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Eye movement control in reading: word predictability has little influence on initial landing positions in words

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Abstract

We examined the initial landing position of the eyes in target words that were either predictable or unpredictable from the preceding sentence context. Although readers skipped over predictable words more than unpredictable words and spent less time on predictable words when they did fixate on them, there was no difference in the launch site of the saccade to the target word. Moreover, there was only a very small difference in the initial landing position on the target word as a function of predictability when the target words were fixated which is most parsimoniously explained by positing that a few programmed skips of the target word fell short of their intended target. These results suggest that low-level processing is primarily responsible for landing position effects in reading.

1. Introduction

A great deal has been learned recently about the control of eye movements during reading (Rayner, 1998). One argument that has been made about eye movement control is that the decision about *where* to look next and the decision about *when* to move the eyes are often made somewhat independently of each other (Rayner & McConkie, 1976). The major evidence for this argument is that it has been demonstrated (see Rayner & Pollatsek, 1981) that certain types of experimental manipulations primarily influence the length of a saccade (the decision about where to look next) while other manipulations primarily influence the duration of a fixation (the decision about when to move the eyes). In particular, "low level" (i.e., non-linguistic) variables such as word length and the spaces between words are the primary sources of information used to determine where to fixate next, whereas the ease or difficulty associated with processing the fixated word primarily influences when to move the eyes.

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With respect to the conclusion that low-level variables are mainly used to determine where to fixate next, a large number of studies (Morris, Rayner, & Pollatsek, 1990; O'Regan, 1979, 1980; Pollatsek & Rayner, 1982; Rayner, 1979; Rayner, Fischer, & Pollatsek, 1998; Vitu, 1991) have demonstrated that word length information and the spacing between words primarily influence where readers fixate next. It has been widely demonstrated that readers initially fixate, on average, about half way between the beginning of a word and the middle of the word (Deutsch & Rayner, 1999; McConkie, Kerr, Reddix, & Zola, 1988; Rayner et al., 1998). Rayner (1979) originally labeled this effect the *preferred viewing location*. A parsimonious explanation (McConkie et al., 1988) for why the initial fixations are centered about this location that has been generally accepted is that (a) readers aim their next saccade to the middle of the nearest word in parafoveal vision that they have not yet identified, and (b) on average, the actual saccades fall short of the target due to oculomotor error.

These results have led researchers with very different theoretical orientations to conclude that low-level information is the primary determinant of where to fixate next. It should be noted, however, that based on experiments using unspaced text, Epelboim and colleagues

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(Epelboim, Booth, Ashkenazy, Taleghani, & Steinman, 1997; Epelboim, Booth, & Steinman, 1994) argued that the spaces between words are not particularly important to eye movement control and that when spaces are absent word recognition processes are interfered with. More recently, however, Rayner et al. (1998) demonstrated that both word recognition and eye guidance processes were disrupted by the lack of space information (see also Pollatsek & Rayner, 1982).

With respect to the conclusion that processing activities associated with the fixated word primarily influence when to move the eyes, it has been demonstrated that fixation time on a word is strongly influenced by both the frequency of the currently fixated word and its predictability from the prior context. Low frequency words are fixated longer than high frequency words (Altarriba, Kroll, Sholl, & Rayner, 1996; Henderson & Ferreira, 1990; Henderson & Ferreira, 1993; Hyönä & Olson, 1995; Inhoff & Rayner, 1986; Just & Carpenter, 1980; Kennison & Clifton, 1995; Rayner & Duffy, 1986; Rayner & Fischer, 1996; Rayner & Raney, 1996; Rayner et al., 1998; Rayner, Sereno, Morris, Schmauder, & Clifton, 1989; Rayner, Sereno, & Raney, 1996; Schilling, Rayner, & Chumbley, 1998; Sereno & Rayner, 2000; Vitu, 1991) and unpredictable words are fixated longer than predictable words (Balota, Pollatsek, & Rayner, 1985; Binder, Pollatsek, & Rayner, 1999; Ehrlich & Rayner, 1981; Rayner & Well, 1996; Schustack, Ehrlich, & Rayner, 1987; Zola, 1984).

Research on the effects of contextual constraint during reading has also demonstrated that predictable words are not only fixated for less time than unpredictable words, they are skipped more frequently than unpredictable words (Balota et al., 1985; Ehrlich & Rayner, 1981; Rayner & Well, 1996). This leads to the interesting question of whether or not contextual constraint also influences the initial landing position in words. That is, if contextual constraint can affect one kind of "where" decision (which word to fixate), it is not unreasonable to think that it might also affect the decision of where in a word to fixate. As Balota et al. (see also Binder et al., 1999) found that readers obtained more parafoveal information from a word when it was predictable than when it was unpredictable, it might be optimal to land further into predictable words. That is, a strategy of fixating further into the word when more information has been extracted may be beneficial because most of the information extracted from the parafovea is from the beginning of the word (see Rayner, 1998, for a summary) and thus landing further into the word would place the largely unprocessed part of the word closer to the fixation point. Such a strategy would be consistent with Underwood, Clews, and Everatt's (1990) model of eye movement control in which the location of informative information in unidentified parafoveal words influences where the eyes land.

We thus thought that testing whether the contextual constraint on a target word influences where readers land on that word would be an good arena to look for influences on *where* decisions that are not merely based on parameters like word length. As argued above, this manipulation has already been shown to influence one kind of *where* decision – which word to land on – and thus seems like a good candidate to influence a more subtle *where* decision – where to land on – a word. Clearly, a negative result in such an experiment (no effect of contextual constraint on landing position) can't rule out the possibility of there being no such higher order influences on *where* decisions. Nonetheless, a negative result would raise the question of whether such higher order influences are plausible. Another reason for why the question of whether contextual constraint influences where readers initially fixate in a word is interesting is that it is related to the question of whether or not words in foveal and parafoveal vision are identified serially or in parallel. According to the influential model of eye movement control originally articulated by Morrison (1984; and modified by Pollatsek & Rayner, 1990) and the more recent computational E-Z Reader model (Reichle, Pollatsek, Fisher, & Rayner, 1998; Reichle, Rayner, & Pollatsek, 1999), which is a descendent of Morrison's model but with a number of critical changes, the identification of words in text occurs in a strictly serial fashion. However, if linguistic information extracted from parafoveal words can guide where the fixation on them is targeted, it would mean either that lexical information extracted late in a fixation can affect the landing position on a word – a hypothesis for which there is no current evidence – or it would cast doubt on the assumption that lexical processing of parafoveal words only proceeds after the fixated word has been identified.

In this article, we will present data from two experiments in which we examined the effect of contextual constraint on landing positions in words. In Experiment 1, subjects read sentences in which a target word was either highly predictable from the preceding context, or was unpredictable. In Experiment 2, subjects read sentences in which a target word was again either highly predictable or unpredictable. However, in this experiment, we also varied whether or not the target word was a high- or low-frequency word.

2. Method

2.1. Subjects

Undergraduate students at the University of Massachusetts, all of whom were native speakers of English, participated in the experiments for either $8 or course credit. They all had normal, uncorrected vision and were all naive with respect to the purpose of the experiment. Twenty-four subjects participated in Experiment 1 and 36 participated in Experiment 2.

2.2. Apparatus

The sentences were displayed on a single line (maximum length was 80 letter spaces) with lowercase letters (except when capitals were appropriate) on a ViewSonic 17G monitor with standard VGA characters. The monitor was interfaced with a 486 computer which was interfaced with a Fourward Technologies Dual Purkinje Eyetracker (Generation V). Eye movements were recorded from the right eye, but viewing was binocular. The eyetracker's resolution is better than 10 min of arc, and its signal was sampled every millisecond by the computer. Subjects were seated 80 cm from the monitor and three characters equaled one degree of visual angle. The letters were presented in light cyan (on a black background) by mixing the green and blue input signals on the display monitor. The room was dimly illuminated, and the brightness of the monitor was adjusted to a comfortable level for each subject and held constant throughout the experiment.

Table 1
Example sentences from the experiments[a]

Experiment 1
1. The baby laughs and giggles when she shakes her new *rattle*/*bottle* for her father.
2. The doctor told Fred that his drinking would damage his *liver*/*heart* very quickly.
3. John is grumpy before he's had his morning *shower*/*coffee* and read the paper.
4. The rabbit was especially *fast*/*slow* as it ran through our vegetable garden.
5. Since the wedding was today, the baker rushed the wedding *cake*/*pies* to the reception.
6. The banker loaned the businessman some more *money*/*tools* for his new project.
7. My brother has brilliantly composed a new *song*/*tune* for the school play.
8. Near the end of the semester, the students look forward to their *summer*/*winter* vacation.
9. The woman jumped on a chair and screamed at the sight of the *mouse*/*snake* in her room.

Experiment 2[b]
1. Most cowboys know how to ride a *horse*/*camel* if necessary.
2. In the desert, many Arabs ride a *camel*/*horse* to get around.
3. The sailor stopped at the deserted *island*/*casino* for a week.
4. The gambler visited the *casino*/*island* as part of his vacation.

[a] Note that the predictable and unpredictable words are both shown (in italics) in the sentence frame; in the experiment, only one word was presented with each frame.

[b] Note: horse and island are high frequency words; camel and casino are low frequency words.

2.3. Materials

In Experiment 1, subjects read 96 sentences[1] which were taken from the materials used by Balota et al. (1985). Example sentences are shown in Table 1. For each sentence, two different target words could fit into the sentence frame. In the high predictability condition the target word was highly predictable from the preceding context, while in the low predictability condition it was not predictable. The word frequency, based on the Francis and Kučera (1982) norms, was 58.8 per million for the predictable target words and 57.8 per million for the unpredictable target words. Two different norming tasks were used by Balota et al. to assess the predictability of the target words. In the first task, a group of subjects was presented with the sentences up to and including either the high predictable or low predictable word and they had to indicate, on a scale of 1–5, how well the base word fit into the sentence (1 meant that the word did not fit very well and 5 meant that the word fit very well). The mean rating was 4.47 for the predictable target words and 2.32 for the unpredictable target words. In the second norming task, a separate group of subjects was given the sentence frame up to, but not including the target word, and were asked to generate the next word in the sentence. The predictable target words were generated 64% of the time, whereas the unpredictable target words were generated less than 1% of the time.

In Experiment 2, subjects read 48 target sentences along with 96 filler sentences. Example target sentences are shown in Table 1. As in Experiment 1, there was a high predictability and a low predictability condition. In each of these two conditions, the target word could be either a high frequency word or a low frequency word. The frequency of the high frequency words was 150 per million and for the low frequency words was 5 per million (again based on Francis and Kučera). The same two norming tasks that were used for the stimuli in Experiment 1 were used to assess the predictability of the target words in Experiment 2. However, in the first task, a scale of 1–7 was used (instead of 1–5). The mean rating was 6.6 for the high frequency-predictable target words, 6.3 for the low-frequency predictable target words, 4.4 for high-frequency unpredictable target words, and 4.6 for low-frequency unpredictable target words. In the second norming task, the predictable target words were generated 78% of the time

[1] The data reported here were collected as part of the Binder et al. (1999) study, which included eye-contingent display changes. Binder et al.'s primary analysis contrasted contingent display changes that occurred prior to or after a given target word had been read. The data reported here are from trials in which there was no display change prior to reading the target word. As a result, 64 out of the 96 sentences that a given subject read were useable for the analyses reported here.

and the unpredictable target words were generated less than 1% of the time.

Since word length strongly influences word skipping (Brysbaert & Vitu, 1998; Rayner & McConkie, 1976), we made sure to include a range of word lengths. Since words that are longer than 8 letters are rarely skipped and short words (less than 3 letters) are skipped very frequently, we wanted to make sure that there would be enough instances in which words were skipped to confirm that the contextual strength manipulation was affecting eye movement behavior. Thus, the target words in both experiments ranged in length from 4 to 8 letters with a mean of 5.2 letters. Word length was matched across the predictable and unpredictable conditions within a given sentence frame. Subjects read all 96 sentences in Experiment 1 and all 48 target sentences in Experiment 2, but on half of the trials a predictable target word was presented for a given sentence while on the other half the unpredictable member of the pair was present (Table 1). In Experiment 2, half the target words were high frequency and half were low frequency. As a result of using each sentence frame only once for each subject, the predictability of the target word in a given sentence frame was counterbalanced across subjects. The sentences were presented in a different random order to each subject.

2.4. Procedure

When a subject arrived for the experiment, a bite bar was prepared which served to eliminate head movements. Then the initial calibration of the eyetracking system took place, which lasted about 10 min. Subjects were told that they were to read sentences on the monitor as their eye movements were recorded. They were also told to read normally for comprehension and that they would be asked questions about the sentences. Prior to the presentation of each sentence, a series of five boxes appeared on the monitor, extending from the first to the last character position of a 80 character sentence. During a calibration check, subjects were instructed to look at each box to verify the accurate recording of eye position (a dot that moved with the eyes represented the computed eye position).

Before reading the target sentences, each subject read 12 practice sentences to become familiar with the procedure. Prior to the presentation of each sentence, the experimenter checked to make certain that the eyetracking system was accurately tracking the eyes (i.e., the subject looked at the fixation boxes). If the calibration was not accurate, the subject was recalibrated. If calibration was accurate, the subject looked at the first box (which coincided with the location of the first letter of the sentence) and the experimenter displayed the sentence. After the subject finished reading the sentence, he/she pushed a button that blanked the monitor. Then, on two-thirds of the trials, the "check calibration" signal came up immediately and a new trial began. On the other one-third of the trials, a yes–no question about the meaning of the sentence that was just read came up and the subject answered it before the "check calibration" signal came up to signal the next trial; subjects had little difficulty answering the questions correctly (over 90% accuracy in both experiments).

3. Results

Our primary interest in the experiments was the landing position (where in the target word the readers' eyes initially landed). However, we also calculated the probability of skipping the target word and the fixation time on the target word to make certain that the pattern of data was consistent with prior findings. The two measures of fixation time that were examined were the *first fixation duration* and the *gaze duration*. The first fixation duration is the duration of the first forward (left-to-right) fixation on the target word, independent of the number of fixations on the first pass reading. The gaze duration is the sum of all forward fixations on the target word prior to an eye movement to another word in the text. If the target word was skipped over during the first pass, that trial did not contribute to either first fixation duration or gaze duration. Across all trials in both experiments, less than 4% of the data were lost due to track losses.

We will first report the results from Experiment 1, describing them in a bit more detail than the results of Experiment 2. We will then use the data from Experiment 2 to address uncertain issues from Experiment 1.

3.1. Word skipping

Readers skipped the predictable words 30% of the time compared to 18% for the unpredictable words, $F(1,23) = 8.93$, $P < 0.01$. This 12% difference between predictable and unpredictable words is quite consistent with prior research (Balota et al., 1985; Ehrlich & Rayner, 1981; Rayner & Well, 1996). Moreover, although we used single sentences (as did Balota et al.), the size of the effect of predictability was of the same magnitude as that reported by Ehrlich and Rayner (1981), who used passages of text.

Examination of the *launch site* (i.e., the location of the fixation prior to landing on the target word) as a function of predictability indicated that there was no difference in the mean launch site: it was 4.96 letters to the left of the first letter of the target word for predictable targets and 5.01 letters for unpredictable targets. The equality of means, however, leaves open the question of whether the pattern was different in the

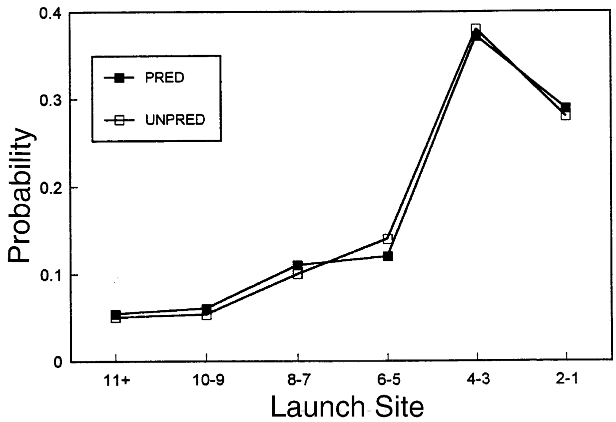

Fig. 1. Launch site probabilities as a function of the distance from the beginning of the target word for predictable and unpredictable words that were subsequently fixated.

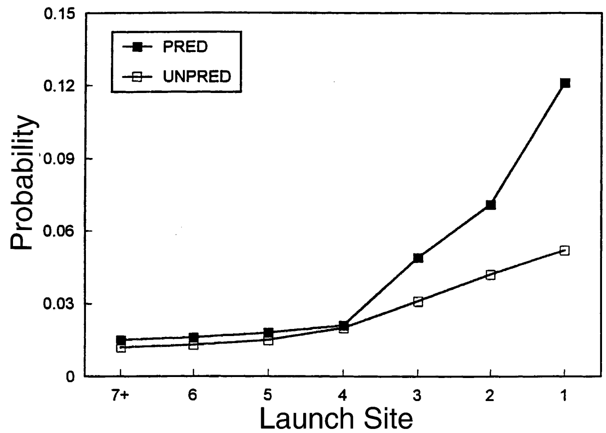

Fig. 2. Probability of skipping the target word conditional on its predictability and launch site.

two conditions, but an examination of the frequency distribution for all fixations that immediately preceded a fixation on the target word revealed no differences between the two conditions (Fig. 1). We also examined the durations of these launch site fixations and found no difference (238 ms for predictable and 239 ms for unpredictable target words). On the other hand, the probability of skipping the target word was influenced by the launch site location: readers were much more likely to skip a predictable target word than an unpredictable target word when they were fixated just to the left of the beginning of the word. Fig. 2 shows the probability of skipping the target word conditional on its predictability and launch site. As seen in Fig. 2, when the launch site was either 1, 2, or 3 letters to the left of the first letter of the target word, skips were more likely ($P < 0.05$) for predictable than for unpredictable target words, whereas there was no effect of predictability when the launch site was further from the target word.

3.2. Fixation times

When readers did fixate on the target words, they fixated for less time on the predictable words than the unpredictable words; the mean first fixation durations and gaze durations were 227 ms and 242 ms, respectively, on predictable words compared to 249 ms and 269 ms on unpredictable words, $F(1,23) = 10.31$, $P < 0.01$, for first fixation duration and $F(1,23) = 12.74$, $P < 0.01$, for gaze duration. Once again, the size of the difference in fixation times is comparable to that found in prior research (Balota et al., 1985; Ehrlich & Rayner, 1981; Rayner & Well, 1996), and more importantly, is comparable to studies (Ehrlich & Rayner, 1981; Schustack et al., 1987) which used passages of text. Given that the word skipping and fixation time analyses revealed robust effects that were comparable to effect sizes obtained when readers read passages of text, we are quite confident that the results reported below for landing position effects are generalizable.[2]

3.3. Initial landing position

When readers fixated on the target word, we calculated the mean initial landing position across all word lengths and found no difference between the predictable and unpredictable words: the mean landing position in both cases was 2.8 letters into the word ($F < 1$). Given that the mean launch site and the mean landing position were almost identical for predictable and unpredictable words, the mean saccade length into the target word was also virtually identical for predictable (7.7 letter spaces) and unpredictable (7.8 letter spaces) words. Consistent with prior research (Deutsch & Rayner, 1999; Rayner, 1979) the mean landing position was further into the word as word length increased: the average landing position was 2.4, 2.7, 3.0, 3.1, and 3.2 letters into the word for 4, 5, 6, 7, and 8 letter words, respectively. However, there was no systematic difference between predictable and unpredictable words. Fig. 3 shows the frequency distribution for the landing positions of both the predictable and unpredictable words averaged across all word lengths according to a zoning algorithm that normalizes the different word lengths into five different landing zones (see Rayner & Fischer, 1996; Vitu, O'Regan, Inhoff, & Topolski, 1995). The distributions in Fig. 3 are very similar to others that have been previously reported (see Rayner & Fischer, 1996; Rayner et al., 1998; Vitu et al., 1995). Since readers were more likely to skip predictable

[2] Given that the size of the effects are comparable to prior context effect studies in which no display change took place, we are confident that display changes per se (which occurred on a relatively small fraction of all saccades) did not lead to atypical reading strategies on the part of our subjects.

words than unpredictable words when they were fixated within 3 letter spaces from the beginning of the target word, we computed two frequency distributions: one for far trials in which they were fixated 4 or more letter spaces to the left of the target word (the top panel of Fig. 3) and one for near trials in which readers were fixated 1–3 letter spaces to the left of the beginning of the target word (the bottom panel of Fig. 3). As expected, and consistent with prior research (McConkie et al., 1988; Rayner et al., 1996), the shapes of the distributions were different (with more fixations toward the beginning of the word for the far trials and more toward the end of the word for near trials). More critically, there was no hint of any difference between the distributions for predictable vs. unpredictable words, even for the trials on which the launch site was quite close to the target word.

Inasmuch as Fig. 3 presents probabilities, Fig. 4 shows the number of times the eyes landed on each

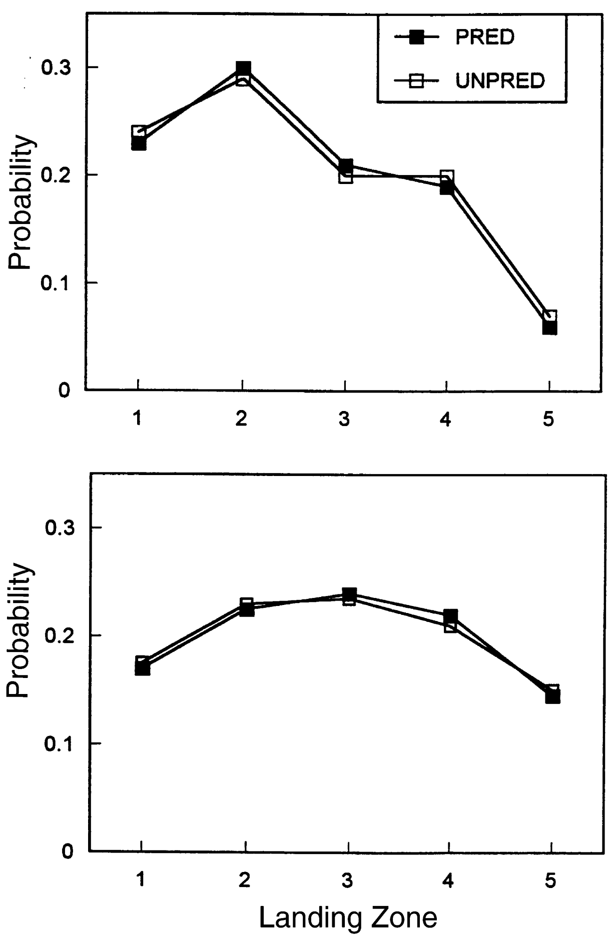

Fig. 3. Probability of landing in different landing zones as a function of predictability of the target word. The top panel is for trials in which the reader was fixated 4 or more letter spaces from the beginning of the target word and the bottom panel is for trials in which the reader was fixated 3–1 letter spaces to the left of the target word.

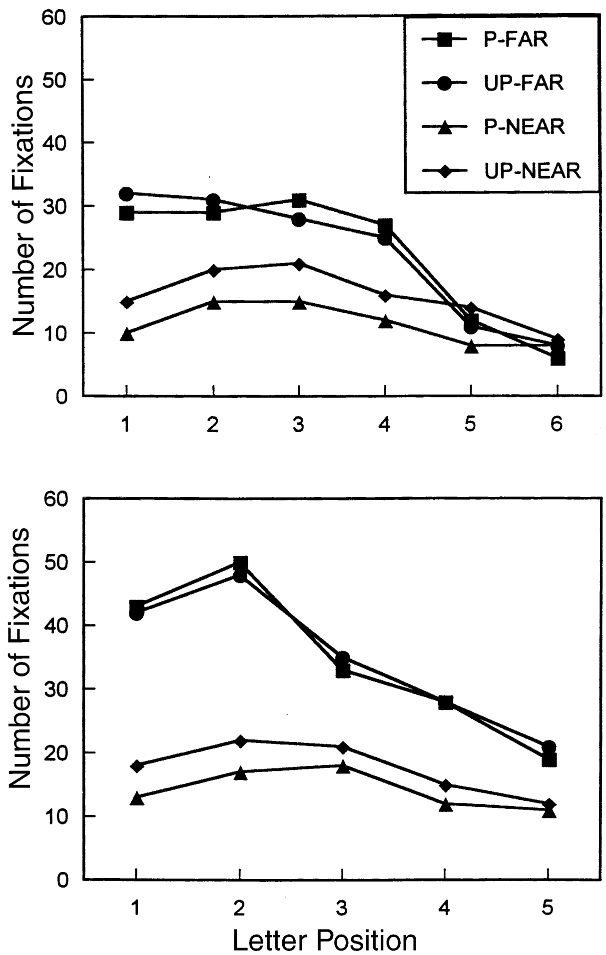

Fig. 4. Number of fixations landing on different letter positions for 5 letter words (bottom panel) and 6 letter words (top panel) for near and far launch sites and predictable and unpredictable target words.

letter position within 5 and 6 letter words for both near and far launch sites and for predictable and unpredictable target words. (Because there were more 5 and 6 letter target words than 4, 7, or 8 letter words, 5 and 6 letter words provided the most stable data pattern.) These raw data demonstrate that little, if anything, is obscured by presenting the data as probabilities. They show that, for the far condition, there is not much in the way of a difference between the predictable and unpredictable conditions. For the near condition, the data show, not surprisingly, that the two curves are separated (reflecting the fact that there is more skipping in the predictable condition than in the unpredictable condition). However, there are two interesting aspects to the near data in Fig. 4. First, for both the 5 and 6 letter words, the number of saccades landing on the last letter position is the same for predictable and unpredictable target words, whereas the number of saccades landing on the other letter positions is smaller for the predictable target words (i.e., the two curves are closer together at the end of the word). This indicates that for these target words, the conditional probability of fixating on the last letter is somewhat greater for the predictable target words: the probability of fixating on the last letter position is about 0.02 higher for the predictable than for the unpredictable target words (0.155 vs. 0.136 for the 5-letter target words and 0.118 vs. 0.095 for the 6-letter target words). This suggests that there may be an effect of predictability when the launch site is near to the target word (although we failed to see this pattern in the overall data plotted in Fig. 3). Second, the data presented in Fig. 4 are somewhat unusual in that when the launch site is near the beginning of a target word, the distribution typically shifts more dramatically to the right, with more saccades landing on the 3rd and 4th letters of 5-letter words and on the 4th and 5th letter of 6-letter words (see McConkie et al., 1988; Rayner et al., 1996). We are not sure why such an increase of fixations landing further into the target word did not occur in the present experiment. On the other hand, the average landing position in the word is clearly shifted to the right for the near distribution in comparison to the far distribution.

Given the uncertainty in these two aspects of the data from Experiment 1, we turn now to the results from Experiment 2. It should be noted that Lavigne, Vitu, and d'Ydewalle (2000) recently reported data suggesting that predictability may have an effect on initial landing position, but only for high-frequency words when the launch site was quite close to the target word. We did not include word frequency as a variable in Experiment 1, so we cannot comment directly on whether or not it has an effect on landing position from those data. Thus, as noted above, in Experiment 2, predictability and frequency were manipulated.

3.4. *Word skipping, launch sites, and fixation times in Experiment 2*

Readers skipped predictable words 23% of the time compared to 13% of the time for unpredictable words, $F(1,35) = 5.35$, $P < 0.05$. However, neither the effect of frequency on skipping probability nor the interaction of frequency with predictability approached significance ($Fs < 1$). As in Experiment 1, there was no effect of predictability (or frequency) on the launch site; launch sites averaged between 5.5 and 5.7 letters to the left of the target word. Examination of the distribution of launch sites revealed a pattern very similar to that shown in Fig. 1. Also, an examination of the launch site fixation durations revealed no effect of either the predictability or frequency of the target word (the four means were within 3 ms of each other: 245–248 ms). As in Experiment 1, an examination of skipping revealed a pattern like that in Fig. 2 except that the curves began to depart 4 letters from the beginning of the target word (rather than 3 letters in Experiment 1).

When readers did fixate on the target word, they fixated for less time on the predictable words than the unpredictable words and for less time on high-frequency words than on low-frequency words. Mean first fixation durations and gaze durations were 260 ms and 270 ms, respectively, on predictable words compared to 273 ms and 285 ms, respectively, on unpredictable words, $F(1,35) = 3.05$, $P < 0.09$, for first fixation duration and $F(1,35) = 4.51$, $P < 0.05$, for gaze duration; mean first fixation durations and gaze durations were 257 ms and 276 ms, respectively, on high frequency words compared to 272 and 293 ms, respectively, on low frequency words, $F(1,35) = 18.8$, $P < 0.001$ for first fixation duration and $F(1,35) = 9.58$, $P < 0.01$ for gaze duration. There was no interaction of the two variables ($Fs < 1$).

It should be noted that the effects of predictability in Experiment 2 on both skipping and fixation times are slightly smaller than those found in Experiment 1. Likewise, the effect of frequency on fixation time is a bit smaller than often reported. On the other hand, the size of the effects are certainly in the range of those typically reported and, given that the effects were statistically significant, we can be sure that the frequency and predictability manipulations were effective. Given that the manipulations were effective, we now turn to results for landing position effects.

3.5. *Initial landing position*

When readers fixated on the target word, the mean initial landing position was 3.1 letters into the word for the predictable-high frequency target word and 3.0 letters into the word for the other three conditions ($F < 1$). Given that the mean launch site and mean landing position were about the same for the different types of target words, the mean saccade length into the target word ranged between 8.1 and 8.3 letter spaces and did not differ as a function of target word condition. Fig. 5 shows the frequency distributions for the landing positions, again using the zoning algorithm described earlier, for near and far launch sites. Since readers were more likely to skip predictable words than unpredictable words when they were fixated within four letter spaces from the beginning of the target word, the far distribution is for trials in which readers were fixated 5 or more letter spaces to the left of the target word (the top panel of Fig. 5) and the near distribution is for trials in which they were fixated 1–4 letter spaces to the left of the beginning of the target word (bottom panel of Fig. 5). As seen in the figure, there was a clear rightward shift of the near launch site distribution in comparison to the far launch site distribution. However, as in Experiment 1, there was little hint of any difference between the distributions for the predictable vs. unpredictable words. More importantly, the landing position was not further into the word for high frequency predictable target words than for the other three conditions.

Fig. 6 is analogous to Fig. 4 and shows the number of fixations on each of the landing sites for each of the four conditions. Since there was a higher percentage of 5 letter words in Experiment 2 than in Experiment 1 (and, accordingly, fewer 6 letter words in Experiment 2), we only present the raw data for 5 letter words (far launch sites are in the top panel and near launch sites are in the bottom panel). There are two striking aspects to these data. First, as noted with respect to the probabilities shown in Fig. 5, the distribution for the near launch sites is shifted dramatically to the right for the near condition relative to the far condition. Second, the number of fixations on the last letter was about equal for the predictable and unpredictable target words, whereas the number of fixations on the other letters is greater for the unpredictable words (due to lower skipping rates). These data are thus also indicative of a pattern in which there are relatively more fixations on the last letter of the predictable target words. This latter point is more obvious in Fig. 7 where we have collapsed across frequency to show data comparable to that shown in the bottom panel of Fig. 4. Thus, as in Experiment 1, there appears to be a small effect of predictability on landing position, almost completely confined to the last letter position.

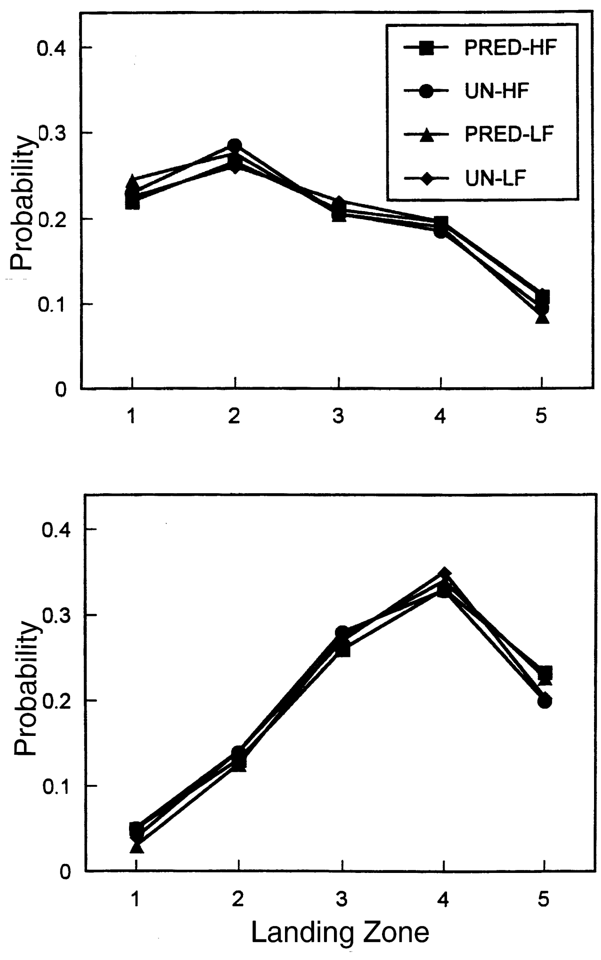

Fig. 5. Probability of landing in different landing zones as a function of predictability and frequency of the target word. The top panel is for trials in which the reader was fixated 5 or more letter spaces from the beginning of the target word and the bottom panel is for trials in which the reader was fixated 4–1 letter spaces to the left of the target word.

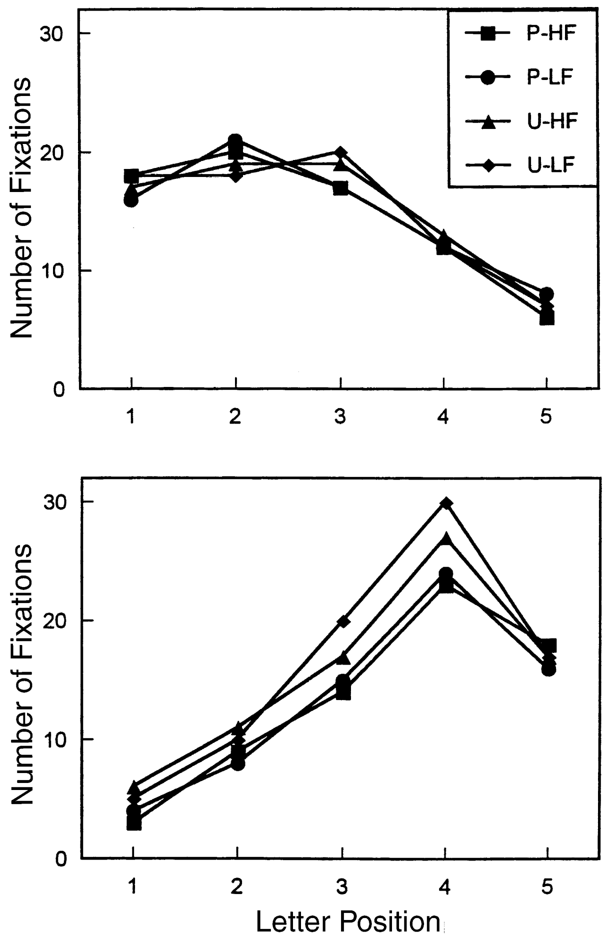

Fig. 6. Number of fixations landing on different letter positions for 5 letter words (varying in predictability and frequency) for near (bottom panel) and far (upper panel) launch sites.

4. General discussion

The data indicated that the predictability of a word had little influence on the initial landing position in that word. In Experiment 1, we found that, averaged over all the stimuli, predictability had no effect on the mean landing position (2.8 letters into the word for both predictable and unpredictable target words) and virtually no effect on the pattern of landing positions, even when the launch site was close to the target word (Fig. 3). However, our subsidiary analysis of the 5- and

6-letter words in Experiment 1 suggested that (for those words) the probability of initially landing on the last letter of the predictable target word (given that the target word was fixated) was a bit higher than the probability of initially landing on the last letter of the unpredictable target word. In Experiment 2, we also found that frequency and predictability had little effect on the initial mean landing position (3.1 letters into the word for the predictable high-frequency condition and 3.0 letters into the word for the other conditions). However, both in the overall analyses and in the analysis of the 5-letter words, there was again a small tendency for the probability of fixating the last letter of the predictable word to be higher than for the unpredictable word (given that the target word was fixated).

Our results are consonant with Rayner et al.'s (1996) finding that word frequency did not influence the initial landing position on words. Thus, both of these variables (predictability and frequency), which plausibly primarily affect the speed of identifying a word in sentence context, appear to have little effect on decisions about where to land on a word. Of course, both predictability and word frequency strongly influence the amount of time that readers fixate on a word (and hence, the decision of when to move the eyes), consistent with their likely influence on the speed of word identification. In addition, of course, both of our experiments replicated the standard result (Ehrlich & Rayner, 1981; Rayner & Well, 1996) that predictability has a clear effect on whether or not a word is skipped. Although the decision of whether to skip a word is logically a decision of where to move the eyes, we think it is quite a different kind of decision than the decision of where to land in a word. That is, the decision to skip or not is a decision about which word to target, whereas the decision where to land in a word is a "micro-decision" about how to target a response.

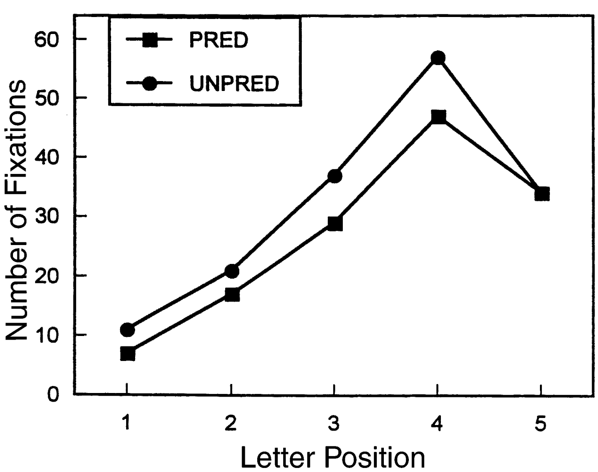

Fig. 7. Number of fixations landing on different letter positions for 5 letter predictable and unpredictable target words (collapsed over frequency) with near launch sites.

In our model of reading, the E-Z Reader model (Reichle et al., 1998), the decision of which word to target is influenced by the speed of lexical identification. The way this is accomplished in the model is the following. When the reader identifies the fixated word to a certain criterion, a signal goes out to program a saccade to the next word (word $n+1$). However, if word $n+1$ is identified rapidly enough (presumably affected by its predictability), a signal goes out to program a saccade to word $n+2$, which in turn cancels the program to fixate word $n+1$. In a further specification of the model (Reichle et al., 1999), we posited that the computed target of each initial fixation on a word is the middle of the word (McConkie et al., 1988). Thus, the two kinds of decisions – which word to fixate and where to fixate in the word – are based on different kinds of processes: the former on word identification (and the relative speed of various processes) and the latter on low-level visual information, such as where the word boundaries are. The E-Z Reader model also assumes that when a word is targeted for a saccade, the target is invariably the center of the word. However, the landing position on the word will not, of course, invariably be the center of the word due to oculomotor error. In our model, we fit landing positions on target words incorporating the work of McConkie et al. (1988), who showed that landing position data can be explained by assuming (a) there is a bias to undershoot the assumed target – the middle of the word; and (b) that both the average undershoot and the variability of the landing position increase as the launch site gets further from the target. (Both of these mirror standard findings in the motor movement control literature.)

As mentioned earlier, Lavigne et al. (2000) reported a significant effect of predictability on mean landing position, but only for high-frequency words when the launch site was close to the target word.[3] This finding is apparently in contradiction to the assumptions of the E-Z Reader model stated above. However, we think that it may not be. We will flesh out the argument more fully below, but we think it is likely that much of the difference can be explained by assuming that there were many saccades in their study that were intended skips of the target word but fell short and landed toward the end of the target word. Several factors in their experiments suggest that they may have had a higher than usual number of such saccades. First, the target words in their experiments tended to be somewhat longer than in ours; in their first experiment the words ranged between 6 and 8 letters and in their second experiment

[3] It is worth noting that Vonk, Radach, and van Rijn (2000), like us, reported no effect of contextual constraint on the initial landing position. Though they obtained a significant effect of contextual constraint on first fixation duration and gaze duration, they used rather long target words so that there would be little skipping.

they ranged between 5 and 7 letters long. Second, the average launch site was quite far from the target word, so that their "near condition" consisted of launch sites that were 8 or fewer letters from the target word in their first experiment and 6 or fewer letters from the target word in their second experiment. As a result, saccades into the target word were considerably longer in their experiments than in ours; the mean saccade into the target word was 12.4 letter spaces in their first experiment, and 9.2 letter spaces in their second experiment. These saccades are considerably longer than is typical (Rayner et al., 1998; Vitu et al., 1995) and their close launch sites involve saccades beginning farther from the beginning of the target word than is typical; for example, Vitu et al.'s (1995) close launch sites extended only to 4 letter spaces to the left of the beginning of the target word (which is quite similar to our close launch sites). Third, perhaps as a consequence of the first two factors, the target words in their experiments were skipped far less frequently than in our experiments; the target words were skipped 4% of the time in their first experiment and 3% of the time in their second experiment.

As indicated above, we think that the simplest way to account for their landing position data is that readers were attempting to skip the predictable target word on a significant number of trials, but fell short enough so that these intended skips became fixations on the right-hand part of the target word. Such saccades would shift the average landing position on the target word to the right. Consider how long the targeted saccade would be for an intended skip, even in Lavigne et al.'s (2000) near condition. Readers were presumably on average 4–5 letter positions from the target word in the near condition, and if we assume that the word following the target word was typically something like 5 letters long, that would imply that the target for a skip saccade would typically be about 14–15 characters distant from the launch site. As indicated above, McConkie et al.'s data imply that, on average, these saccades would fall short of the target, and furthermore, there would be considerable variability, so that one would expect a non-trivial number of these programmed skips to land on the target word. In fact, given that predictability in the Lavigne et al. (2000) experiment had very little effect on skipping rate, it could be that virtually all of the intended skips landed short of the intended saccade target (word $n+1$) and hence landed on the target word (word n), presumably somewhere near the end of it. Needless to say, this would shift the mean landing position to the right for predictable words. The size of the effect may have been limited to some extent, however, because the launch sites were typically quite far from the target word, and thus the target word may not have been easy to process before it was fixated. Thus, the percent of trials on which readers intended to skip a predictable target word was likely smaller than is usually the case. Moreover, there was likely no landing position effect in their far condition because readers were too far from the target word to be able to process it sufficiently to intend to skip it.

In contrast, our target words were a bit shorter, our launch sites were closer (on average, about 2 letter positions from the beginning of the target word), so that the target for the skip saccade in our experiment would more like be something like 10 characters from the launch site. If so, both the undershoot and variability for these saccades would be reduced, so that it would make sense that fewer of these saccades would land on the target word and that most of them that did would land on or near the last letter of it.

To summarize, we think that the assumptions of the E-Z Reader model are still quite reasonable and that the decision of whether to fixate a word or not is influenced by quite different variables than the decision of where to send the initial fixation in a word. However, given that there is "noise" in where the saccade actually lands, it is likely that some intended skips of words undershoot the target and land relatively near the end of the word that the reader intended to skip. Thus, in some cases, a condition that produces more intended skipping might also produce more saccades near the end of the word that should have been skipped and be registered as a small effect on the mean landing position on a word. Such an effect, however, would likely be noticeable only if the skipping effect was large.

An alternative type of explanation for landing position effects in reading comes from information-theoretic analyses of alphabetic languages. Clark and O'Regan (1999) and Legge, Klitz, and Tjan (1997) developed computer simulation models in which information from a specific lexicon is provided as a data base to the model. Given this lexicon, both models found that the optimal position to fixate (given a limited visual span) is near or slightly to the left of the center of the word. Thus, if the target word cannot be identified via parafovea preview, then aiming the next saccade to the center of the next word is an optimal strategy (given that saccades often tend to fall short of the target). This type of analysis thus indicates that this simple strategy of targeting the middle of a word may not be "dumb", but close to optimal. However, as we understand it, these models are not different from what we have proposed as process models in that they apparently assume that the mechanism of targeting a saccade relies on the same low-level visual cues that we have been assuming.

Of course, it is possible that these models could be expanded to make more complex predictions, such as having targeting decisions altered by the identification of the beginning of a word (e.g., if a sequence of letters was a prefix). However, we think there are two factors that may combine to prevent the reader from using such more complex information (or in the present case, the fact that the beginning of the word has been processed fairly well in the parafovea). First, the improvement in terms of information acquisition from such targeting strategies may be fairly minimal, and thus the eye movement system may be satisfied to use relatively low-level information to guide the eyes in a task like reading, where the eyes are moving along at a very rapid rate. Second, it may be that the information that would improve on the simple default strategy of targeting the middle of the next word would take long enough to process to cause the eye movement system to slow down appreciably to be able to use it. In formulating the E-Z reader model, we thought the most plausible assumption was that the decision of where to target the next saccade was made in the first 50–100 ms of a fixation – a period in which little useful higher-level information is likely to be extracted from the parafoveal word.

While the data reported here may not rule out all models of eye movement control, they are particularly damaging to models (Underwood et al., 1990) in which high level information obtained from parafoveal vision influences the decision of where to move the eyes (see Rayner & Morris, 1992, for other data inconsistent with such a model). We believe that the fact that predictability has, at most, a minimal influence on the landing position in a target word in reading is most consistent with models that posit that the *when* and *where* decisions are made somewhat independently of each other. That is, the decision of when to leave a word and which word to fixate next are influenced by the ongoing processes of word identification and are influenced by variables such as the frequency of a word and its predictability from the prior text. On the other hand, the target for where to initially fixate in a word is probably the center of the word, which is usually computed from where the spaces are around the word, and appears to be largely influenced by low-level visual factors such as word length and how far the launch site is from the target word.

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