyond the level of orthography influences fixation positions regardless of the visually distinctive characteristics of lower, compared to upper, case text.

EXPERIMENTS 1 AND 2: FURTHER ANALYSES

Three additional analyses were undertaken on the combined data sets from Experiments 1 and 2, which yielded a total of 104 participants. Two analyses further investigated the influence of orthography on where words are first fixated. The first investigated whether the effect is independent of word frequency, and the second whether the effect is dependent on the prior fixation duration. In addition, we also test whether the position of single fixations within words influences fixation durations. Note that although the experiments were not originally designed to test this issue, the availability of such a large data set (with highly controlled materials) provides an excellent opportunity for a rigorous investigation of this topic.

An analysis was undertaken to assess whether the effects of regularity on landing positions can be explained by differences in orthography, independent of word frequency. A total of 12 items were selected in which both the orthographically regular and irregular critical words had low word frequencies, which were defined as 10 or fewer counts per million (regular, $M = 6.5$, $SD = 3.1$; irregular, $M = 1.1$, $SD = 2.3$). The data for these items were combined from both the experiments, collapsing across the variable of case. For only those items with low word frequencies, for saccades launched from the previous word, first fixation positions were nearer the word beginning for orthographically irregular than for regular beginning words, $t_1(103) = 1.97$, $p = .05$; $t_2(11) = 2.39$, $p = .04$. These analyses suggest that orthographic regularity influences where words are first fixated even when word frequency is controlled (see Vonk et al., 2000, for a similar conclusion). Note that although we can not absolutely rule out the possibility that lexical factors (either word or type frequency) may have contributed to the difference in landing positions between orthographically regular and irregular beginning words, we consider this possibility to be extremely unlikely. White and Liversedge (2004) directly manipulated the lexical properties of word beginnings (type frequency, the number of lexical candidates that can be generated from the word initial letters) whilst controlling for orthographic familiarity (token frequency) and showed no effect whatsoever of word beginning lexical properties on word initial fixation positions. In addition if processes involving lexical access modulated fixation positions then fixations should land nearer to the beginning of nonwords than words. However, White and Liversedge (Experiment 2) showed no difference in fixation positions between correctly spelled words and nonwords (words in which the second letter was misspelled).

It has been suggested (O'Regan, 1990) that if linguistic information does influence where the eyes move, this may only occur when prior fixation durations are long. Alternatively, long prior fixation durations might be associated with greater processing difficulty, which may reduce nonfoveal preprocessing and so reduce linguistic influences on saccade programming. In order to test whether prior fixation duration influences the extent of linguistic influences on saccade programming, we undertook an additional analysis of initial fixation positions on the critical word for saccades launched from the previous word. The analysis included data from both Experiments 1 and 2 collapsing across the variable of case. A median split for each subject and each condition was used to categorize prior fixation durations as short ($M = 212$, $SD = 42$) or long ($M = 306$, $SD = 79$). First fixation positions were significantly nearer the beginning of irregular (short, $M = 3.9$, $SD = 1.9$; long: $M = 4.1$, $SD = 1.7$) than regular (short, $M = 4.2$, $SD = 2.0$; long: $M = 4.2$, $SD = 1.8$) beginning words, $F_1(1, 103) = 10$, $p < .01$; $F_2(1, 23) = 12.08$, $p < .01$; there was no reliable effect of prior fixation duration, $F_1(1, 103) = 4.72$, $p = .03$; $F_2(1, 23) = 2.23$, $p = .15$, and no interaction between prior fixation duration and regularity, $F_1(1, 103) = 1.38$, $p = .24$; $F_2 < 1$. Importantly, contrary to O'Regan's suggestion, these results show that orthography influences where words are first fixated for both short and long prior fixation durations. Therefore accounts of such effects should enable orthography to modify saccade programming very quickly, such that the effects hold for even short prior fixation durations. To summarize, these two further analyses of the influence of orthography on fixation positions suggest that the effect is independent of both word frequency and prior fixation duration.

The final additional analysis investigates whether the position of single fixations within words influences fixation durations. Studies using isolated words have shown that the time to identify words is shorter when words are initially fixated near the middle, or slightly left of the middle: referred to as the "optimal viewing position" (O'Regan & Jacobs, 1992; O'Regan, Lévy-Schoen, Pynte, & Brugaillère, 1984). In normal sentence reading, Vitu, O'Regan, and Mittau (1990) found a similar, but much weaker, optimal viewing position pattern for gaze durations, and Rayner et al. (1996) found no clear effect of fixation location on single fixation durations. In contrast, Vitu, McConkie, Kerr, and O'Regan (2001) recently reported inverted optimal viewing position effects such that longer fixation durations occurred on fixations nearer the word centre (see also O'Regan, Vitu, Radach, & Kerr, 1994). Despite the conflicting evidence, Reichle, Rayner and Pollatsek's (1999, 2003) model of eye movement control in reading predicts a standard optimal viewing position effect, such that fixation durations are shorter when the centre of the word is first fixated. Other accounts of eye movements in reading that also use eccentricity as a variable in word processing (Engbert, Longtin, & Kliegl, 2002; Reilly & Radach, 2003; Yang & McConkie, 2001) might predict similar effects of fixation location on fixation duration. Clearly further evidence is required to help resolve the issue of whether an optimal viewing position effect is shown in fixation durations in normal reading. The present experiment provides an opportunity to examine fixation durations in relation to fixation position for 5- and 6-letter words (word $n - 1$ and word $n + 1$) and for 9- and 10-letter words as a function of orthographic regularity (the critical word).

Figure 3 shows mean single first-pass fixation durations plotted for 5- and 6-letter words (Panel A) and 9- and 10-letter words (Panel B). Figure 3 suggests that single first-pass fixation durations are longer when the fixation position is near the word centre for 5- and 6-, and 9- and 10-letter words and for both orthographically regular and irregular beginning words. For the 5- and 6-letter words there was a main effect of landing position,[9] $F_1(4, 410.9) = 22.27$, $p < .01$. Repeated contrasts comparing each fixation position with the subsequent fixation position showed that single first-pass fixations were longer on the first character than on the space, $F_1(1, 103) = 6.79$, $p = .01$, longer on the second character than on the first character, $F_1(1, 103) = 9.38$, $p < .01$, longer on the third character than the second character, $F_1(1, 103) = 11.11$, $p < .01$, no different on the third and fourth characters ($F_1 < 1$), and longer on the fourth character than on the fifth character, $F_1(1, 103) = 9.18$, $p < .01$. The effects of landing position show that fixation position on 5- and 6-letter words influenced single first-pass fixation durations. Furthermore, the results suggest that fixations are longer near the word centre, showing an inverted optimal viewing position pattern.

Analyses of single first-pass fixation durations on the 9- and 10-letter words could not be analysed as a function of specific landing position because there were fewer data points (there were only data from single fixations on the critical word spread over a wider range of possible fixation positions). Consequently the data were grouped into fixations on or just left of the word centre (characters three, four, and five) and away from the word centre (the space before the word and all other characters). Mean single fixation durations[10] were significantly longer near the word centre (regular, $M = 320$, $SD = 105$; irregular, $M = 373$, $SD = 140$) than away from the word centre (regular, $M = 294$, $SD = 98$; irregular, $M = 319$, $SD = 120$), $F_1(1, 87) = 15.6$, $p < .01$; $F_2(1, 23) = 77.92$, $p < .01$, and single fixations were longer on irregular than on regular beginning words, $F_1(1, 87) = 49.34$, $p < .01$; $F_2(1, 23) = 25.17$, $p < .01$. There was no reliable interaction between fixation position and regularity, $F_1(1, 87) = 3.28$, $p = .07$; $F_2(1, 23) = 8.32$, $p < .01$. Similar to the 5- and 6-letter words, the results show an inverted optimal viewing position pattern such that single first-pass fixations nearer the word centre are longer than those towards the ends of the word. Furthermore, the main effect of orthographic regularity shows that the characteristics of a word influence fixation durations as well as the fixation position.

To summarize, analyses of both 5- and 6-letter words and 9- and 10-letter words show an inverted optimal viewing position effect on fixation durations, such that single fixation durations are longer nearer the word centre. These results are consistent with Vitu et al.'s (2001) finding of an inverted optimal viewing position effect on fixation durations. The results are in contrast to those of Rayner et al. (1996) who found no effect of fixation position on single fixation duration for

[9] For the 5- and 6-letter words, an ANOVA was undertaken with six levels of the landing position variable including the space before the word and characters one to five. The sixth character was not included because not all participants fixated this letter. For the analysis of the effect of landing position, the Mauchly test of sphericity was significant, and so the Greenhouse–Geisser epsilon adjustment was used.

[10] The participants' analysis for effects of preferred viewing position and regularity on single fixation durations were based on the data of 88 readers because 16 readers did not produce single fixations in all four of the conditions on the critical word.

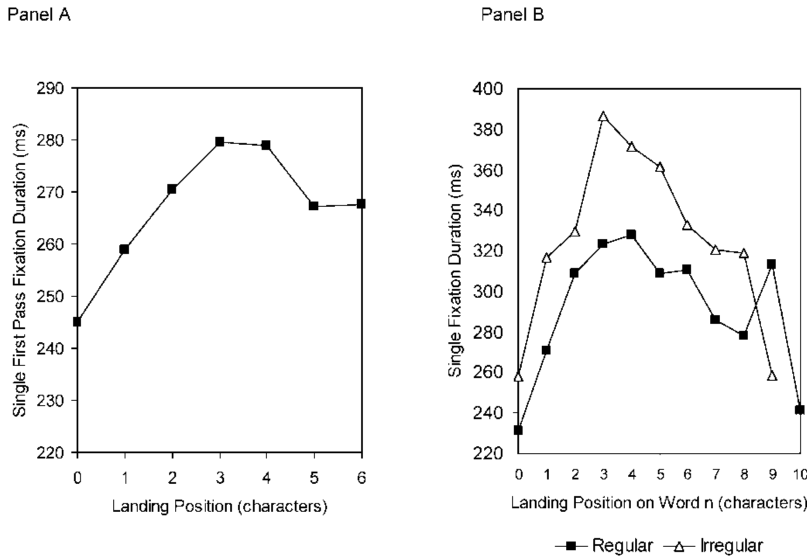

Figure 3. *Mean single first-pass fixation duration for each fixation position for 5- and 6-letter words (Panel A) and 9- and 10-letter words (Panel B). Data for the 5- and 6-letter words are taken from word n − 1 and word n + 1, and data for the 9- and 10-letter words are taken from the critical word. Panel B shows the mean single first-pass fixation durations plotted separately for orthographically regular and irregular beginning words.*

5- to 7-letter words. Importantly, the present results help resolve the controversy by providing support for the inverted optimal viewing position effects in two separate new analyses.

GENERAL DISCUSSION

The two experiments presented here address four important issues related to eye movement control in reading. The theoretical implications of the results are described separately for each of the four issues.

Linguistic influences on fixation positions within words

The present study shows that processing at or beyond the level of orthography influences saccade programming for both initial fixations and refixations on words in correctly spelled English sentences. The results are particularly striking since current models of eye movements in reading do not predict an effect of orthographic influences on where words are first fixated or refixated (Reichle et al., 1999, 2003; Reilly & O'Regan, 1998; Reilly & Radach, 2003). Note that although O'Regan (1990) suggested that linguistic influences on eye movements may occur with long prior fixation durations, the further analyses show that the effects hold for both short and long prior fixation durations.

In contrast to previous studies, individual letter frequency of the word initial letters was carefully controlled. Therefore models should predict that the familiarity of letter sequences, not just individual letters, can influence where words are first fixated. Although there are robust effects of orthography on initial fixation positions, it is not entirely clear whether these effects arise from differences in either saccade lengths or launch site or both. At least in Experiment 2 the findings suggest that the landing position effects at least partly result from differences in saccade length. Also note that the size of the landing position effects are very small, and they only hold for saccades launched from near launch sites. Nevertheless, the presence of these reliable effects shows that a modular system, in which linguistic processing can not influence saccade programming, is incorrect. Accounts of eye movement control in reading should at least incorporate the potential for linguistic factors to influence saccade programming.

Linguistic influences on fixation positions for upper case text

Experiment 2 showed that orthographic regularity also influences where words are first fixated and refixated for upper case text. These results indicate that the effects for lower case text are not dependent on the greater visual distinctiveness (e.g., presence of ascenders and descenders) of lower than of upper case text. It seems doubtful that such low spatial frequency information (Reichle et al., 2003) might explain landing position effects in upper case text. In addition, the fact that there were orthographic landing position effects regardless of type case is consistent with the notion that abstract orthographic preprocessing might influence saccade programming. Importantly, these results suggest that the saccade programming system receives input from a linguistic processor such that this influences saccade targeting to words.

Effects of type case on eye movements in reading

Experiment 2 showed that, contrary to Tinker and Paterson (1939), there was little difference in reading measures for lower and upper case text. Furthermore, contrary to findings using isolated word tasks (Perea & Rosa, 2002), there was not even an effect of case on reading times for infrequent (orthographically irregular) words. These results suggest that in a normal reading task there is almost no effect of case on reading behaviour, even for words that are linguistically more difficult to process. Therefore, despite any differences in visual familiarity or distinctiveness between lower and upper case text, psycholinguistic processing of text is not substantially slowed when it appears in upper compared with lower case text. These results are consistent with the notion that patterns of eye movement behaviour in reading are determined by abstract linguistic information and visual features such as word length, which are the same for lower and upper case text.

Effects of fixation position on fixation duration

The finding of an inverted optimal viewing position for both 5- and 6-letter and 9- and 10-letter words challenges models of eye movements in reading that suggest that fixation durations on words should be shorter at central fixation positions due to acuity limitations (e.g., Reichle et al., 2003).

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APPENDIX

Experimental sentence frames and critical words. The critical words are shown in italics. For each sentence frame, Version a is the orthographically irregular beginning word condition, and Version b is the orthographically regular beginning word condition.

1a. He knew that the clever *auctioneer* would ask him about the valuable lots.
1b. He knew that the clever *candidates* would produce impressive answers.
2a. Last Friday the modern *ergonomic* chairs were transported to the shops.
2b. Last Friday the modern *miniature* chairs were placed in the dolls house.
3a. It is true that the daily *oestrogen* level varied but it was not harmful.
3b. It is true that the daily *infection* level increased over the critical period.
4a. Eventually the funny *ostriches* walked over to the fence near the visitors.
4b. Eventually the funny *foreigner* walked over to the bar to tell his new joke.
5a. He would need some strong *ammunition* before taking the troops into battle.
5b. He would need some strong *explosives* before the rocks could be removed.
6a. He read the recent *veterinary* report before he made his recommendations.
6b. He read the recent *assessment* report before he decided on the changes.
7a. She knew that the recent *fumigation* effort had been a success.
7b. She knew that the recent *inspection* effort had helped to improve food hygiene.
8a. It is difficult to truly *jeopardize* talks because no one ever listens.
8b. It is difficult to truly *transcribe* talks when there is background noise.
9a. On Tuesday the young *rhinoceros* would need her first injections.
9b. On Tuesday the young *management* would be asked to outline the new plans.
10a. Suddenly the angry *usherette* rushed up the aisle to the noisy children.
10b. Suddenly the angry *alligator* rushed towards the small canoe.

11a. He knew that he could easily *eradicate* houses that were infested with mice.
11b. He knew that he could easily *entertain* houses full of guests.
12a. She knew that the modern *ointments* would work if she could get them in time.
12b. She knew that the modern *extension* would add value to the house.
13a. He took the usual *eucalyptus* after his other medication.
13b. He took the usual *supplement* after he considered changing to the new one.
14a. He was mainly *omnivorous* during the summer season.
14b. He was mainly *monotonous* during the long lectures.
15a. He said that three *emulsions* could be used to paint the old house.
15b. He said that three *accidents* could have been prevented.
16a. He used a clever *pseudonym* trick to deceive the authorities.
16b. He used a clever *plausible* trick to avoid embarrassment over the mistake.
17a. Finally the major *nunneries* became very busy as tourists began to visit them.
17b. Finally the major *statement* became available and was issued to the employees.
18a. Often the quiet *lullabies* would send the babies to sleep.
18b. Often the quiet *spectator* would read a book or listen to a personal stereo.
19a. They asked about the small *cemeteries* after the rumours about the closures.
19b. They asked about the small *challenges* after the group completed the report.
20a. She asked about the social *etiquette* during the important dinner party.
20b. She asked about the social *programme* during the Christmas celebrations.
21a. He hated the heavy *pneumatic* tools that were used to dig up the road.
21b. He hated the heavy *primitive* tools that the farmer gave him to use.
22a. The trainees used the usual *mnemonics* until they understood the new material.
22b. The trainees used the usual *treatment* until their wounds had healed.
23a. Yesterday the three *agnostics* asked each other about the meaning of life.
23b. Yesterday the three *graduates* asked about the new employment scheme.
24a. Eventually the young *fugitives* asked if they could have some food.
24b. Eventually the young *designers* asked if they could have a pay rise.