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Vision Research 39 (1999) 4403–4411

Vision Research

www.elsevier.com/locate/visres

Eye movement control in reading: accounting for initial fixation locations and refixations within the E-Z Reader model

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Received 16 November 1998; received in revised form 25 March 1999

Abstract

Reilly and O'Regan (1998, *Vision Research*, *38*, 303–317) used computer simulations to evaluate how well several different word-targeting strategies could account for results which show that the distributions of fixation locations in reading are systematically related to low-level oculomotor variables, such as saccade distance and launch site [McConkie, Kerr, Reddix & Zola, (1988). *Vision Research*, *28*, 1107–1118]. Their simulation results suggested that fixation locations are primarily determined by word length information, and that the processing of language, such as the identification of words, plays only a minimal role in deciding where to move the eyes. This claim appears to be problematic for our model of eye movement control in reading, *E-Z Reader* [Rayner, Reichle & Pollatsek (1998). Eye movement control in reading: an overview and model. In G. Underwood, *Eye guidance in reading and scene perception* (pp. 243–268). Oxford, UK: Elsevier; Reichle, Pollatsek, Fisher & Rayner (1998). *Psychological Review*, *105*, 125–157], because it assumes that lexical access is the engine that drives the eyes forward during reading. However, we show that a newer version of E-Z Reader which still assumes that lexical access is the engine driving eye movements also predicts the locations of fixations and within-word refixations, and therefore provides a viable framework for understanding how both linguistic and oculomotor variables affect eye movements in reading. © 1999 Elsevier Science Ltd. All rights reserved.

Keywords: Reading; Eye movement control; Initial fixation location; Refixation; E-Z Reader model

1. Introduction

There is a long-standing debate concerning eye movement control in reading (Rayner, 1998). One group of researchers (see O'Regan, 1990, 1992) has focused primarily on low-level oculomotor factors and how they influence where readers fixate during reading. A second group of researchers (see Just & Carpenter, 1980, 1987) has been primarily interested in how higher level linguistic factors determine when readers move their eyes. A third group (ours) advocates a middle-of-the-road view of eye movement control in reading (Rayner & Pollatsek, 1989). As we see it, there is ample evidence that both oculomotor and linguistic variables play a role in eye movement control during reading, so the real challenge is to develop a theoretical framework that is comprehensive enough to account for both factors on eye movement control. Our first attempt to do so resulted in the *E-Z Reader* model (Rayner, Reichle & Pollatsek, 1998; Reichle, Pollatsek, Fisher & Rayner, 1998), a computational model of eye movement control in reading. Although we have conducted a number of studies to examine the factors that influence the decision of where to move the eyes next (Rayner & McConkie, 1976; Rayner & Pollatsek, 1981; Pollatsek & Rayner, 1982; Morris, Rayner & Pollatsek, 1990; Rayner, Sereno & Raney, 1996; Rayner, Fischer & Pollatsek, 1998), the E-Z Reader model was intended to primarily deal with the issue of when to move the eyes. When discussing the issue of where to move the eyes, the model only handles decisions about which words to fixate or skip.

Reilly and O'Regan (1998) recently used a predecessor of the E-Z Reader model (i.e. the model of Morrison, 1984, that was subsequently modified and expanded by Rayner & Pollatsek, 1989 and Pollatsek & Rayner, 1990) to argue against linguistic-based models of eye-movement control. This claim was based on their finding that a computer simulation of the original Morrison model (dubbed the *attention shift strategy* by Reilly & O'Regan) had difficulty generating many of

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PII: S0042-6989(99)00152-2

the characteristics of the fixation location distributions that are normally observed in reading (McConkie, Kerr, Reddix & Zola, 1988; McConkie, Zola, Grimes, Kerr, Bryant & Wolff, 1991; Rayner et al., 1996; Radach & McConkie, 1998).

Typically, the locations of initial fixations on a word are normally distributed, with the tails of the distributions being truncated at the word boundaries, and the means of the distributions falling slightly to the left of center (i.e. the *preferred viewing location*; Rayner, 1979). Furthermore, as the distance between the prior fixation location (i.e. the *launch site*) and the current fixation location (i.e. the *landing site*) increases, the mean of the distribution shifts towards the beginning of the word, and the distribution becomes more variable. Although the length of the target word affects neither the mean nor the variance of the distributions, longer fixation durations on the launch site tend to decrease the leftward deviation that results from increasing the distance between the launch site and target site (McConkie et al., 1988)[1].

These regularities, and the finding that word identification is most rapid when the center of the word is fixated, led O'Regan (1981); O'Regan & Lévy-Schoen, 1987) to suggest that readers aim their initial saccade into a word towards the center of the word, or what he originally called the *convenient viewing position* (but more recently called the *optimal viewing position*; O'Regan, 1992), so as to facilitate word identification as much as possible. However, presumably because of oculomotor error, their saccades often miss. This error stems from two sources: (a) a systematic range error that causes the eyes to undershoot distant targets and overshoot near targets; and (b) random error that is due to oculomotor variability. As with other forms of motor error, the variability that is associated with the latter source of error increases with the length of the movement trajectory (i.e. saccade) and decreases with preparation (i.e. fixation duration on the launch site word).

The McConkie et al. (1988) analysis provides a framework for understanding how low-level, oculomotor variables affect where the eyes fixate during reading. Our approach in the next section will be to add assumptions that incorporate their findings to the E-Z Reader model to determine whether the model, as it currently stands, can account for the locations of initial fixations and within-word refixations.

2. Additional assumption

The model that is presented in this section is simply an extended version of our earlier model (E-Z Reader 5; as reported in Reichle et al., 1998). This incremental approach of model development makes it possible to maintain our minimalist approach to understanding the process of reading. This is necessary if we are (as claimed above) to demonstrate that E-Z Reader provides a viable framework for understanding how both linguistic and oculomotor variables influence eye movements in reading. Also, because the core model remains unchanged, most of the details of the model will not be specified in this paper (the interested reader should consult Reichle et al., 1998 for details).

In E-Z Reader, eye movement control is determined by five processes: (1) a familiarity check on a word, f; (2) the subsequent completion of lexical access on a word, l_c; (3) an early stage of saccadic programming; (4) a late stage of saccadic programming; and (5) saccades. The first two processes are jointly determined by each word's normative frequency of occurrence (as tabulated by Francis & Kuĉera, 1982) and context-specific predictability (as determined empirically). These processes can be conceptualized as being the product of a single cognitive module that is responsible for word recognition. The familiarity check indicates that a word is likely to be recognized by the reader (i.e. lexical access is imminent) and hence cues the motor system to begin programming a saccade to the next word. The completion of lexical access corresponds to the process of uniquely identifying a word (i.e. lexical access, as the term is usually defined), and is the signal to shift covert spatial attention to the next word. This distinction between f and l_c is consistent with several two-stage models of lexical access (e.g. Paap, Newsome, McDonald & Schvaneveldt, 1982; Van Orden, 1987), and it allows the model to decouple the signal to program a saccade from the signal to shift attention. If attention and eye movement programming are not decoupled, one is unable to explain 'spillover' effects in reading (e.g. the finding that the frequency of word$_n$ can affect the fixation time on word$_{n+1}$) or how the difficulty of the fixated word can affect the intake of parafoveal information (see Pollatsek & Rayner, 1990; Reichle et al., 1998).

The early and late stages of saccadic programming, along with the actual saccades, are the products of an oculomotor module that plans and executes eye movements. The distinction between early and late stages of programming follows Morrison's (1984) notion (based on the findings of Becker & Jürgens, 1979) that a program to make an eye movement can be cancelled by a subsequent program if a second program is initiated soon enough after the first[2]. Thus, during the course of

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[1] Radach and McConkie (1998), however, did not replicate this effect.

[2] Becker and Jürgens (1979) found that saccades occasionally moved the eyes to positions in between the initial fixation target location (which was canceled) and the location of a second fixation target (that was presented subsequently). We did not attempt to simulate these intermediate, or 'blend,' saccades because they occur infrequently and because doing so would increase the complexity of the model and our modeling effort.

programming a saccade, there is a 'point of no return:' before this point, the program is labile, and can be cancelled by subsequent saccadic programs; after this point, the program is nonlabile, and the saccade will be executed. This feature of E-Z Reader is essential because it provides the basis for skipping words. Skipping occurs when word$_n$ is fixated, but the first stage of lexical access, *f*, has completed on word$_{n+1}$. Because *f* signals the oculomotor systems to begin planning a saccade to word$_{n+2}$, the labile program to move the eyes to word$_{n+1}$ is cancelled, and word$_{n+1}$ is skipped.

As discussed in Reichle et al. (1998), E-Z Reader was originally designed to account for eye movements at the level of individual words. Thus the model needs to be refined so that it can make predictions about the locations of fixations on the level of individual characters. To do this, our data base of the Schilling, Rayner and Chumbley (1998) sentence corpus was expanded to include each word's length in characters. This information was then used to calculate each word's center, or optimal viewing position. The center of each word is posited to be the functional target of any saccade targeted on the word: Thus, both inter-word and intra-word saccades targeted to word$_n$ are assumed to be directed towards the center of word$_n$.

Although the target for all saccades is the center of the word, the simulated saccades (like real saccades) are prone to two types of error. The first is due to systematic range error, which causes the saccades to undershoot distant targets and overshoot near targets. The second source of saccadic error is the random variability associated with oculomotor movements. To determine the predicted location of each fixation in the simulation, the absolute distance (in terms of the number of character spaces, where letters, punctuation, and blank spaces are all assumed to occupy a single character) between the current fixation and the saccade target is calculated. This value is the planned saccade length, or PSL. The systematic range error, or SRE, is given by:

$$\mathrm{SRE} = (\Psi_{\mathrm{b}} - \mathrm{PSL}) * \Psi_{\mathrm{m}} \tag{1}$$

where Ψ_{b} is a free parameter that represents the saccade length for which the saccade neither undershoots nor overshoots the intended target. Because McConkie et al. (1988) found that this tended to be around seven characters, Ψ_{b} was fixed at a value of 7. Similarly, Ψ_{m} is a free parameter that modulates the effect of the systematic range error. Because McConkie et al. (1988) estimated this value to be slightly less than a half a character, we fixed the value of Ψ_{m} at 0.4. Thus, for every character that a planned saccade extends beyond 7, the length of the saccade that is executed will fall short by almost half a character.

The second source of saccadic variability, the random error associated with oculomotor movements, *E*, is a random deviate sampled from a Gaussian distribution, with $\mu = 0$, and σ given by:

$$\sigma = \beta_{\mathrm{b}} + (\beta_{\mathrm{m}} * \mathrm{PSL}) \tag{2}$$

where β_{b} and β_{m} are free parameters that adjust the oculomotor variability as a linear function of the planned saccade length. The length of the saccade that is actually executed is then given by:

$$\text{Saccade length} = \mathrm{PSL} + \mathrm{SRE} + E \tag{3}$$

As mentioned earlier, these assumptions regarding fixation locations are taken directly from McConkie et al. (1988). It is important to point out, however, that the model (as it has been described up to this point) is identical to E-Z Reader 5 (Reichle et al., 1998). Consequently, our decision to add McConkie et al.'s assumptions about the source of saccadic errors should be conceptualized as an attempt to specify our model more precisely rather than as an attempt to develop another version of the model. Consistent with this goal, one additional modification was necessary. In E-Z Reader 5, the rate of lexical processing was modulated as a function of *eccentricity*, or the distance between the word being processed and the word being fixated (see Reichle et al., 1998, Eq. (6)). Because the model only made predictions on the level of individual words, it made sense to measure eccentricity in terms of the number of words intervening between the fixation point and the word being processed. However, because the current model predicts the character that is being fixated, eccentricity, *x*, was redefined as the number of character spaces between the current fixation location and the center of the word being processed. The lexical processing rate is then adjusted using:

$$\mathrm{duration}(x) = \mathrm{duration}_0 * \varepsilon^{x} \tag{4}$$

where duration$_0$ represents the time (in ms) required to complete each of the lexical processing components (i.e. the familiarity check, *f*, and the completion of lexical access, l_{c}; see Reichle et al., 1998) when the center of the word is fixated, and ε is a free parameter (actually, two free parameters, because different values of ε are used for *f* and l_{c}) that modulates duration. Because the eccentricity parameters were originally added to E-Z Reader to enhance the model's psychological plausibility, it was important that the current values of ε modulate the lexical processing rate no less than in our previous simulations. Fig. 1 shows how eccentricity affected the lexical processing rates in the current simulations ($\varepsilon = 1.10$ and $\varepsilon = 1.13$ for *f* and l_{c}, respectively) as compared to our previous simulations ($\varepsilon = 1.25$ and $\varepsilon = 1.75$ for *f* and l_{c}, respectively). Because the mean word length in our sentence corpus was 5.8 characters, the current values of ε were selected so that the processing rate at an eccentricity (as currently defined) of 5.8 characters was at least as great as the processing rate at an eccentricity (as previously defined) of one word.

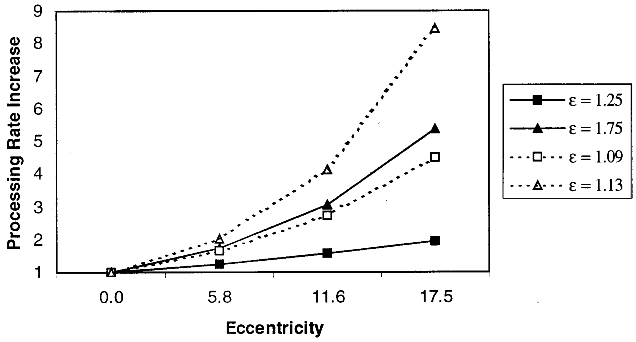

Fig. 1. Processing rates as a function of eccentricity (i.e. the number of character spaces between fixation and the middle of the word being processed) for the standard E-Z Reader 5 (solid lines) and the modified version of the model (dashed lines). Because the mean word length in our sentence corpus was 5.8 characters, the values plotted along the x-axis correspond to disparities of zero to two words (on average) between the word being fixated and the word being processed. The squares (i.e. $\varepsilon = 1.25$ and $\varepsilon = 1.09$) indicate how the duration of the familiarity check, f, is affected by eccentricity; the triangles (i.e. $\varepsilon = 1.75$ and $\varepsilon = 1.13$) show how the completion of lexical access, l_c, is affected by eccentricity.

3. Simulation results

3.1. Modeling initial landing position

To evaluate how well E-Z Reader can reproduce the McConkie et al. (1988) results, we ran the model on our standard sentence corpus (i.e. the Schilling et al., 1998, data that we used in all of our previous simulations) using 1000 statistical subjects[3]. The locations of the first fixations in the simulation were recorded for all four-, five-, six- and seven-letter words (excluding the first and last words of each sentence) for cases where the fixations followed saccades from launch sites one-, three-, five-, and seven-character spaces to the left of the word boundaries. Histograms were then constructed to evaluate the predicted landing site distributions as a function of word length and launch site. These distributions excluded simulation trials in which a word was skipped due to oculomotor error because of our assumption that, with real subjects, these inadvertent skips would often lead to regressions. (In fitting E-Z Reader to the Schilling et al. data, all trials on which readers actually made regressions were eliminated.) Statistical trials on which a word was undershot due to oculomotor error were included, however, and were expected to inflate the predicted number of refixations. Because our corpus of sentences was relatively small, the empirical distributions were extremely noisy and thus comparing them to the predicted distributions would be of little value. Instead, our emphasis is on showing that the distribu-

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[3] Although our sentence corpus was not rich enough to examine the fixation location distributions within the corpus, the properties of the distributions that we wanted to simulate with our model have been reported in several places (e.g. McConkie et al., 1988; 1991; Rayner et al., 1996) and appear to be quite robust.

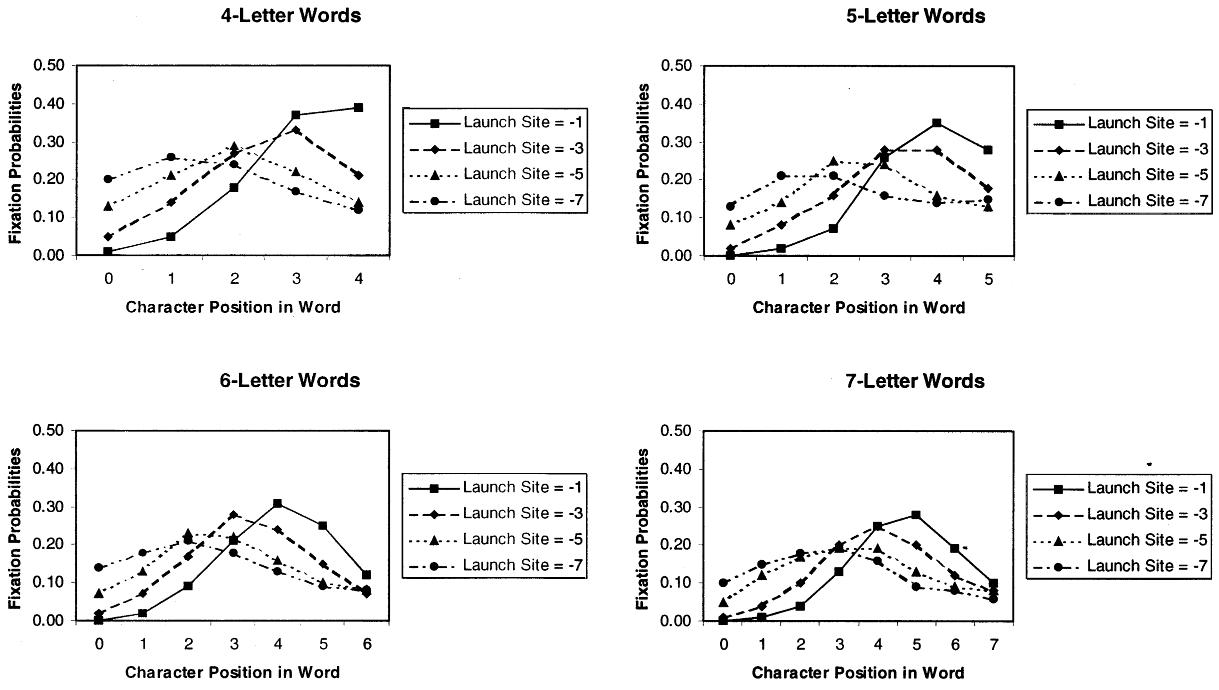

Fig. 2. Predicted landing site distributions on four-, five-, six- and seven-letter words as a function of launch site. The locations of fixations and launch sites are indicated by numbers representing ordinal position, from left to right, with the blank space to the left of the word being zero.

tions are consistent with those observed when extremely large data bases have been analyzed (McConkie et al., 1988).

Fig. 2 shows the landing site distributions for four-, five-, six- and seven-letter words, as a function of four different launch sites. Following prior convention (McConkie et al., 1988; Rayner et al., 1996; Reilly & O'Regan, 1998), the figure shows how the distribution of fixation locations within a word is influenced by the distance of the launch site. Both the locations of the fixations and launch sites are indicated with respect to their distance (in number of character spaces) from the left word boundaries, with the blank space to the left of the words being designated as zero. As mentioned, the values of two of the new parameters were estimated from McConkie et al. (1998): $\Psi_b = 7$ and $\Psi_m = 0.4$. The remaining parameter values were hand-selected to give reasonable fits[4].

As the figure indicates, the landing site distributions are quite similar to those that have been reported elsewhere (e.g. cf. Figs. 1 and 2 of McConkie et al., 1988). That is, the distributions are roughly normal in shape, with tails truncated at the word boundaries, and means located near the center of the words. As the saccade length increases (i.e. as the launch sites move further away from the left word boundary), the centers of the distributions shift leftward, and their variability increases. This second result is evident if one compares the relative heights of the distributions; that is, as saccade length increases, so too does the variability of the landing sites, thereby reducing the modes of the distributions. Notice, though, that the variability of the distributions does not change markedly as a function of word length (see Fig. 2). This is also congruent with previous reports (McConkie et al., 1988, 1991; Rayner et al., 1996). On a first pass, then, E-Z Reader does a fairly good job of predicting the locations of first fixations.

Nonetheless, the model (as specified up to this point) fails to explain several well-known properties of initial fixation locations. For example, the model cannot account for McConkie et al.'s (1988) finding that the magnitude of the systematic range error decreased as the duration of the fixation on the launch site increased because the size of the systematic range error is determined by a single, fixed parameter, Ψ_m. To handle this effect, our assumption about the systematic range error has to be modified, so that the value of Ψ_m can vary as a function of fixation duration on the launch site word. This was done as follows:

$$\Psi_m = [\Omega_b - \ln(\text{FD})]/\Omega_m \tag{5}$$

In Eq. (5), the parameter that modulates the systematic range error, Ψ_m, is a linear function of the natural logarithm of the fixation duration (FD; in ms) on the launch site word. Ω_b and Ω_m are free parameters that determine how much the fixation duration affects the systematic range error. Conceptually, Eq. (5) is congruent with McConkie et al.'s (1988) account of the relationship between the launch site fixation duration and the systematic range error. That is, by increasing the fixation duration on the launch site, it is assumed that the eye guidance system can more accurately locate the functional target of the upcoming saccade. This explanation was based on the fact that launch site fixation duration affected the magnitude of the systematic range error, but not the error due to the random component of the oculomotor movement (Coëffé & O'Regan, 1987).

The values of the two new parameters were hand-chosen to provide reasonable fits ($\Omega_b = 7.3$; $\Omega_m = 4.5$). A simulation was then completed using 1000 statistical subjects and our standard sentence corpus. The predicted fixation locations for four-, five-, six- and seven-letter words were then sorted according to: (a) the location of the launch site; and (b) the fixation duration on the launch site. The latter was carried out by first calculating the mean predicted fixation duration on the launch site words (241 ms), and then dividing our predicted fixation locations into two groups: those following short launch fixations (i.e. fixation durations < 241 ms), and those following long launch fixations (i.e. fixation durations > 241 ms). The means of the fixation location distributions were then calculated within each group, and compared to determine whether or not the magnitude of the systematic range error was affected by the launch site fixation duration. The means of the landing site distribution for four-, five-, six- and seven-letter words (conditional upon whether the launch site fixation duration was above or below 241 ms) are presented in Fig. 3.

As Fig. 3 shows, the landing site distribution means tend to converge towards the center of the words as the fixation duration on the launch site word increases. This is evident in the range of mean values; that is, the means of the 'below mean' groups are more spread out (i.e. take on a larger range of values) than the means in the 'above mean' groups. This indicates that, as we had intended, the systematic range error can be made to be sensitive to the fixation duration on the launch site word.

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[4] The intercept (β_b) and slope (β_m) parameters for the random error component of the saccades (see Eq. (2)) were set equal to 0.85 and 0.11, respectively. The remaining parameters (as described in Reichle et al., 1998) and their values are as follows: the slope ($f_b = 150$ ms) and intercept ($f_m = 12$ ms) parameters of the function relating the familiarity check duration, $t(f)$, to the logarithm of word frequency; the parameter ($\Delta = 0.85$) that determines how much additional time [i.e. a multiple of $t(f)$] is necessary for the completion of lexical access, $t(l_c)$; the parameter ($\theta = 0.5$) that attenuates the affect of predictability on $t(f)$; and the parameters that determines how long it takes to complete the labile [$t(m) = 135$ ms] and nonlabile [$t(M) = 50$ ms] stages of inter-word saccadic motor programming. The intra-word motor programming parameters, $t(r)$ and $t(R)$, were set equal to $t(m)$ and $t(M)$, respectively.

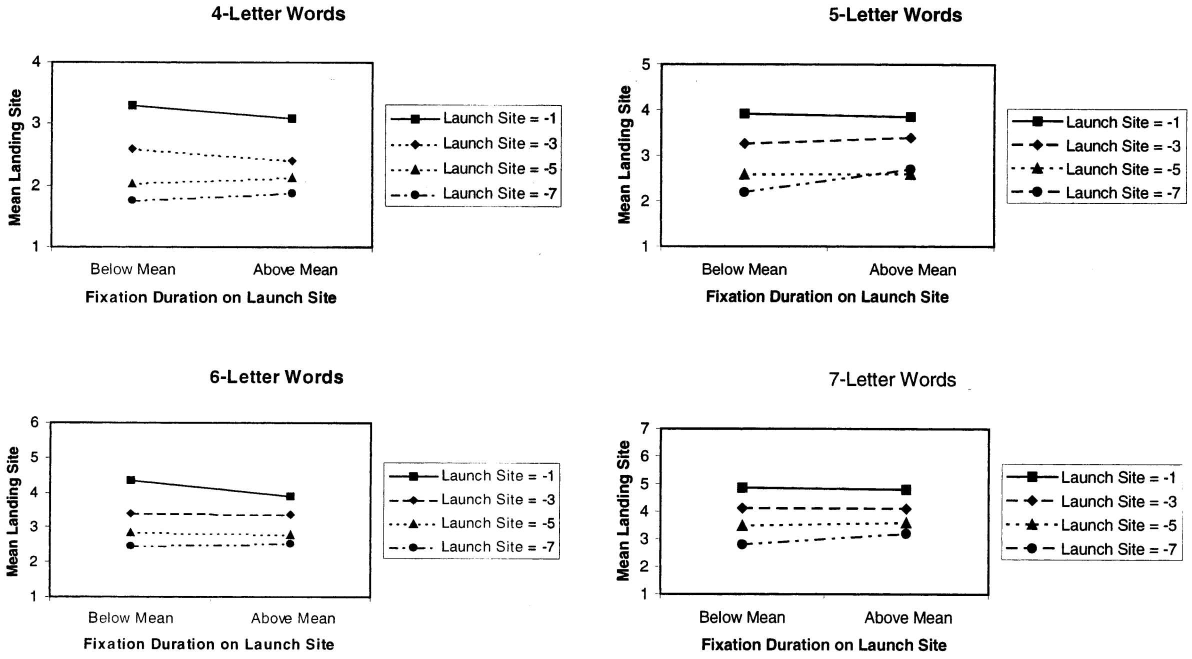

Fig. 3. Predicted landing site distribution means for four-, five-, six- and seven-letter words as a function of launch site and launch site fixation duration. The locations of the landing site means and launch sites are indicated by numbers representing ordinal position, from left to right, with the blank space to the left of the word being zero. The launch sites are sorted by fixation duration (above and below the mean value).

3.2. Modeling refixations

So far, we have not addressed refixations (i.e. making another fixation on a word before moving to another word). Specifically, a major issue has been what determines where and when the eyes refixate during reading. Because the process of refixation is probably one of the least understood components of eye movement control (Rayner, 1998), it has often been sidestepped by theories of eye movement control. For example, Reilly and O'Regan (1998) used a probability function to generate predictions about how often and where the eyes refixate so that the locations of these refixations could be used as launch sites in their study of landing site distributions. Typically, the probability of making a refixation is greatest following fixations on the beginning of the word, decreases towards the center of the word, and rises slightly near the end of the word (giving an asymmetrical V-shaped function; Rayner et al., 1996, Fig. 3). Although Reilly and O'Regan (1998) correctly predict this type of function (see Fig. 3), their simulation does not provide a functional account of why the eyes behave in this manner. They maintain that 'lexical processing is not assumed to affect the likelihood of refixating,' and that 'it is simply the eye's landing position which, when it deviates from the 'optimal' position, makes a refixation more likely' (Reilly & O'Regan, 1998). However, Rayner et al. (1996) demonstrated that even when landing position was equated that readers refixated more often on low-frequency words than on high-frequency words (see Hyönä & Pollatsek, 1998; Rayner, 1998, for other evidence that lexical processing influences refixation probability on a word.)

In E-Z Reader, the same process underlies both inter- and intra-word saccades: a 'horse race' between the completion of the first component of lexical access (i.e. the familiarity check, *f*, which initiates a new eye movement program) and the completion of the labile component of a prior eye movement program. In the case of intra-word saccades, a previously programmed intra-word saccade program (*r*) wins. In the case of an inter-word saccade, *f* wins and the intra-word saccade program is cancelled. As a result, the E-Z Reader 5 model can explain when and why intra-word saccades (i.e. refixations) occur, but it does not say how they are modulated by the location of the initial fixation. However, the model as specified above gives a reasonably good account of how the initial fixation location can modulate the probability of a refixation without making any additional assumptions. Remember that in the model, as specified to this point, the rate of lexical processing (f and l_c) is modulated as a function of the distance between where the eyes are currently fixated and the center of the word that is being processed (see Eq. (4)). As a result, the familiarity check completes most rapidly when the center of the word is fixated, and takes longer as the fixation deviates to either side of the word. Because refixations occur when the labile program to make an intra-word saccade completes before the familiarity check (i.e. f), our assumption about eccentricity means that refixations should be more likely to occur when the initial fixation is near the beginning or end of a word. This, in turn, should give rise to a symmetric V-shaped refixation function. However, there is a second factor that will influence refixations: undershoots. That is, according to the model, some of the time that an initial fixation is near the end of word$_n$, it is because word$_{n+1}$ was the target, but there was an undershoot. In those cases, the succeeding fixation will be on word$_{n+1}$ or word$_{n+2}$. As a result, the probability of refixation should in general be somewhat greater when the initial fixation is near the beginning of a word than when the initial fixation is near the end of a word (all else being equal).

To test these predictions more quantitatively, we ran the model on our sentence corpus (using 1000 statistical subjects) and calculated the probability that a saccade from a particular location would be a refixation as function of the landing position of the initial fixation on a word. Once again, we ran the simulation for four-, five-, six-, and seven-letter words (see Fig. 4).

As the figure indicates, the model was largely successful in producing the V-shaped refixation functions. Although refixations are more likely to occur after the eyes have fixated the beginning of the word, the probability of making a refixation first decreases to a low-point near the center of the word, and then increases towards the end of the word. However, the overall conditional probability of making a refixation was only approximately correct. For example, Rayner et al. (1996) found that nearly 38% of the first fixations that landed in the space immediately to the left of seven-letter words were followed by refixations, as compared to the predicted value of 20%. The low-frequency, longer words also tend to be refixated more often than high-frequency, shorter words, again consistent with Rayner et al. Finally, although the probability of making a refixation drops slightly following initial fixations that land on the final letter of seven-letter words, Rayner et al. observed a similar pattern in that the probability functions tended to become less regular near the ends of long words (six or more characters). This suggests that initial fixations that land near the end of long words are intended for subsequent words, and hence unlikely to result in refixations.

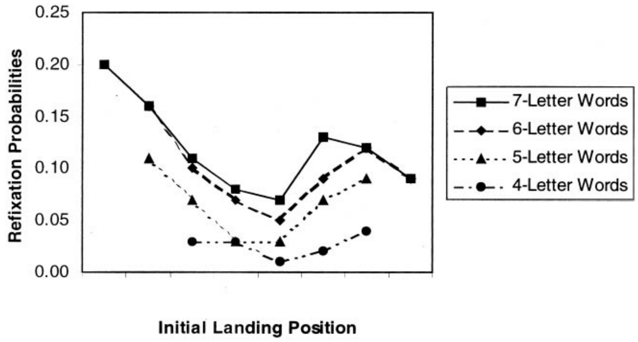

Fig. 4. Predicted probabilities of making refixations on four, five-, six- and seven-letter words following initial fixations at different locations. Each curve represents a different word length and is centered on the x-axis with the left-most point corresponding to the blank space preceding the word, the next point corresponding to the first letter in the word, etc.

Although our model gives a fairly good general account of refixations, there is evidence that it is likely to be incomplete. For example, there is evidence that the morphemic composition of words affects both the probability of a refixation and the location of a refixation (Hyönä & Pollatsek, 1998). This suggests that morphemes, as well as words, are cognitive units whose processing is triggering eye movements. Because our model treats words as complete units, it ignores this potentially useful source of eye-guidance information. One possible complication of the model would be to assume that the identification of a morpheme, in addition to the identification of a word, triggers an eye movement. For the case of morphemes, however, the issue of where the eye movement would be directed to is unclear. That is, one would ideally want the saccade targeted to something like the middle of the next morpheme; however, it seems unlikely that the eye movement system can actually locate this spot in the text quickly as there are no spaces delineating morphemes. (Hyönä and Pollatsek's, 1998, data indicate that refixations generally fall quite short of the middle of the second lexeme of a long compound word.) One possible simple strategy might be to direct the saccade towards the end of the word in hope that it would be a reasonable location for processing the second morphemic unit. Including processing of morphemes into the model, however, would involve major changes of the model and be beyond the scope of this paper.

3.3. Does the model still predict what it was first designed to predict?

We have added assumptions to the model that: (a) changed the assumption about how eccentricity affects word identification; and (b) posited that the 'wrong' word can sometimes be fixated. Initially E-Z reader was designed to explain the duration of fixations on words (individual fixation durations and gaze durations) as well as the probability of skipping and refixating words. One might expect that either change would harm the fit of the model. In particular, the deliberate introduction of the possibility that the 'wrong' word is fixated should affect the skipping and refixation probabilities. It should presumably also affect fixation durations, because there are now fixations actually made on one word when the processing of a different word is determining the duration of the fixation. The issue, however, is whether these errors will substantially weaken the fit

Table 1
Comparison of the overall performance of E-Z Reader 5 with E-Z Reader 6

Frequency class	Mean frequency	Gaze duration			First-fixation duration			Single-fixation duration		
		Obs[a]	EZ5[b]	EZ6[c]	Obs	EZ5	EZ6	Obs	EZ5	EZ6
1	3	293	291	286	248	251	253	265	274	272
2	45	272	271	268	234	253	252	249	263	263
3	347	256	257	247	228	246	240	243	252	245
4	4889	234	226	216	223	223	215	235	224	217
5	40 700	214	211	206	208	210	206	216	210	210
		Probability of skipping			Probability of making single fixation			Probability of making two fixations		
		Obs	EZ5	EZ6	Obs	EZ5	EZ6	Obs	EZ5	EZ6
1	3	0.10	0.09	0.06	0.68	0.73	0.78	0.20	0.17	0.17
2	45	0.13	0.16	0.11	0.70	0.76	0.80	0.16	0.07	0.09
3	347	0.22	0.27	0.21	0.68	0.68	0.74	0.10	0.04	0.04
4	4889	0.55	0.49	0.44	0.44	0.50	0.53	0.02	0.01	0.03
5	40 700	0.67	0.68	0.64	0.32	0.32	0.34	0.01	0.00	0.02

[a] Obs, Observed performance (see Reichle et al., 1998, Table 5). These values were calculated from our data base of the Schilling et al. (1998) sentence corpus.

[b] EZ5, Predicted performance of E-Z Reader 5 (see Reichle et al., 1998, Table 5). The following parameter values were used: $f_b = 195$ ms; $f_m = 17$ ms; $\Delta = 0.70$; $\theta = 0.5$; $t(m) = 150$ ms; $t(M) = 50$ ms; $\varepsilon_1 = 1.25$; and $\varepsilon_2 = 1.75$. The within-word motor programming parameters, $t(r)$ and $t(R)$, were assumed to have the same values as $t(m)$ and $t(M)$, respectively. (See footnote 4 for a description of the parameters.) Root-mean-square deviation = 0.198.

[c] EZ6, Predicted performance of the modified version of E-Z Reader (E-Z Reader 6); that is, the model with the added McConkie et al. (1988) assumptions. The simulation used the following parameter values: $f_b = 150$ ms; $f_m = 12$ ms; $\Delta = 0.85$; $\theta = 0.5$; $t(m) = 135$ ms; $t(M) = 50$ ms; $\varepsilon_1 = 1.09$; and $\varepsilon_2 = 1.13$. The within-word motor programming parameters, $t(r)$ and $t(R)$, were assumed to have the same values as $t(m)$ and $t(M)$, respectively. The new parameters and their values were: $\Psi_b = 7$; $\beta_b = 0.85$; $\beta_m = 0.11$; $\Omega_b = 7.3$; and $\Omega_m = 4.5$. Root-mean-square deviation = 0.218.

Table 1 shows the performance of the present model (with its added assumptions, and which is referred to as E-Z Reader 6 in Table 1) in predicting the mean gaze durations, first fixation durations, single fixation durations, probability of skipping, making a single fixation, and making two fixations, for five frequency classes of words. These values are presented along side of the observed values, and the values that were reported in an earlier simulation (see Reichle et al., 1998, Table 4).

As Table 1 shows, the model's performance was only slightly degraded by the addition of McConkie et al.'s (1988) assumptions regarding oculomotor error. Overall, the assumptions necessary to predict the initial fixation locations and refixations had little affect on the model's ability to fit the fixation duration measures.

Of course, we could have improved the current model's overall performance by finding optimal values for the parameters that were added to account for the initial landing site distributions and refixations instead of simply setting the parameters equal to values that were estimated from other sources. Our reasons for not doing so were twofold: for the sake of simplicity, and to show that the general outcome of the simulation results are not crucially dependent on assuming specific parameter values.

4. Discussion

In this paper, we have tried to explain several basic aspects of eye-movement control related to the locations of initial fixations and within-word refixations; namely, the distributions of these fixations, how these distributions are affected by low-level oculomotor variables, and the etiology of refixations. Our primary goal was to demonstrate that the assumptions of McConkie et al. (1988) are not inconsistent with the basic E-Z Reader framework, and one can gain a further understanding of eye-movement control by combining the two. Prior to this point, our model did a fairly good job of accounting for when the eyes move (both within and between words) and where the eyes fixate at the level of individual words (Rayner et al., 1998; Reichle et al., 1998). By adding a few assumptions about the relationship between the oculomotor system and saccadic accuracy, the current model now explains where the eyes fixate within words. Finally, and most importantly, the model provides a unified theory about why these various aspects of eye-movement control operate as they do. The model thus provides a tool for understanding how both oculomotor and linguistic variables affect eye movement control during reading.

Acknowledgements

This work was supported by Grant HD26765 from the National Institutes of Health. The second author was supported by a Senior Scientist Award (MH01255) from the National Institute of Mental Health. We would like to thank two anonymous reviewers for their insightful comments on an earlier version of this article.

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