

Comparing the E-Z Reader Model to Other Models of Eye Movement Control in Reading

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Short Abstract

The E-Z Reader model (Reichle, Pollatsek, Fisher, & Rayner, 1998; Reichle, Rayner, & Pollatsek, 1999) provides a theoretical framework for understanding how word identification, visual processing, attention, and oculomotor control jointly determine when and where the eyes move during reading. Thus, in contrast to the other reading models reviewed in this article, E-Z Reader can simultaneously account for many of the known effects of linguistic, visual, and oculomotor factors on eye movement control during reading. Furthermore, the core principles of the model have been generalized to other task domains (e.g., equation solving, visual search), and are broadly consistent with what is known about the architecture of the neural systems that support reading.

Abstract

Because of the temporal constraints on word identification and saccadic programming, it has been claimed that lexical access cannot be the “engine” driving eye movements during reading, and that when and where the eyes move are instead primarily determined by visual and oculomotor factors (Reilly & O’Regan, 1998). Our simulation model, E-Z Reader (Reichle, Pollatsek, Fisher, & Rayner, 1998; Reichle, Rayner, & Pollatsek, 1999), falsifies this claim, and provides a theoretical framework for understanding the complex temporal relationships among several basic reading components, including lexical access, visual processing, attention, and oculomotor control. In this article, we first review what is known about eye movement control during reading and describe how the E-Z Reader model accounts for these findings. We then review several alternative models of eye movements in reading, discussing both their core assumptions and their theoretical scope. On the basis of this discussion, we conclude that E-Z Reader provides the most comprehensive account of eye movement control during reading. Finally, we describe several recent attempts to apply the core principles of our model to reading (e.g., lexical ambiguity) and non-reading (e.g., equation solving, visual search) domains to show the generality of these principles. We also provide a brief overview of what is known about the neural systems that support the various components of reading, and suggest how the cognitive constructs of our model might map onto this neural architecture.

Key Words: Attention, Eye-Movement Control, E-Z Reader, Fixations, Lexical Access, Models, Reading, Saccades

1. Introduction

Reading is a complex skill that involves the orchestration of many different stages of information processing. As the eyes move across the printed page, the visual features of the text are converted into orthographic and phonological patterns, which are then used to guide further language processing so that the content of the text can be understood. In this target article, we will compare different models that have been proposed to account for how eye movements are controlled in reading. We will not review all of the models that have been proposed to explain various components of reading. Instead, we will only discuss those models that have attempted to explain the interface between vision and low-level aspects of language processing; that is, models that specify some combination of the following components of reading: Eye movement control, visuospatial attention, and/or the visual processing of words¹. Not surprisingly, we will argue that the model that we implemented, the E-Z Reader model (Reichle, Pollatsek, Fisher, & Rayner, 1998; Reichle, Rayner, & Pollatsek, 1999) does a better job of accounting for a wide range of data than does its competitors. However, we will also point out some shortcomings of the model.

The remainder of this article will be organized into 5 major sections. First, we will briefly review some important findings regarding eye movements in reading; within this section we will describe some findings that we believe a model of eye movement control should be able to accommodate. Second, we will provide an overview of the E-Z Reader model. Third, we will provide an overview of other reading models (including discussions of the pros and cons of the models compared to E-Z Reader). Fourth, we will discuss future directions and ways that we intend to extend the E-Z Reader model. In this section, we will also discuss possible neurophysiological mechanisms. Finally, we will provide some concluding comments.

2.0 Eye Movements in Reading

Any discussion of models of eye movement control must begin with a brief overview of eye movements during reading. In this section, we will describe what is known about eye movements during reading as background material. The following topics will be discussed: (1.) saccades and fixations, (2.) visual acuity, (3.) saccade latency, (4.) perceptual span, (5.) parafoveal preview effects, (6.) regressions, (7.) eye movement control (where to fixate next and when to move the eyes), and (8.) measures of processing time. It is not our intention to provide a complete and comprehensive review of each of these topics since our primary purpose in this article is to compare different models of eye movement control in reading. The interested reader is invited to consult Rayner (1998) for a more complete review of each of the eight topics discussed in this section.

2.1 *Saccades and fixations.* Contrary to our subjective impression, the eyes do not move smoothly across the printed page during reading. Instead, the eyes make short and rapid movements, called *saccades*, that typically move the eyes forward about 6-9 character spaces, although there is considerable variability (Rayner, 1978, 1998). Since saccade size is largely independent of visual angle when the number of character spaces is held constant, virtually all studies of reading use number of character spaces as the appropriate metric (Morrison & Rayner, 1981; O'Regan, 1983). Saccades take 20-50 ms to complete depending upon the length of the movement and virtually no visual information is extracted during eye movements (Ishida & Ikeda, 1989; Wolverton & Zola, 1983). Between saccades, the eyes remain stationary for brief periods of time (typically 200-250 ms) called *fixations* (Rayner, 1978, 1998). Because visual information is only extracted from the printed page during fixations, reading is similar to a slide show in which short segments of text are displayed for approximately a quarter of a second. It is important to note that, even within a given reader, there is considerable variability in both saccade length and fixation duration. Some saccades only move the eyes a single character and others are as large as 15-20 characters (although such long saccades typically follow regressions and place the eyes beyond the place from where the regression was initiated); likewise, some fixations will be shorter than 100 ms and some will be longer than 400 ms (Rayner, 1978, 1998). Much of this variability apparently is related to the ease or difficulty involved in processing the currently fixated text.

2.2 *Visual acuity.* Other constraints also severely curtail how much visual information can be processed during each fixation. First, because visual acuity is maximal in the center of the retina and rapidly decreases towards the periphery, fine visual discriminations can only be made within the *fovea*, or central 2° of vision. As a result, the visual features that make up individual letters can only be encoded from a very narrow window of vision. The practical significance of this fact is that it is necessary to fixate most words so that they can be identified. Indeed, there is considerable evidence that a word becomes increasingly difficult to identify as the angular disparity between the fovea and the retinal image of a word increases (Rayner & Bertera, 1979; Rayner & Morrison, 1981).

2.3 *Saccade latency.* A second set of constraints stems from the "race" between the processes identifying words and the need to plan a saccade early enough in a fixation so that reading can carry on at about 300 words per minute. That is, experiments in which subjects move their eyes to visual targets indicate that the *saccadic latency*, or the time needed to plan and execute a saccade, is approximately 180-200 ms (Becker & Jürgens, 1979; Rayner, Slowiaczek, Clifton, & Bertera, 1983), which suggests that the decision to make a saccade is often made within the first 100 ms of a fixation. This is seemingly at odds with the intuitively appealing idea that word recognition is a major contributor to driving eye movements during reading because most estimates indicate that

lexical access requires 100-300 ms to complete (Sereno, Rayner, & Posner, 1998; Rayner & Pollatsek, 1989; Schilling, Rayner, & Chumbley, 1998). On first appearances, therefore, it is not immediately obvious how the identification of one word can be the signal to begin planning a saccade to the next. Indeed, early theories of eye movements in reading (Bouma & deVoogd, 1974; Kolers, 1976) posited that word identification was too slow to be the engine driving eye movements.

2.4 *Perceptual span*. The solution to the quandary mentioned in the previous sentence is that words can be partially processed in the *parafovea*, or region of the retina that extends 5° on either side of the fovea. McConkie and Rayner (1975) demonstrated the importance of parafoveal processing using an *eye-contingent display change technique*, called the *moving-window paradigm* (illustrated in Figure 1). In this paradigm, the letters outside of a “window” spanning a given number of character spaces is distorted in some way (e.g., replaced with Xs). By varying the size of the window and making its location contingent upon where the reader is looking, it is possible to determine the *perceptual span*, or region from which useful visual information can be encoded. With English text, readers progress at a more-or-less normal rate when the window is 14-15 character spaces to the right (McConkie & Rayner, 1975; Rayner, 1986; Rayner & Bertera, 1979; Rayner, Well, Pollatsek, & Bertera, 1982; DenBuurman, Boersma, & Gerrissen, 1981) and 3-4 character spaces to the left of the fixation point (McConkie & Rayner, 1976; Rayner, Well, & Pollatsek, 1983). However, word encoding probably does not extend more than 7-8 characters to the right of fixation (Rayner et al., 1982; McConkie & Zola, 1984; Underwood & McConkie, 1985); beyond this distance, only low-spatial frequency information about letter shape (e.g., descenders vs. ascenders; letters vs. blank spaces) is extracted from the page. The left-right asymmetry reflects covert attention and is language specific; with Hebrew text (which is read from right to left), the perceptual span extends asymmetrically to the left of fixation (Pollatsek, Bolozyk, Well, & Rayner, 1981).

Insert Figure 1 here

Four other points about the perceptual span are relevant. First, the perceptual span does not extend below the line that is currently being read (Inhoff & Briehl, 1991; Inhoff & Topolski, 1992; Pollatsek, Raney, LaGasse, & Rayner, 1993); readers focus their attention on the line that they are currently reading. Second, studies using various eye-contingent display change techniques have revealed that the size of the span is fairly constant for readers of similar alphabetic orthographies (such as English, French, and Dutch; see Rayner, 1998 for further details). Third, characteristics of the writing system influence not only the asymmetry of the span, but also the overall size of the perceptual span. Thus, the span is smaller for Hebrew than English (Pollatsek et al., 1982) since Hebrew is a more densely packed language than English. And, it is much smaller for writing systems like Japanese (Ikeda & Saida, 1978; Osaka, 1992) and Chinese (Inhoff & Liu, 1998) that have ideographic components and hence are even more densely packed than Hebrew. Fourth, the perceptual span is not hardwired, but rather seems to be attention based. The fact that there is an asymmetry due to the direction of the writing system is consistent with the span being attention based. In fact, Pollatsek et al. (1982) found that the perceptual span of Israeli readers who were bilingual in Hebrew and English had opposite asymmetries when reading the two languages. Furthermore, Rayner (1986) found that the span was smaller for beginning readers than skilled readers and that the span got smaller when 4th graders were given text that was too difficult for them. Analogous to this finding, Henderson and Ferreira (1990; see also Inhoff, Pollatsek, Posner, & Rayner, 1988; Kennison & Clifton, 1995; Schroyens, Vitu, Brysbaert, & d’Ydewalle, 1999) found

that the span got smaller when the fixated word was difficult to process. Finally, Balota, Pollatsek, and Rayner (1985) found that readers obtained more information to the right of fixation when the upcoming word was highly predictable from the preceding text.

2.5 Parafoveal preview effects. Consistent with the last finding, it has also been found that orthographic (Rayner, 1975; Balota et al., 1985; Binder, Pollatsek, & Rayner, 1999) and phonological (Pollatsek, Lesch, Morris, & Rayner, 1992) processing of a word can begin prior to the word being fixated. These results suggest that, during normal reading, the *parafoveal preview* of a word can reduce the duration of the subsequent fixation on the word, which is one measure of the time needed for identification (Schilling et al., 1998). Surprisingly, neither semantic (Altarriba, Kambe, Pollatsek, & Rayner, 2001; Rayner, Balota, & Pollatsek, 1986) nor morphological (Lima, 1987, Lima & Inhoff, 1985) information extracted from the parafoveal appears to be of any benefit when the word is later fixated. However, parafoveal preview can produce skipping because words that can be identified in the parafovea do not have to be fixated and can therefore be skipped. Many experiments (Balota et al., 1985; Binder et al., 1999; Ehrlich & Rayner, 1981; Rayner, Binder, Ashby, & Pollatsek, 2001; Rayner & Well, 1996; Schustack, Ehrlich, & Rayner, 1986) have demonstrated that predictable words are skipped more than unpredictable words and short function words (like “the”) are skipped more than content words (O’Regan, 1979, 1980; Gautier, O’Regan, & LeGargasson, 2000). When words are skipped, the durations of the fixations preceding and following the skip are inflated (Pollatsek, Rayner, & Balota, 1986; Reichle et al., 1998).

2.6 Regressions. One indicator of the inherent difficulty of reading (even for skilled readers) is that 10-15% of the saccades move the eyes back to previous parts of the text. These backward movements, called *regressions*, are thought to result both from problems with linguistic processing and oculomotor error. This hypothesis is supported by the finding that regressions can be induced with structurally difficult “garden path” sentences; because such sentences often lead to incorrect syntactic analyses, the reader must make a regression and then re-interpret the sentence (Frazier & Rayner, 1982). The idea that regressions are sometimes due to simple motor error is supported by the finding that when the eyes fixate near the end of a word, they often move back a few character spaces (O’Regan, 1990). This presumably happens because the eyes overshoot their intended target (near the middle of the word) and a second fixation location affords a better place from which to see the word. This interpretation is consistent with the finding that identification is most rapid if a word is fixated just to the left of its center, on the *optimal viewing position* (Clark & O’Regan, 1999; O’Regan, Lévy-Schoen, Pynte, & Brugailière, 1984; O’Regan, 1990, 1992).

2.7 Eye movement control. Numerous studies have attempted to determine the characteristics of the mechanisms that control eye movements during reading. There are two different activities that must be explained: (1) what determines where the reader decides to look next? and (2) what determines when the reader moves his/her eyes (either forward or backward in the text)? Although there is not total consensus on these issues, there is some evidence to suggest that decisions about where to fixate next and when to move the eyes are made somewhat independently (Rayner & McConkie, 1976; Rayner & Pollatsek, 1981). The earliest unambiguous demonstration that the duration of the current fixation and the length of the next saccade are computed on-line was provided by Rayner and Pollatsek (1981). They varied physical aspects of the text randomly from fixation to fixation and found that the behavior of the eyes mirrored what was seen on a fixation. In their first experiment, they used the moving window paradigm described above and varied the size of the window randomly from fixation to fixation and found that saccade

length varied accordingly. Thus, if the window on the current fixation was small, the eyes only moved a few characters, while if it was large, the eyes moved further. In their second experiment, they delayed the onset of text in the fovea via a mask that appeared at the beginning of a fixation (with the time the mask was on varying randomly from fixation to fixation) and found that fixation durations were adjusted accordingly. In addition, the manipulations affected saccade length and fixation duration independently; in the first experiment, saccade length was affected, but fixation duration was not, while in the second experiment, fixation duration was affected, but saccade length was not. Thus, while the decisions about where to fixate next and when to move the eyes may sometimes overlap (see Rayner, Kambe, & Duffy, 2000), there is reason to believe the two decisions are made somewhat independently.

2.7.A Where to fixate next. Decisions about where to fixate next seem to be determined largely by low-level visual cues in the text, such as word length and the spaces between words. Five types of results are consistent with this claim. First, saccade length is influenced by the lengths of both the fixated word and the word to the right of fixation (Blanchard, Pollatsek, & Rayner, 1989; O'Regan, 1979, 1980; Rayner, 1979; Rayner & Morris, 1992). Second, when readers do not have information about where the spaces are between upcoming words, saccade length decreases and reading is slowed considerably (McConkie & Rayner, 1975; Morris, Rayner, & Pollatsek, 1990; Pollatsek & Rayner, 1982; Rayner, Fischer, & Pollatsek, 1998). Third, although there is some variability in where the eyes land on a word, readers tend to make their first fixation about halfway between the beginning and the middle of the word (Rayner, 1979; McConkie, Kerr, Reddix, & Zola, 1988; McConkie, Kerr, Reddix, Zola, & Jacobs, 1989; McConkie, Zola, Grimes, Kerr, Bryant, & Wolff, 1991; Vitu, 1991). Recently, Deutsch and Rayner (1999) demonstrated that the typical landing position in Hebrew words is likewise between the beginning (i.e., right-most end) and middle of a word. Rayner (1979) originally labeled this prototypical location *the preferred viewing location*. This position where the eyes typically land in a word is different from the optimal viewing location, which is the location in the word at which recognition time is minimized. According to O'Regan and Levy-Schoen (1987), the optimal viewing position is a bit to the right of the preferred viewing location, closer to the center of the word. Fourth, while contextual constraint influences skipping, in that highly predictable words are skipped more than unpredictable words (Balota et al., 1985; Ehrlich & Rayner, 1981), contextual constraint has little influence on where the eyes land in a word (Rayner et al., 2001)². Fifth, and finally, the landing position on a word is modulated by the *launch site* (McConkie et al., 1988; Radach & Kempe, 1993; Radach & McConkie, 1998; Rayner, Sereno, & Raney, 1996) as the landing position varies as a function of the distance from the prior fixation. As the launch site moves further from the target word, the distribution of landing positions shifts to the left and becomes more variable (see Fig. 2).

Insert Figure 2 here

2.7.B When to move the eyes. The ease or difficulty associated with processing a word influences when the eyes move. A very robust finding is that readers look longer at low-frequency words than at high-frequency words (Altarriba, Kroll, Sholl, & Rayner, 1996; Henderson & Ferreira, 1990, 1993; Hyona & Olson, 1995; Inhoff & Rayner, 1986; Just & Carpenter, 1980; Kennison & Clifton, 1995; Lavigne, Vitu, & d'Ydewalle, 2000; Raney & Rayner, 1995; Rayner, 1977; Rayner & Duffy, 1986; Rayner & Fischer, 1996; Rayner & Raney, 1996; Rayner et al., 1996; Rayner et al., 1998; Sereno, 1992; Vitu, 1991). There are three additional points with respect to this finding that are relevant. First, there is a *spillover* effect associated with fixating a low-frequency word as

fixation time on the next word is inflated (Rayner & Duffy, 1986). Second, although the duration of the first fixation on a word is influenced by the frequency of that word, the duration of the prior fixation is not (Carpenter & Just, 1983; Henderson & Ferreira, 1993; Rayner et al., 1998). Third, high-frequency words are skipped more than low-frequency words, particularly when they are short and the reader is fixated close to the beginning of the word (O'Regan, 1979; Rayner et al., 1996).

A second important finding is that there is a predictability effect in addition to a frequency effect. Words that are highly predictable from the preceding context are fixated for less time than are words that are not so constrained (Altarriba et al., 1996; Balota et al., 1985; Binder et al., 1999; Inhoff, 1984; Lavigne et al., 2000; Rayner et al., 2001; Rayner & Well, 1996; Schustack et al., 1987; Zola, 1984). Generally, the strongest effects of predictability on fixation time are not as large as those of the strongest frequency effects. Also, as we noted above, predictability has a strong effect on word skipping: Words that are highly predictable from the prior context are skipped more than words that are not so constrained.

2.8 Measures of processing time. To investigate the components of reading, researchers typically have subjects read sentences or passages of text while an eye tracker interfaced with a computer records the locations and durations of individual fixations. Because an average college-level reader can read approximately 300 words per minute (Rayner & Pollatsek, 1989), this technique produces a staggering amount of data. Accordingly, the data are usually reduced to *word-based measures*, which are across-subject averages that reflect how often and for how long individual words are fixated. A number of word-based measures are standard (Inhoff & Radach, 1998; Rayner, 1998; Rayner, Sereno, Morris, Schmauder, Clifton, & Rayner, 1989). The first is *gaze duration*, which is defined as the sum of all fixations on a word, excluding any fixations after the eyes have left the word (i.e., including only *refixations* before the eyes move on to another word). Gaze duration is usually averaged only over words that are fixated, and not skipped, during the initial encounter (or *first pass*) through that region of text. Two other common measures are *first-fixation duration* and *single-fixation duration*. The former is the duration of the first fixation on a word (again conditional on the word being fixated during the first pass through the text), while the latter is the average fixation duration on words that are fixated exactly once during the first pass. These indices are typically reported along with indices of how often a word was fixated: The probability of a word being skipped, fixated once, and fixated more than once before moving to another word. Often the *total time* (the sum of all fixations on the word, including regressions back to the word) is also reported.

The word-based measures provide a complete record of where and when fixations occurred. These two parameters (where vs. when) also provide a useful framework for organizing a discussion of reading models because much of the controversy surrounding reading concerns the determinants of where and how long the eyes remain fixated. The models that have been developed to explain eye movement control can be separated into two classes: Those in which eye movements are determined primarily by oculomotor factors (*oculomotor models*), and those in which eye movements are guided by some form of cognitive control (*processing models*). Prior to comparing different models, we will discuss our model, E-Z Reader (Pollatsek, Rayner, Fischer, & Reichle, 1999; Rayner, Reichle, & Pollatsek, 1998, 2000; Reichle et al., 1998, 1999; Reichle & Rayner, 2001) in some detail.

3.0 E-Z Reader

E-Z Reader is a processing model, and extends the earlier work of Morrison (1984). Morrison drew much of the inspiration for his model from the work of Becker and Jürgens (1979)

and McConkie (1979). McConkie (1979) suggested that during reading, visual attention progressed across a line of text until the limitations of the visual system made it difficult to extract further lexical information. Once this point of difficulty has been established, attention shifts and an eye movement is programmed and subsequently initiated, sending the eyes to the problematic location. Although elegantly simple, the model was soon discarded due to problems in defining and explaining what the point of difficulty was and how it might be computed and whether it could be computed soon enough to be of any use in skilled reading (Rayner & Pollatsek, 1989).

The limitations inherent in McConkie's (1979) early model of eye movement control led Morrison (1984) to propose a model in which the movement of the eyes was a function of successful processing. According to Morrison, the identification of word_n (i.e., the word that is currently being fixated) causes the attention "spotlight" (Posner, 1980) to move to word_{n+1}, which in turn causes the oculomotor system to begin programming a saccade to word_{n+1}. If the program finishes before word_{n+1} is identified, then the saccade will be executed and the eyes will move to word_{n+1}. However, if word_{n+1} is identified before the program finishes, then the saccade to word_{n+1} can be canceled. This occurs when attention shifts to word_{n+2}, and the oculomotor system begins programming a saccade to word_{n+2}, which overrides the program to saccade to word_{n+1}. Thus, according to Morrison, attention moves serially, from word to word, whereas saccades can be programmed in parallel.

Morrison's (1984) assumption about parallel programming of saccades followed Becker and Jürgens' (1979) demonstration that saccadic programming is completed in two stages: An initial (labile) stage that is subject to cancellation, and an ensuing (non-labile) stage in which the program cannot be canceled. They showed that if the oculomotor system begins programming a saccade while another saccadic program is in its labile stage of development, then the first program is aborted. However, if the second program is initiated while the first saccadic program is in its non-labile stage, then both saccades will be executed, which typically results in a very short fixation between the two saccades.

With these simple assumptions, Morrison (1984) was able to provide an elegant account of both frequency effects and parafoveal preview effects: Because short frequent words are more easily identified in the parafovea than long infrequent words, the former tend to be fixated for less time (and skipped more often) than the latter. Despite its successes, however, Morrison's model cannot explain refixations because the strictly serial attention shifts cause each word either to be fixated exactly once or to be skipped. More fundamentally, however, because Morrison's model posits both strictly serial processing of words and that attention shifting is time-locked to word identification, the model is unable to handle some simple, robust phenomena in reading. The first is that one often gets "spillover" effects due to word frequency (e.g., Rayner & Duffy, 1986). That is, lower frequency words often not only cause longer fixations on that word (word_n, but also lengthen either gaze durations and/or first fixations on the succeeding word (word_{n+1}). According to Morrison's model, this shouldn't happen because attention doesn't shift until word_n has been processed. Because parafoveal processing on word_{n+1} begins after this attention shift, the amount of information extracted from word_{n+1} before it is fixated will only be a function of how long it takes to program and execute the saccade, and will not vary as a function of the frequency of word_n. As a result, Morrison's model predicts no delayed effects of word frequency (or any other effects of word processing difficulty). A related phenomenon (Henderson & Ferreira, 1990; Kennison & Clifton, 1995) is that the benefit gained through parafoveal preview decreases as foveal processing becomes more difficult (e.g., because the fixated word is lower frequency). By essentially the same argument

as above, Morrison's model predicts that this shouldn't happen because parafoveal preview time is only a function of the latency of moving the eye after covert attention has shifted.

There are at least three ways to circumvent the limitations of Morrison's (1984) model. The first is to add the assumption that if word identification is not completed by a processing deadline, attention does not shift to the next word, but instead remains on the current word, resulting in a refixation (Henderson & Ferreira, 1990; Sereno, 1992). This leads to the prediction (which has not been supported; Rayner et al., 1996; Schilling et al., 1998) that the first of two fixations should be longer than single fixations because the former reflect cases in which the processing deadline must have been reached. The second solution is to simply assume that difficulties with higher-order linguistic processing somehow cause the eyes to remain on the current word (Pollatsek & Rayner, 1990; Rayner & Pollatsek, 1989). Unfortunately, how this happens has not been well specified. Finally, a third way to avoid the shortcomings of Morrison's proposal is to assume that word identification is completed in two stages. This last approach is instantiated by E-Z Reader, which is discussed next.

3.1 *Overview of the E-Z Reader model.* E-Z Reader, like other processing models, shares the basic assumption that on-going cognitive (i.e., linguistic) processing influences eye movements during reading. Because the model was not intended to be a deep explanation of language processing, however, it does not account for the many effects of higher-level linguistic processing on eye movements (for reviews, see Rayner, 1998; Rayner & Sereno, 1994; Rayner et al., 1989). Although this is clearly a limitation, it should also be noted that many of these effects typically occur when the reader is having difficulty understanding the text that is being read, such as when a reader makes a regression to re-interpret a syntactically ambiguous "garden path" sentence (Frazier & Rayner, 1982). The model should therefore be viewed as the "default" reading process. That is, we view the process of encoding words to be the forward "driving engine" in reading, as the process of knitting the words into larger units of syntax or meaning would be too slow (whether successful or not) to be a signal to decide how and when to move the eyes forward for skilled readers. Hence, we posit that higher-order processes intervene in eye movement control only when "something is wrong" and either send a signal to stop moving forward or a signal to execute a regression. Hence, we view E-Z Reader as a simulation of what happens during reading when higher-level linguistic processing is running smoothly and doesn't intervene. One implication of this is that the model currently does not explain inter-word regressions.

In E-Z Reader, fixation locations are determined by a combination of visual, oculomotor, and linguistic factors, whereas fixation durations are primarily determined by linguistic processing. Five processes determine when and where the eyes move: (1.) a "familiarity check", (2.) the completion of lexical access, the (3.) labile and (4.) non-labile stages of saccadic programming, and (5.) the actual saccades. Crucially, unlike Morrison's (1984) model, word identification is completed in two stages. Figure 3 is a schematic diagram that illustrates how these five processes are related to the attention, word-identification, and oculomotor systems, and how control is passed among these processes as they are completed.

Insert Figure 3 here

The familiarity check and the completion of lexical access correspond to early and late stages of word identification, respectively. The *familiarity check* is a quick assessment of whether or not word identification is imminent, whereas the *completion of lexical access* corresponds to a later stage of identification, in which a word's identity has actually been determined. The distinction between

the familiarity check and the completion of lexical access is broadly consistent with the *activation-verification model* of lexical access (Paap et al., 1982), with the familiarity check corresponding to an initial, activation stage of lexical access, and the completion of lexical access corresponding to a later, verification stage.

The mean times required to complete the two stages of lexical processing are determined for each word, and are a function of two variables: (1.) each word's normative frequency of occurrence, and (2.) each word's predictability within the local sentence context. These two variables determine the mean durations (in ms) of the familiarity check, $t(f_n)$, and completion of lexical access, $t(lc_n)$, processes as follows:

$$t(f_n) = \{f_b - [f_m * \ln(\text{frequency}_n)]\} * (1 - \theta * \text{predictability}_n) \quad (1)$$

$$t(lc_n) = \Delta * \{f_b - [f_m * \ln(\text{frequency}_n)]\} * (1 - \text{predictability}_n) \quad (2)$$

where f_b (195 ms) and f_m (17 ms per $\ln[\text{frequency}]$ unit) are free parameters that determine the linear relationship between the process durations and the natural logarithm of word_n's frequency. Likewise, θ (0.5) is a free parameter that attenuates the degree to which predictability shortens the duration of the familiarity check stage, and Δ (= 0.85) is a free parameter that makes the duration of the completion of lexical access stage some multiple of the duration of the familiarity check stage. Finally, the actual times that are required to complete $t(f_n)$ and $t(lc_n)$ are determined stochastically by sampling random deviates from gamma distributions with means equal to $t(f_n)$ and $t(lc_n)$, respectively, and standard deviations equal to one third of their means.

Because words require more time to identify when they are viewed in the parafovea (Rayner & Morrison, 1981), the rate of lexical processing is also modulated by *foveal eccentricity*, or the distance between the center of the word that is being processed and the character position that is being fixated. This is done using:

$$\text{duration}(x) = \text{duration}_0 * e^x \quad (3)$$

where $\text{duration}(x)$ is the time required to complete lexical processing at a foveal eccentricity of x character spaces, and duration_0 is the time required to complete lexical processing when the eyes are fixated on the center of word_n. The free parameters ϵ (1.09 and 1.13 for the familiarity check and completion of lexical access, respectively) modulate the rate at which increases in foveal eccentricity slows lexical processing³. It is reasonable that later stages of lexical processing, which probably require more precise information, are slowed down somewhat more than the early stages are when acuity is poorer.

The *labile* and *non-labile* stages of saccadic programming refer to the motor commands that are necessary to move the eyes, contingent upon whether or not those commands can be canceled. This distinction is consistent with Becker and Jürgens' (1979) work, and allows the model to explain skipping. To understand this, imagine the case in which the eyes are fixated on word_n. After a certain amount of time, the familiarity check on word_n completes, and the oculomotor system begins programming a saccade to word_{n+1}. After completion of lexical access, word_n is identified, which causes attention to shift to the next word. At this point, one of two things will happen: (1) if the labile stage of the saccadic program finishes first, a saccade will be executed, and word_{n+1} will be fixated; or (2) if the familiarity check on word_{n+1} finishes first, the labile program will be canceled, and the oculomotor system will instead begin programming a saccade to word_{n+2}. This second sequence of events causes word_{n+1} to be skipped.

Another of the model's assumptions is that the oculomotor system immediately begins to program a second saccade to the center of the word being processed as soon as it is fixated. (This

is presumably the optimal viewing location.) A “race” between the familiarity check and the labile stage of saccadic programming, similar to the “race” described above, produces refixations, but only when processing of the word is slow. That is, if this program to fixate the center of word_n completes before the familiarity check on word_n, then an intra-word saccade will be executed, and word_n will be refixated (except in those cases where oculomotor error causes the eyes to overshoot their intended target; see below). However, if the familiarity check finishes before the labile stage of programming, then the intra-word saccade program will be canceled, and the oculomotor system will instead begin to program a saccade to the next word. Because the outcome of this “race” is largely determined by how rapidly the familiarity check can be completed, low-frequency words will tend to be refixated more often than high-frequency words. Moreover, because the duration of the familiarity check increases as a function of foveal eccentricity (see Equation 3), the probability of refixating increases as the distance between the location of the initial fixation and the optimal viewing position increases. The model thus provides a mechanism for O’Regan’s (1990, 1992) observation that, if the eyes fail to land on the optimal viewing position, then the oculomotor system will attempt to move the eyes to another position within the word so as to provide a better viewing location from which to identify the word, so that a refixation will be more likely if the initial landing position is “bad”.

Like the word-identification processes, the actual durations of the labile and non-labile programming stages, $t(m)$ and $t(M)$, respectively, are determined stochastically by sampling random deviates from gamma distributions having fixed means and standard deviations equal to 1/3rd of their means. Thus, the mean durations of $t(m)$ and $t(M)$ are free parameters (135 and 50 ms, respectively), as is the time required to complete a saccade (which was set equal to a fixed value of 25 ms).

As Figure 2 indicates, the distinction between the familiarity check and the completion of lexical access is important because the former signals the oculomotor system to cancel any pending saccades and to begin programming a saccade to the next word, whereas the latter causes attention to shift to the next word. However, it is important to point out that, by “attention,” we do not mean those mechanisms that are necessary for the spatial orientation of low-level visual processing; instead, we mean those mechanisms that are used in the service of word identification. The separation between these two types of attention has precedent in the literature (LaBerge, 1990); for example, Treisman (1969) distinguished between *input selection*, which refers to the mechanisms involved in spatial orientation, and *analyzer selection*, which refers to the mechanisms that enhance target identification. This distinction is important for several reasons: First, the evidence which suggest that saccades to particular target locations are preceded by attentional shifts to the same locations (Hoffman & Subramaniam, 1995; however, see Stelmach, Campsall, & Herdman, 1997) are not inconsistent with our assumption that saccadic programming (which may require input selection to be moved to a new spatial location) is decoupled from the shifting of attention, or analyzer input.

The second ramification of this decoupling is that E-Z Reader, like Morrison’s (1984) model, maintains the assumption that word identification is serial; that is, attention is repeatedly disengaged and shifted from word to word so that each word can be identified and then integrated into the sentence representation. Although the results of several recent experiments (Kennedy, 1998, 2000; Inhoff, Starr, & Shindler, 2000; Starr, 2001) suggest that properties of two words (particularly visual/orthographic properties) can sometimes be encoded in parallel, we suspect that this does not

usually occur in normal reading. Serial processing instead preserves the temporal organization of the text, thereby enabling linguistic processing and comprehension.

Finally, by decoupling eye movements from attention, our model can explain aspects of eye movement control that Morrison's (1984) model could not. For example, E-Z Reader can explain why parafoveal preview benefit decreases as foveal processing difficulty increases (Henderson & Ferreira, 1990; Kennison & Clifton, 1995). If the eyes are on word_n, parafoveal processing of word_{n+1} begins, not with completion of the familiarity check, but after the completion of lexical processing of word_n, and ends with the onset of the saccade to word_{n+1}. As Figure 4 illustrates, the disparity between word_n's familiarity check duration and the time required to complete lexical access increases as the normative frequency of word_n decreases (see Equations 1 and 2). Notice, however, that the time required to initiate a saccade to word_{n+1} is not modulated by word frequency, so that the saccadic latency will (on average) follow the familiarity check by 185 ms (i.e., the sum of the labile and non-labile saccadic programming durations). Thus, with other things being equal, the amount of time available for parafoveal processing of word_{n+1} decreases as the frequency of word_n decreases (or becomes more difficult).

Insert Figure 4 here

As described thus far, fixation durations are largely determined by lexical processing. Fixation locations on words, however, are largely subject to visual and oculomotor constraints. In E-Z Reader, these factors determine fixation locations in a manner suggested by McConkie and his colleagues (1988, 1991): Saccades are always directed towards the optimal viewing position within the intended word targets (O'Regan, 1990, 1992), but because of both random and systematic motor error, the saccades often deviate from their targets. Thus, occasionally an unintended word may be fixated. The length of the saccade that is actually executed is the sum of three components:

$$Saccade = PSL + SRE + random\ error \quad (4)$$

where *PSL* is the programmed saccade length (in character spaces), *SRE* is the systematic range error, and the final term is a random error component. The systematic range error, *SRE*, is given by:

$$SRE = (\Psi - PSL) [\Omega_b - \ln(\text{fixation duration}) / \Omega_m] \quad (5)$$

where Ω_b and Ω_m are free parameters that specify the degree to which the natural logarithm of the launch site fixation duration modulates the size of the systematic range error. The values of these parameters (7.3 and 4.5, respectively) were selected so that the systematic range error would decrease as the fixation duration on the launch site increased. The parameter Ψ determines the saccade length for which saccades neither undershoot nor overshoot their intended targets. On the basis of previous research (McConkie et al., 1988), the value of Ψ was set equal to 7. Finally, the *random error* component in Equation 4 is sampled from a Gaussian distribution with $\mu_{random\ error} = 0$ and $\sigma_{random\ error}$ given by:

$$\sigma_{random\ error} = \beta_b + (\beta_m * PSL) \quad (6)$$

where β_b and β_m are free parameters that specify how much the random error component increases with programmed saccade length. The values of β_b (0.85) and β_m (0.11) were also broadly consistent with those that have been reported elsewhere (Kowler, 1990).

3.2 Simulation results. The model's performance was evaluated using the data from an eye-tracking experiment in which 30 college students read 48 sentences containing 8-14 words each (Schilling et al., 1998). Because regressions are outside of the scope of our model, we did not include data from sentences in which readers made interword regressions. We then calculated the token frequency (i.e., number of occurrences per million; Francis & Kučera, 1982) for each word

in the sentence corpus. (For example, the word “torpedo” is used very infrequently, and occurs only once per million words of text, whereas “the,” the most frequent word in the English language, has a token frequency of 69,975 per million.) We also completed a separate *cloze* task experiment (i.e., in which participants had to guess the identity of word_{n+1} given the sentence up through word_n) to determine each word’s mean predictability within its sentence context. Finally, the words were divided into five frequency classes (see Table 1).

The first set of simulations (Reichle et al., 1998) evaluated the model’s capacity to predict the temporal dynamics of eye movements during reading. Overall, these simulations were very successful. The model predicted the mean values of six word-based measures (gaze, first-fixation, and single-fixation durations, and the probabilities of skipping, making a single fixation, and refixating) for the five frequency classes of words (see Table 1), and it generated gaze duration and first-fixation duration distributions that closely resembled those that were observed in the data. Although this is not entirely surprising given the prominent role of word frequency in Equations 1 and 2, the model also generated frequency effects that closely resembled those reported by Schilling et al. (1998) on length-controlled target words (see Table 2). Moreover, the model produced both spillover effects and preview effects that were comparable to those reported in the literature (see Table 3). Finally, as Table 3 also shows, the model predicted a processing cost, or gaze duration increase, on word_n for skipping word_{n+1}, as well as a similar cost on word_n for having skipped word_{n-1}. Although both predictions were confirmed in the data, the latter finding is noteworthy because it had not been previously reported in the literature.

Insert Tables 1-3 here

The second set of simulations (Reichle et al., 1999) evaluated the model’s capacity to account for the spatial properties of eye movements during reading. To do this, we examined the landing site distributions that were generated by the model on 4-, 5-, 6-, and 7-letter words (again using the Schilling et al., 1998, sentences). As Figure 5a indicates, the predicted landing site distributions closely resembled those reported by McConkie and his colleagues (1988, 1991; see Fig. 2): The landing sites were normally distributed with means that tended to shift towards beginnings of the words as the distance between the launch sites and landing sites increased. As Figure 5b indicates, the magnitude of this leftward shift was also modulated by the duration of the launch fixation, so that longer fixations on the launch site attenuated the effect of saccade length. These simulation results thus contradict Reilly and O’Regan’s (1998) claim that processing models cannot explain the patterns of landing site distributions that are normally observed during reading. Finally, as Figure 5c shows, the model predicted fewer refixations following initial fixations near the centers of words. As already mentioned, this happens because fixations near the optimal viewing position generally allow the familiarity check to be completed very rapidly, so that the eye movement system begins programming an interword saccade (to the next word) rather than the default intraword saccade (which would result in a refixation). Such parabolic patterns of refixation probabilities have been reported in the literature (McConkie et al., 1988; Rayner et al., 1996).

Insert Figure 5 here

4.0 Alternative Models of Eye Movement Control

4.1 *Oculomotor models.* In stark contrast to E-Z Reader and other processing models (which are reviewed below), oculomotor models do not assign language processing a prominent role in guiding eye movements during reading. Instead, oculomotor models share the core principle that visual properties of the text (e.g., word length) and operating characteristics of the visual and

oculomotor systems (e.g., visual acuity, saccade accuracy) largely determine fixation locations. An auxiliary assumption is that fixation durations are largely determined by where the eyes have fixated.

4.1.A. *Strategy-tactics*. One such account of eye movement control in reading is provided by the *strategy-tactics model* (O'Regan, 1990, 1992; O'Regan & Lévy-Schoen, 1987). This model originated from two observations: First, words are identified most rapidly if they are fixated slightly to the left of center, on the *optimal viewing position*; and second, words are also less likely to be refixated if they are initially viewed from this position. These results lead O'Regan to suggest that readers adopt a "strategy" of directing their eyes from word to word, in an attempt to fixate each word's optimal viewing position. This "risky" variant of the basic reading strategy can also be supplemented with a "careful" variant that includes the following within-word "tactic:" If the eyes do not land near the optimal viewing position, then immediately move them to the other end of the word. Using this tactic ensures that every word will either be viewed from its optimal position (in the case of single fixations) or will be viewed from two different locations (in the case of refixations).

Because the within-word tactics are guided by visual factors (e.g., word length), the model predicts that linguistic variables (e.g., word frequency) (1) should only modulate fixation durations when there is a single long fixation or when the fixation is the second of the two, and (2) should not modulate refixation probabilities. Unfortunately for the strategy-tactics model, neither of these predictions has been confirmed. Rayner et al. (1996) found that word frequency effects were evident in the first of two fixations (see also Sereno, 1992) and that refixations were more likely on low-frequency words than on high-frequency words (with length controlled). In addition, Rayner et al. found that neither fixation durations nor frequency effects on single-fixations varied as a function of landing position, which suggests that the optimal viewing position may be much less important in normal reading than in the identification of single words when they are presented in isolation (see also Vitu, O'Regan, & Mittau, 1990).

4.1.B. *Word-targeting*. A second class of oculomotor theories was largely motivated by the seminal work of McConkie and his colleagues (McConkie et al., 1988, 1989, 1991; Radach & McConkie, 1998). As mentioned previously, they expanded upon the observation that readers typically fixate the preferred viewing location (Rayner, 1979) and found that landing site distributions behaved very systematically with respect to both the saccade length and the launch site fixation duration. These findings led McConkie and his colleagues to conclude the following: First, the shape of the landing site distributions (which resembled truncated Gaussian distributions; see Fig. 2) reflects random noise in the oculomotor system, with the missing tails being due to cases in which the eyes under/overshot their intended targets. The oculomotor system is also biased to make saccades approximately seven character spaces in length, so that longer saccades tend to undershoot their targets, while shorter saccades tend to overshoot their targets. This systematic range error causes the distributions to shift towards the beginnings of words as the launch site becomes more distant from the intended saccade target. With longer launch site fixation durations, however, the eye movement system has more time to plan its saccades; the resulting increase in saccadic accuracy, in turn, reduces the systematic range error.

The relationships among saccade length, the duration of the launch site fixation, and saccadic accuracy led to the development of precise mathematical descriptions of how these variables affect the landing site distributions during reading (McConkie, Kerr, & Dyre, 1994). Although there have also been attempts to provide similar mathematical descriptions of fixation durations (McConkie et

al., 1994; McConkie & Dyre, 2000; see also Brysbaert & Vitu, 1998), these accounts are little more than precise descriptions of the data, and do not attempt to explain how linguistic processing affects fixation durations during reading. Also, because these descriptions address the “where?” and “when?” questions of eye movement control independently, they fail to explain why the durations of fixations are related to their spatial locations.

Recently, however, several word-targeting strategies were implemented as computer simulations (Reilly & O’Regan, 1998) so that various assumptions regarding eye movement control could be evaluated with respect to how well they handle the findings related to landing-site distributions (McConkie et al., 1988). These simulations included several alternative oculomotor (e.g., *word-by-word*, *target long words*, and *skip short words*) and processing strategies (e.g., *skip high-frequency words*). The results of these simulations indicated that the target-long-words strategy fit the landing-site distributions better than the other strategies, while the language-based strategies fared rather poorly overall. On this basis, Reilly and O’Regan proposed that language-processing models cannot provide an adequate account of eye movement control during reading. However, the language-based model that they implemented was little more than a straw man version of the early Morrison model and, as we indicated earlier, their claim that language-processing models cannot account for eye movement control is contradicted by our demonstration that E-Z Reader can, in fact, generate reasonable looking landing site distributions (Reichle et al., 1999).

4.1.C. *Minimal-control*. One final oculomotor account of eye movement control is provided by Suppes’ (1990, 1994) *minimal-control model*. In this model, neither fixation durations nor saccade lengths are affected by linguistic or cognitive factors, but are instead affected only by the physical layout of the text. The model consists of a small number of axioms that describe the fixation duration distributions and a random-walk process that determines where the eyes will move next.

The axioms describing fixation durations are as follows: First, the duration of each fixation is a function of the number of operations (which are never specified) that must be completed during each fixation. Second, fixation durations are stochastically determined by sampling from an exponential distribution if a single operation must be completed; in cases requiring two operations, the durations are described by the convolution of two independent exponential distributions. Finally, fixation times are independent of both earlier processing and the current text content. Thus, the model stipulates that variability in fixation durations is not due to variability in the duration of the underlying cognitive processing, but instead reflects the probabilistic nature of the processing.

Saccades are determined by a similar set of rules. First, if the processing within a region of regard has been completed, then the eyes are moved to the next word; otherwise, they remain in the same location. Second, if processing has not finished and the memory for a prior region of regard has decayed, then move the eyes back to the prior region. Third, if perceptual processing of the upcoming word has finished from the current location, then skip the upcoming word. Finally, each saccade is independent of earlier processing and previous saccades.

Unfortunately, the minimal-control model has only been used to simulate eye movements during an arithmetic task (Suppes, 1990; Suppes, Cohen, Laddaga, Anliker, & Floyd, 1982, 1983), so that it is difficult to evaluate its adequacy with respect to reading. It is clear, however, that the model only makes predictions on the level of individual words, and hence cannot account for either landing site distributions (McConkie et al., 1988) or the optimal viewing position effects (O’Regan, 1990). The model also fails to account for many other factors that are acknowledged by Suppes

(1994) to affect eye movements during reading.

In the final analysis, therefore, it is clear that the oculomotor models have provided important insights into the nature of eye movement control during reading. Moreover, the phenomena that these models have attempted to explain are important benchmarks for evaluating any model of reading. However, the models are limited; because they have focused on the roles of oculomotor and visual determinants of eye movement control, they have generally ignored language processing, which has also been shown (during the past three decades of research) to have important effects. Rather than being incorrect, therefore, the oculomotor models are incomplete because they provide only a limited account of the entire reading process.

4.2 *Processing models.* As already stated, the processing models differ from the oculomotor models in that they tend to emphasize the role of language processing in influencing eye movements during reading. Generally speaking, the decision about how long to fixate is determined by on-going linguistic processing, while the question of where to fixate is jointly decided by linguistic, visual, and oculomotor factors.

4.2.A. *Reader.* One of the most widely known processing models is *Reader* (Carpenter & Just, 1983; Just & Carpenter, 1980, 1987; Thibadeau, Just, & Carpenter, 1982). In contrast to the other models discussed in this article (including E-Z Reader), *Reader* attempts to explain reading in its entirety, including the low-level encoding of visual features, lexical processing, semantic and syntactic analysis, and the schema-guided comprehension and abstraction of key ideas that normally occurs during reading.

In *Reader*, eye movements are posited to be tightly linked to cognitive processing. This coupling is based on two assumptions: The first is the *immediacy hypothesis*, which stipulates that each word is processed to the farthest extent possible when it is fixated. The second assumption is the *eye-mind hypothesis*, which stipulates that the eyes remain fixated on a word until the processing on that word has been completed. Both the durations and locations of individual fixations are thus determined by the immediate processing of the word that is being fixated.

Reader was implemented as a computer simulation with a production-system cognitive architecture (Anderson, 1983; Anderson & Libiere, 1998; Newell, 1990). *Productions* are procedural condition-action pairs (i.e., if-then statements) that perform operations on units of declarative knowledge. For example, the production:

If ($\text{letter}_1 = \text{"m"} \ \& \ \text{letter}_2 = \text{"a"} \ \& \ \text{letter}_3 = \text{"n"} \text{"})$, then ($\text{word} = \text{"man"} \text{"})$

encodes the percept "man," so that the meaning of the word can then be retrieved from semantic memory. In *Reader*, the productions are activation-based; that is, they direct activation towards units of declarative knowledge. These units of declarative knowledge, in turn, have thresholds that must be exceeded if the information is to be "active" in working memory (and thereby satisfy the conditions of other productions). The values of these thresholds are adjusted to modulate the cost associated with using each production. For example, the thresholds of those productions that mediate lexical access are adjusted to reflect each word's normative frequency of occurrence, so that low-frequency words take longer to identify (and are consequently fixated longer) than high-frequency words. Also, in the most recent version of the model (Just & Carpenter, 1992), the amount of activation that is available to support processing is limited (and is a free parameter) so that individual differences in working memory capacity can be used to simulate individual differences in reading ability.

The major strength of the *Reader* model is its comprehensiveness. As mentioned above, the

model attempts to explain the entire reading process. The model therefore does reasonably well simulating a number of language-related reading phenomena, such as word-frequency effects, increased reading times on lexically ambiguous words, and the processing difficulties which are found with syntactically ambiguous sentences. Unfortunately, however, the model is extremely complex (it consists of 225 productions; Just & Carpenter, 1987), and hence lacks the conciseness and controllability of other computational models (e.g., the inner workings of the model are not transparent, and can only be described verbally). It is also difficult to evaluate the model's performance because it depends upon the complex interplay of productions, many free parameters, and the regression weights on several independent variables (e.g., whether or not a word is the first in a sentence) that are necessary to convert production cycles (arbitrary units of time) into processing time. Furthermore, the model only makes predictions about the locations of fixations at the level of individual words, using a composite measure (*gazes*) that counts skipping a word as zero duration in the average. This means that the model does not really make precise predictions about which word is fixated. In addition, apart from word-length effects, the model fails to account for any of the phenomena that are explained by the oculomotor models (e.g., landing site distributions).

In addition to the above shortcomings, Reader has been criticized because of the immediacy and eye-mind assumptions. With respect to the former, there is considerable evidence that the lexical processing of a word is often initiated before the word has been directly fixated (i.e., parafoveal preview; Balota et al., 1985; McConkie & Rayner, 1975; Pollatsek et al., 1992; Rayner, 1975). With respect to the eye-mind hypothesis, there is evidence that the normative frequency of word_n can modulate how long the eyes remain on word_{n+1} (Rayner & Duffy, 1986; Rayner et al., 1989). These *spillover effects* indicate that the eyes often leave a word before the processing of that word is complete, contrary to the eye-mind assumption. Thus, even if eye movements during reading are partially guided by language processing, the Reader model greatly over-simplifies how this occurs. Furthermore, the depth of linguistic processing assumed before the eyes are allowed to move seems somewhat implausible.

4.2.B. *Attention-shift*. A second processing model, the *attention-shift model* or *ASM* (Reilly, 1993), relaxes the assumption that linguistic processing and eye movement control are tightly coupled. As Figure 6 indicates, ASM is implemented as a pair of interacting connectionist (i.e., PDP; McClelland & Rumelhart, 1986; Rumelhart & McClelland, 1986) networks. The model's architecture consists of two single-layer networks that were trained using a back-propagation learning algorithm (Rumelhart, Hinton, & Williams, 1986). One network is responsible for word recognition; the other is responsible for programming saccades. As each word is identified, the lexical-encoding network signals attention to shift to the next word, so that it can be processed. The movement of attention, in turn, causes the saccadic-programming network to begin programming a saccade to the next word. In contrast to E-Z Reader, ASM does not allocate attention serially, from one word to the next. The attention "spotlight" is instead fixed in size, so that whatever falls within the spotlight will be the focus of attention. This means that, in cases where two or more short words follow in immediate succession, they both may be in the spotlight and thus more than a single word can be encoded on a given fixation.

Insert Figure 6 here

In ASM, the times needed to complete both lexical access and saccadic programming are determined by the number of cycles that the two networks require to settle into stable activation patterns. As in E-Z Reader, the visual input to the word recognition is affected by retinal acuity

limitations. Thus, the activation patterns that represent letter features become more “degraded” (i.e., the activation values of the units representing the letters decrease and are more prone to noise) as they are encoded further from the fovea, especially for letters that share many features with other letters. This degradation allows the model to account for the finding that word identification becomes more difficult as the distance between the word and the fovea increases (Morrison & Rayner, 1981).

Although Reilly (1993) does not provide a detailed account of his model’s performance, it does simulate a few of the basic phenomena related to eye movement control in reading. For instance, the model generates mean fixation durations and saccade lengths that are in close agreement to values that have been reported in the literature. In contrast to E-Z Reader, however, ASM is not fitted to the various word-based measures, nor has it been shown to generate means and distributions for the different frequency classes of words. Nonetheless, because the amount of training that the word-recognition module receives on each word is proportional to each word’s frequency of occurrence, the model does predict that low frequency words are fixated longer than high frequency words. Moreover, because two successive short words are sometimes encoded in parallel, the model is able to account for the skipping of short (and typically high frequency) words, as well as parafoveal preview benefit. As mentioned earlier, though, ASM does not account for either of these phenomena the same way that E-Z Reader does. In E-Z Reader, skipping occurs whenever the fixated word has been identified, attention has shifted to the next word, and this word has also been identified (in the parafovea). In contrast to E-Z Reader, there is nothing in ASM to account for how highly predictable words than are not short could be skipped.

Finally, like E-Z Reader, saccadic programming in ASM is prone to noise, so that individual words can be refixated and/or skipped due to simple oculomotor error. Reilly (1993) has not, however, demonstrated that the model can reproduce the complex dependencies between the locations and durations of launch sites and the landing site distributions. We therefore contend that, unlike E-Z Reader, ASM does not provide an adequate account of the visual, oculomotor, and language-processing determinants of eye movement control in reading.

4.2.C. *Mr. Chips*. A third processing model, *Mr. Chips* (Legge, Klitz, & Tjan, 1997; Klitz, Legge, & Tjan, 2000), represents a very different approach to understanding the inter-relationships among visual processing, word recognition, and eye movement control during reading. The model was proposed as a means to evaluate how an *ideal-observer* (i.e., a reader with perfect lexical knowledge and a well specified goal: maximizing reading speed) would move his/her eyes. The model does this using three pieces of information: First, input from a “retina” that encodes a small number of letters in the fovea and indicates whether letters in the periphery are present or absent. The second piece of information is knowledge about the relative frequencies with which words occur in text. Finally, the model knows the likelihood of making a saccadic error of a given size for each given saccade length. These three types of knowledge are depicted in Figure 7.

Insert Figure 7 here

Mr. Chips attempts to use all of the information that is available from a particular fixation location to identify the next word in text using the fewest saccades possible. To do this, the model calculates the expected uncertainty that is associated with being able to identify a word for saccades of each possible length. It then executes a saccade that minimizes this uncertainty. For example,

imagine that the model has the following information about a word: It is five letters long and begins with “abo” (see Figure 7). The model uses this information in conjunction with its lexical knowledge to calculate conditional probabilities of the letter string being each of the words that satisfy these constraints. This is done using Equation 7:

$$p_i = P_i / \sum_j P_j \quad (7)$$

where p_i is the conditional probability of the letter string being word_{*i*}, P_i is the absolute probability of the letter string being word_{*i*}, and the P_j s are the absolute probabilities of the letter string being each of the other candidate words. In the Figure 7 example, the conditional probability that “abo--” is “about” is $p = 0.849$.

The conditional probabilities are then used to compute the conditional entropy, or degree of uncertainty, H , that would result from a saccade of length, L , under the assumption that the letter string is word_{*i*}:

$$H(L, \text{word}_i) = -\sum_j p_j \log_2(p_j) \quad (8)$$

For example, from the current fixation, the entropy associated with the letter string is $H(0, \text{abo--}) = 0.613$. (Smaller entropy values represent less uncertainty about the identity of a word, so that identification occurs with certainty when the entropy value associated with a letter string equals zero.) A saccade of $L = 1$ would reveal one letter, which, given the model’s lexical knowledge, must be either “u” or “v.” If the letter is “u,” then the conditional probability of the word being “about” is $p = 1$, and the conditional entropy would be reduced to $H(1, \text{about}) = 0$. Likewise, if the letter is “v,” then the conditional entropy would also be reduced to $H(1, \text{above}) = 0$.

After the conditional entropies are calculated for each possible saccade length, Mr. Chips computes a probability-weighted average to determine the expected entropy associated with a saccade of each given length. This is done using Equation 9:

$$H(L) = -\sum_i p_i H(L, \text{word}_i) \quad (9)$$

In the example, $H(L) = 0$ for saccades of lengths 1-5. Because of saccadic error, however, each saccade of intended length L has an associated landing-site distribution, $P_L(x)$, which determines the probability of making a saccade of actual length x . The model uses this knowledge to calculate the entropy associated with each saccade length, L , averaged across all of the possible landing sites. This gives the expected uncertainty, H_L , associated with making a saccade of intended length L :

$$H_L = \sum_i P_L(x) H(x) \quad (10)$$

Finally, the model makes the saccade that minimizes H_L , and thereby maximizes the probability of identifying the word. In cases where more than one possible saccade yields the same expected entropy, Mr. Chips executes the longest saccade possible so as to maximize reading speed.

Because Mr. Chips was only developed with the intent of examining the way lexical knowledge and restrictions on visual encoding affect saccade lengths and fixation locations, the model does not address the “when?” question of eye movement control. Several of the model’s emergent properties, however, are consistent with research findings about where the eyes move. For example, the model predicts that the mean saccade length will be around seven character spaces (McConkie et al., 1988), and that saccades will tend to be directed towards the optimal viewing position (O’Regan, 1990). The model also predicts parafoveal preview effects because the left-most letters of upcoming words are often identified before the words are actually fixated.

Unfortunately, it does not seem plausible that human readers compute the expected amount of information to be gained from each possible saccade length so as to make the saccade that

maximizes this gain. Klitz et al. (2000) acknowledge this fact, and say that their model “is not intended as an exact model of how humans perform a task, but rather establishes an upper bound (i.e., a level of competence) for human performance.” Furthermore, the Mr. Chips algorithm is well approximated by the simple heuristic of left-justifying the target word in the high-resolution part of vision, so that, on some level, the model is psychologically plausible.

Moreover, it is important to point out that Mr. Chips, unlike the other models discussed in this article, was developed to investigate how visual impairment might affect eye movements during reading. In this capacity, the model has been successful (Klitz et al., 2000). A comparison of the model’s performance to that of a human in a reading task⁴ with a simulated *scotoma* (i.e., a blind spot in the visual field) indicated that, in contrast to the model, the human had difficulty integrating information across central scotomas more than a single character-space in size. The human reader appeared to primarily use visual information from one side of the scotoma and use the visual strategy of moving the eyes in order to place the region of normal vision over all of the character spaces in turn, rather than using lexical knowledge to winnow down the possible identities of letter strings from a single fixation. Although the human reader’s natural strategy produced shorter saccades, it markedly increased reading speed over when they tried to execute the Mr. Chips strategy. These analyses, therefore, suggest that, while the seemingly erratic eye movements of readers with scotomas do not allow the maximal amount of information to be extracted from the page during each fixation, they are nevertheless adaptive in that they allow a maximal overall rate of information extraction.

In summary, the processing models extend the theoretical coverage of the oculomotor models by attempting to specify how *the* key component of reading - word identification - affects (and is affected by) vision and the oculomotor system. This is important because a large number of linguistic variables have well-documented effects on eye movements during reading (for reviews, see Rayner, 1998; Rayner & Duffy, 1988; Rayner & Sereno, 1994). Indeed, much of the interest surrounding the use of the eye-tracking methodology is that it affords a relatively non-intrusive, on-line way to study language processing. Of course, the processing models are not equally successful in handling the phenomena addressed by the oculomotor models. Table 4 lists the various eye-movement phenomena that have been observed during reading, and which our model, E-Z Reader (Reichle et al., 1998, 1999), explains. Table 4 also summarizes the performance of the other reading models with respect to these phenomena. On the basis of our analysis, we conclude that E-Z Reader provides the most comprehensive and complete theory of eye movement control in reading. In the final section of this paper, we will briefly discuss the possible roles that E-Z Reader may play in future reading research.

Insert Table 4 here

5.0 Future Research

In this section, we will focus on a few of the ways that the E-Z Reader model may be used to guide future reading research, and, conversely, how this research may guide the development of future reading models. This discussion will focus on four main issues. First, we will briefly discuss how the model has been used as a analytical tool to examine key assumptions about eye movement control in reading. Second, we will consider how the basic assumptions of the model might be used to examine other task domains, such as scene perception, which depend upon many of the same cognitive processes as reading (e.g., eye movements, object identification, etc.). The third issue concerns language processing and, more specifically, a discussion of the ways in which the model

might be used to better understand higher-level linguistic processing in the context of natural reading. Finally, we will consider how recent advances in cognitive neuroscience have influenced our understanding of eye movement control in reading, and then speculate on how the E-Z Reader model might be conceptualized in light of this new information.

5.1 Eye movement control during reading. One virtue of computational models is that they can be used to answer questions that, because of their very complexity, might otherwise be too difficult to even ask. For instance, Engbert and Kliegl (2001) sought to evaluate the basic assumption in E-Z Reader that lexical processing is the “engine” driving eye movements during reading. That is, they wanted to know if the time course of saccades is always determined by the time course of lexical processing. To answer this question, they implemented a computational model that, like E-Z Reader, accounts for eye movement control during reading in terms of a few assumptions about lexical access and saccadic programming. There are two versions of the model, a two-state and a three-state version. The former is quite similar to a simpler version of E-Z Reader (Model 2 in Reichle et al., 1998), but there is no separate familiarity check stage, and it makes somewhat different assumptions about the variability of processes. The three-stage model is similar to the version of E-Z Reader that we are discussing except that, functionally, the familiarity check is replaced by an all-or-none process. That is, the reader is either assumed to wait until lexical access is completed before programming a saccade or an “autonomous saccade” (i.e., completely independent of lexical processing) is executed. This all-or-none process (i.e., fully process the word before making a saccade or don’t pay any attention to lexical processing) contrasts with E-Z Reader, in which the signal to make the saccade is partial lexical processing of the attended word.

The basic model was first fitted to the same sentences (taken from Schilling et al., 1998) that were used to evaluate E-Z Reader. The model successfully predicted the mean fixation durations and skipping rates for the five frequency classes of words, and in so doing demonstrated that the state transitions can in fact be described using different distributional assumptions (i.e., residence-time dependent probabilities). Because these residence-time dependent probabilities can be implemented as an exact algorithm, whereas sampling from gamma distributions cannot, the model advances our understanding of eye movement control by providing something like a process model of where the variability is coming from. The introduction of autonomous saccades in the three-state model marginally improved the ability of the model to fit frequency effects on both gaze durations and probability of word skipping. It also allows the model to (at least qualitatively) predict other phenomena that the E-Z Reader model can predict such as spillover effects and word frequency effects on preview benefit. However, it is by no means clear that this improvement can be taken as evidence for the existence of autonomous saccades during reading (as Engbert & Kliegl claim) since E-Z Reader predicts the same phenomena by positing the familiarity check stage.

5.2 Other tasks. In the context of reading, eye movements have primarily been used to study language processing. However, eye movements have also been used in other tasks (e.g., visual search, scene perception, etc.) to study other aspects of cognition, such as high-level vision, attention, and working memory. Because reading depends upon many of the same cognitive systems (Rayner, 1998), it seems reasonable that many of the basic principles that were used to develop models of eye movement control in reading might be adapted to provide a theoretical framework for understanding these other tasks. This is important because, if a model of one domain can be used to inform our understanding of another, then (all else being equal) our confidence in the model should also increase. A few examples of how several of the basic principles of E-Z Reader are being

used to inform our understanding of other task domains are discussed next.

5.2.A. *EMMA*. Salvucci (2000a, 2000b) has recently extended the core principles in E-Z Reader to provide a general theory of the interrelationships among cognition, attention, and eye movements. This model, *EMMA* (Eye Movements and Movements of Attention), has been implemented within the ACT-R/PM production-system architecture (Anderson & Lebiere, 1998; Byrne & Anderson, 1998). In *EMMA*, the encoding time for both words and objects, T_{enc} , is given by Equation 11:

$$T_{enc} = K [-\log(\text{frequency})] e^{k\epsilon} \quad (11)$$

where the frequency of occurrence is scaled within the range (0, 1), ϵ is the eccentricity of the word or object (as measured by the angular distance between it and the fovea), and K and k are free parameters which scale the encoding time and eccentricity parameter, respectively. *EMMA* shares the following assumptions with E-Z Reader: First, encoding times are a function of both normative frequency and foveal eccentricity. Second, the actual amount of time that is required to encode a given object or word is determined stochastically by sampling random values from gamma distributions having fixed means (cf. Equations 1 & 2, in E-Z Reader, and Equation 11, in *EMMA*) and standard deviations. Third, saccadic programming is completed in two sequential stages (the first being subject to cancellation by subsequent programs, the second not), the durations of which are sampled from gamma distributions having fixed means and standard deviations. Finally, although saccades are directed towards the centers of their intended targets, they often deviate from their targets because of Gaussian motor error.

5.2.B. *Non-reading tasks*. Although *EMMA* and E-Z Reader share many common assumptions, there are also a few notable differences. First, in contrast to E-Z Reader, the encoding time in *EMMA* is not modulated by predictability, so that the model cannot account for predictability effects (Balota et al., 1985; Ehrlich & Rayner, 1981; Rayner & Well, 1986). Second, the distinction between the familiarity check and the completion of lexical access in E-Z Reader corresponds to the encoding and cognitive-processing stages in *EMMA*, respectively. As cognitive processing completes, it directs the visual system to encode additional information. However, because only the rate of encoding (and not cognitive processing) is modulated by normative frequency, *EMMA* cannot account for the interaction between parafoveal preview benefit and foveal processing difficulty (Henderson & Ferreira, 1990). Finally, in *EMMA*, foveal eccentricity is measured in terms of angular disparity rather than character spaces. Although this last difference between the two models is largely cosmetic, it allows *EMMA* to simulate tasks other than reading.

So far, *EMMA* has successfully predicted the patterns of fixation durations and locations in equation solving (i.e., mental arithmetic) and visual search (i.e., subjects scan visual arrays and indicate the presence of pre-defined targets) tasks. *EMMA* has also been fitted to the same six word-based measures used to evaluate E-Z Reader (i.e., the mean fixation duration and fixation probability values observed in the Schilling et al., 1998, sentence corpus). In each of these tasks, the core principles governing attention and eye movements were the same, and only the productions mediating the central, or cognitive, components of the tasks were changed. We view the successes of *EMMA* as being very encouraging because they suggest that the core principles of the model (which are shared by E-Z Reader) are general enough to describe the link between cognitive processing and eye movements in a variety of task domains. These successes also provide converging evidence supporting the validity of the basic principles shared by E-Z Reader and

EMMA. However, the link between cognitive processes and eye movements might not be as tight in tasks where there are no externally composed task demands (such as scene perception).

5.3. *Language processing.* With respect to our understanding of reading, the fact that the core principles of E-Z Reader have been adapted to several different task domains also suggests that, as better quantitative models of language processing are developed, these models could be interfaced with the E-Z Reader model as it is currently implemented. This would undoubtedly be beneficial for two reasons: First, the development of the language models could also be guided by what is known about eye movements during reading. Second, because a large number of higher-level language processing phenomena are known to affect eye movements during reading (see Rayner, 1998, Table 2), the capacity to simulate these results using language models could provide additional benchmarks for evaluating future models of eye movement control. Two examples of this bootstrapping approach to understanding reading and language are discussed below.

5.3.A *Lexical ambiguity.* There are now a large number of eye movement studies (Binder & Rayner, 1998; Dopkins, Morris, & Rayner, 1992; Duffy, Morris, & Rayner, 1988; Kambe, Rayner, & Duffy, 2001; Rayner & Duffy, 1986; Rayner & Frazier, 1989; Sereno, 1995; Sereno, Pacht, & Rayner, 1992; Wiley & Rayner, 2000) that have examined how lexically ambiguous words are processed during reading. The basic findings from this research suggest that both meaning dominance and contextual information influence the processing of such words. For ambiguous words (like “straw”) where there are two equally likely meanings, readers’ gaze durations are longer on such words in neutral contexts than on a control word matched in length and word frequency. However, when the prior context disambiguates the meaning that should be instantiated, gaze durations are no longer than on the control word. Thus, the contextual information helps the reader choose the appropriate meaning. For ambiguous words (like “bank”) where one meaning is much more dominant than the other, in neutral contexts readers look no longer at the ambiguous word than the control word. On the other hand, if the following parts of the sentence make it clear that the subordinate meaning should be instantiated, fixation times on the disambiguating information are quite long and regressions back to the target word are frequent (suggesting that the reader incorrectly selected the dominant meaning and now has to recompute the subordinate meaning). Conversely, when the disambiguating information precedes the biased ambiguous word and the subordinate meaning is instantiated, readers’ gaze durations on the ambiguous word are lengthened. Apparently, the contextual information increased the level of activation for the subordinate meaning so that the two meanings are in competition (just as the two meanings of a balanced ambiguous word like “straw” are in competition in a neutral context). This general pattern of results has been interpreted in the context of the reordered access model (Duffy et al., 1988) and the data have been simulated using a constraint-satisfaction framework (Duffy, Kambe, & Rayner, 2001).

Using the basic principles of the E-Z Reader model, we were able to successfully simulate the pattern of data present in these eye movement studies. However, the successful simulation was accomplished by (1) simply treating the subordinate meaning of ambiguous words as if readers were dealing with a low frequency word and (2) allowing disambiguating context to decrement the time required to complete the familiarity check and lexical access of ambiguous words. While we were able to nicely simulate the gaze duration on the ambiguous target words, we were unable to simulate an important finding from Sereno et al. (1992), namely that spillover fixations are much longer for ambiguous words than for words matched to the frequency of the subordinate meaning. We suspect that some type of competition mechanism (as in the Reordered Access model) will be necessary to

fully account for the pattern of data. The important point for this discussion is that we suspect that by implementing aspects of the reordered access model into the architecture of the E-Z Reader model that progress can be made in understanding lexical ambiguity resolution in reading.

5.3.B *Compound words.* A recent survey of prominent reading researchers indicated that one of the major areas of residual ignorance in the domain of reading research concerns the role of morphology in visual word identification (Kennedy, Radach, Heller, & Pynte, 2000). In the last few years, researchers have had some success investigating the role of morphology in word identification by examining how eye movements are affected by the morphemic variables during natural reading (Andrews, Miller, & Rayner, 2001; Hyönä & Pollatsek, 1998, 2000; Pollatsek, Hyönä, & Bertram, 2000). For example, Hyönä and Pollatsek (1998) examined the eye movements of Finnish readers while reading long compound words embedded in single sentences. The data indicated, among other things, that although the whole-word frequency influenced fixation durations on the word, the frequency of the constituent words of the compounds influenced fixation durations as well. Interestingly, the effect of the frequency of the second constituent was first seen a bit later in processing than the effects of either the frequency of the first constituent or the frequency of the whole word (i.e., on the duration of the second fixation on the word instead of the duration of the first fixation of the word). These findings suggest that access of the compounds is a “race” between a direct lexical look-up process and a compositional process in which the components are assembled (a similar conclusion comes from a study of English suffixed words, Niswander, Pollatsek, & Rayner, 2000). E-Z Reader, which already includes races between various components, is a natural framework to be expanded upon to explain such phenomena. However, expanding the model in this direction is non-trivial, as it entails positing that units smaller than “the set of letters between the spaces” can influence decision of when to move the eyes. Thus, among other things, one has to think carefully about which letter subsets of a word can play an active role in this decision. We are currently working on an expanded version of the model that will model these data.

5.3.C. *Other aspects of language processing.* Our discussions of lexical ambiguity and the role of morphology in word identification were meant to illustrate how our model of eye movement control might be used to advance our understanding of language-related phenomena. These two examples were selected because researchers in both of these areas have made extensive use of data from eye movement experiments. Of course, this is not to say that eye movements have not already been used in a productive manner to address other language-related questions; on the contrary, eye movements have been used to study a wide array of linguistic phenomena, including (but not limited to) other types of ambiguity resolution (e.g., syntactic and phonological ambiguity), semantic and repetition priming, anaphor and co-reference, and discourse processing (for reviews, see Rayner, 1998; Rayner & Pollatsek, 1989; Rayner & Sereno, 1994). We think that the E-Z Reader model will prove to be a useful platform from which to model these other psycholinguistic phenomena.

5.4 *Cognitive neuroscience.* As mentioned at the beginning of this section, the last decade has witnessed unprecedented advances in our general understanding of the mind-brain relationship. New methodologies, such as brain-imaging (e.g., PET, fMRI), electrophysiological recording (e.g., EEG), and single- and multiple-cellular recording techniques, have provided invaluable tools for examining the relationship between cognitive processes and their neural substrates. Likewise, new theoretical advances, such as those offered by biologically plausible connectionist models (McClelland & Rumelhart, 1986; Rumelhart & McClelland, 1986; Sejnowski & Churchland, 1992), promise to bridge the chasm that has until recently separated cognitive psychology from

neuroscience (Churchland, 1986). It therefore seems appropriate to consider how these recent advances in neuroscience will further our understanding of eye movement control in reading, and, conversely, how cognitive models of reading might be used to guide neuroscience research.

5.4.A *Neural systems*. There is a growing consensus that most high-level and/or complex cognitive processes (e.g., language processing) are supported by large-scale networks that are themselves composed of several cortical and subcortical regions (Mesulam, 1990, 1998; Posner & Raichle, 1997). Consequently, it is not surprising that reading (which subsumes a large number of complex cognitive operations) is mediated by several of these large-scale networks. In the specific case of reading, these include (minimally) the networks that support vision, attention, eye-movement control, and language. In this section, we will provide a brief overview of these systems, and then speculate about how the language-processing system might interface with the systems that are responsible for programming and executing saccades.

The most natural place to begin an analysis of the neural systems underlying reading is the printed page. Visual processing of the text begins in the retina and progresses by way of the optic nerve to the optic chiasm and then the optic tract. From there, the visual “stream” splits into two pathways: The first projects to the lateral geniculate nucleus, and then the occipital cortex; the second innervates several subcortical structures, including one that is known to play a key role in eye movements—the superior colliculus (Leigh & Zee, 1999; Sparks & Mays, 1990). On the basis of results from numerous electrophysiological recording experiments with non-human primates, it has been estimated that there are 30 or more distinct cortical areas involved in vision (Felleman & Van Essen, 1991; Maunsell & Newsome, 1987; Van Essen & DeYoe, 1995), although many of these areas perform functions that are less central to reading (e.g., color perception). However, the low-level visual features (which comprise graphemes) are extracted and represented within the primary visual and extrastriate cortices (Grill-Spector et al., 1998).

The visual-processing stream leaves the occipital cortex via two anatomically and functionally distinct pathways (Maunsell & Newsome, 1987; Sagi & Julesz, 1985; Ungerleider & Mishkin, 1982; Van Essen & DeYoe, 1995). The ventral, or “what,” pathway extends along the inferior temporal cortices, and is thought to play an important role in feature integration and object recognition (Ishai, Ungerleider, Martin, Schouten, & Haxby, 1999; Tanaka, 1996). Because words can be considered to be visual objects, the ventral system has also been implicated in the integration of those visual features which are necessary to represent visual word forms (Cohen et al., 2000; Poldrack, Desmond, Glover, & Gabrieli, 1998). However, the location of the word-form area(s) remains controversial (see Posner, Abdullaev, McCandliss, & Sereno, 1999a, 1999b; and Price, 1997), and there is some evidence suggesting that the left medial extrastriate cortex is also intrinsically involved in the recognition of word forms (Peterson, Fox, Posner, Mintun, & Raichle, 1989; Peterson, Fox, Snyder, & Raichle, 1990; Pugh et al., 2000).

The dorsal, or “where,” pathway is thought to represent spatial information, such as the relative positions and orientations of objects (Ungerleider, Courtney, & Haxby, 1998; Ungerleider & Haxby, 1994). (For this reason, the dorsal system may also provide an interface between perception and action; Goodale & Milner, 1992.) The dorsal pathway has also been implicated in visuospatial attention. In particular, the regions around the intraparietal sulci (i.e., the parietal eye fields) are thought to be central components of the visuospatial attention network. The other components include the superior colliculus (part of the mid-brain), the pulvinar nucleus of the thalamus, and a region that includes the precentral sulci/gyri and the posterior tips of the superior

frontal sulci (i.e., the frontal eye fields) (Corbetta, Miezin, Schulman, & Peterson, 1993; Goldberg, 1994; Leigh & Zee, 1999; Luna et al., 1998; Kim et al., 1999; Posner & Raichle, 1997; Rafal & Robertson, 1995; Sweeney et al., 1996). Recent neuroimaging and electrophysiological recording research suggests that this network is involved in both covert and overt shifts of visuospatial attention, and that covert attention is probably represented in motor (more specifically, eye movement) coordinates (Corbetta, 1998; Kim et al., 1999). This attention network also modulates both the analysis of objects in the ventral visual-processing pathway (Corbetta, 1998) and perceptual processing in the striate and extrastriate cortices (Somers, Dale, Seiffert, & Tootell, 1999).

Although much less is known about language than the other components of reading, a long history of neuropsychological evidence (Kaplan, 1992) and a large number of more recent neuroimaging experiments indicate that the left inferior frontal gyrus (*Broca's area*) and the posterior part of the left superior and middle temporal gyri (*Wernicke's area*) are the two major language-processing areas. Both areas are engaged by a variety of receptive and expressive language tasks, including: (a) reading (Bavelier et al., 1997; Binder et al., 1997; Just, Carpenter, Keller, Eddy, & Thulborn, 1996); (b) speech comprehension (Binder et al., 1997; Caplan, Alpert, & Waters, 1999; Schlosser, Aoyagi, Fulbright, Gore, & McCarthy, 1998; Stromswold, Caplan, Alpert, & Rauch, 1996); and (c) speech production (Bookheimer et al., 1997; Müller et al., 1997). The exact functional roles of these two language-processing areas are not known, but it has been suggested that Broca's area is involved in articulatory-syntactic processing, and that Wernicke's area supports lexical-semantic processing (Mesulam, 1990). This hypothesis is (in part) based on the close proximity between Broca's area and the primary motor cortex. Wernicke's area, which receives input from the primary auditory cortex, may play a large role in lexical processing, such as binding the phonological word forms to their semantic representations (which are distributed elsewhere in the associative cortex; Mesulam, 1998).

Because a single language network is presumably used to understand both written and spoken language, one of the central questions in reading research has been: How are graphemes on a printed page converted into linguistic-based codes? The results of several recent neuroimaging experiments suggest that the left angular gyrus (which is located in the posterior part of the inferior parietal lobule) plays a critical role in computing grapheme-to-phoneme correspondences (Horwitz, Rumsey, & Donohue, 1998; Pugh et al., 2000). Because the left angular gyrus lies at the juncture of the extrastriate cortex and Wernicke's area, it is ideally situated to convert the orthographic word forms into their phonological counterparts. From the angular gyrus, the phonological word forms could then be used to gain access to semantic representations via Wernicke's area.

With respect to the time course of orthographic, phonological, and semantic processing, a recent meta-analysis (Posner et al., 1999a, 1999b) provides compelling evidence that key components of word-form processing can be completed within the time window that is necessary for it to function as a signal to initiate saccadic programming. The results of a recent ERP experiment, for example, indicate that certain aspects of lexical processing (e.g., word frequency) can be discerned within 100-160 ms of word onset (Sereno et al., 1998). This would leave plenty of time (up to 80 ms) to signal the oculomotor system to begin programming a saccade (if one assumes a 180-ms saccadic latency and a 300-ms fixation). Unfortunately, the results of this study do not show that word identification drives eye movements, nor does the study suggest how this happens (if this interpretation of the data is correct). One possibility is discussed in the next section of this paper.

5.4.B *Neural implementation.* E-Z Reader is a functionalist account of eye movement control in reading. As we have stated on previous occasions (Reichle et al., 1998, 1999), the model is neither a deep model of linguistic processing, nor a deep model of oculomotor control; instead, the model is simply our attempt to specify the functional relationships among a few key parameters (i.e., word frequency, predictability, retinal acuity, saccadic accuracy) to explain the temporal dynamics of word identification and eye movement control during reading. Thus, up to now, we have remained completely agnostic about how the cognitive operations in E-Z Reader might be implemented in the brain. Given the current state of cognitive neuroscience, however, it seems appropriate that this question should at least be considered.

Our answer - which at this time is obviously very speculative - is depicted schematically in Figures 8 and 9. Figure 8 depicts the eye movements that might occur as word_n and word_{n+1} are identified during reading, the cognitive processes (as specified by E-Z Reader) which give rise to this pattern of eye movements, and the cortical and subcortical systems in which these cognitive processes occur. Figure 9 shows both where in the brain these neural systems are localized (indicated by the numbers in the text below), and how processing is coordinated among these systems.

The sequence of events depicted in Figures 8 and 9 begins when the visual image of word_n hits the retina. After approximately 70 ms, the features that make up the word's orthographic form are being processed within the primary visual cortex (1). The individual letter features are then integrated at successively higher levels of the visual system as processing cascades from the striate to the extrastriate cortex (2). After approximately 100-160 ms, word_n's orthographic form has been assembled in the left extrastriate cortex (2) and/or left inferior temporal gyrus (3), and this orthographic word form has been used to either access or assemble its phonological representation within the left angular gyrus (4).

Up to this point in time, both the eyes and attention have been focused on word_n. With the identification of word_n, however, the parietal eye fields (5) disengage visuospatial attention. The pulvinar nucleus of the thalamus (6) then moves the attentional "spotlight" forward, so that the frontal eye fields (7) and superior colliculus (8) can start using the low-spatial frequency information (e.g., word length) from the primary visual cortex to begin programming a saccade to word_{n+1}. This saccadic program takes approximately 180 ms to complete. During this time, the processing of word_n continues; its orthographic (2 & 3) and/or phonological form(s) (4) are used to access the word's meaning by way of connections through Wernicke's area (9) to various parts of the associative cortex. If the meaning is accessed before the saccadic program has been completed, then the pulvinar (6) enhances the processing of word_{n+1} (by shifting the internal attentional "spotlight" to the next word) and a preview benefit ensues. Otherwise, a saccade is executed by neural circuitry in the brainstem (10; see Leigh & Zee, 1999) and the eyes move forward to word_{n+1}.

Again, it is important to note that, in our model, saccadic programming is initiated after the familiarity check on an attended word has been completed, whereas attention shifts only occur after an attended word has been identified. Attention is thus allocated serially, from one word to the next as each new word is identified. The serial allocation of attention is necessary because it preserves the temporal order of the words, along with any syntactic information that may be dependent upon word order. This is, of course, not to say that some properties of an upcoming word might not occasionally be encoded in parallel to those of the word that is currently the focus of attention; as reviewed earlier, there is some evidence that (under certain conditions) properties of two words can

indeed be encoded in parallel (Kennedy, 1998, 2000; Inhoff et al., 2000; Starr, 2001). However, we believe that the default process during normal reading is one in which attention is allocated serially, so that the meaning of each new word that is identified can be integrated into a larger sentence representation that is at least partially dependent upon word-order information (Pollatsek & Rayner, 1999).

Insert Figures 8 & 9 here

Although our sketch of how the cognitive processes in E-Z Reader might map onto the neural systems responsible for guiding the eyes during reading is undoubtedly a gross over-simplification of what will undoubtedly turn be a much more complicated story, we would still argue that the mapping is precise enough to guide future cognitive neuroscience research. Indeed, the model is currently being used in this capacity to predict the time course of language-related components of ERP signals relative to the onset of saccades (Reichle, Hart, & Perfetti, in preparation). If this experiment is successful, it will not only support our claim, but will also provide the first physiological evidence showing a direct link between word identification and eye movement control in reading.

6.0 Conclusion

Our contention throughout this paper has been that, although the E-Z Reader model does not provide a deep explanation of language processing, vision, attention, or oculomotor control, it does provide a viable framework for thinking about how these different cognitive processes interact during the course of normal reading. Like the oculomotor models that were discussed earlier in this paper, E-Z Reader can account for the effects of several basic visual and oculomotor variables on eye movements. In contrast to these models, however, E-Z Reader also accounts for many of the important linguistic variables that are known to affect eye movements during reading. The model thus reflects our belief that, in order to account for the complex relationship between language processing and eye movements during reading, any adequate model of eye movement control during reading will (almost by definition) have to include an account of language processing.

Finally, it is worth emphasizing that E-Z Reader, like all of the other models reviewed in this paper, was developed primarily to explain the results of eye-tracking experiments. This should not be surprising because eye-tracking technology has proven to be an invaluable tool for studying reading. It is only natural that, as our understanding of eye movements and their determinants improve, this knowledge should be used to make inferences about the cognitive processes that occur during reading, and that these inferences should in turn be used to guide our modeling efforts. Because the last decade has witnessed unprecedented theoretical and methodological advances in the study of cognitive neuroscience, however, it is almost certain that these advances, too, will guide the development of the next generation of reading models. Like eye movement data in the past, the discoveries of tomorrow will provide important guideposts for developing and evaluating future models.

Endnotes

1. Many models of word-identification have been proposed (Brown, 1991; Bullinaria, 1997; McClelland & Rumelhart, 1981; Paap et al., 1982; Plaut, McClelland, Seidenberg, & Patterson, 1996; Seidenberg, 1989; Seidenberg & McClelland, 1989) to explain how orthography maps onto phonology and/or meaning, and how this process is affected by lexical variables (e.g., normative frequency, grapheme-phoneme regularity, etc.). Unfortunately, these models are generally limited in two ways: First, the entry point into these models is usually some highly abstract orthographic representation that bears little resemblance to the features that one might expect to be encoded by the visual system (e.g., homogenous retina acuity). Second, the models are generally fit to data from paradigms other than natural reading (e.g., lexical decision latencies). The models therefore say very little about the relationships among vision, eye movements, and word identification. One interesting exception to this is McClelland's (1986) *programmable blackboard* model of reading. This model was designed to examine how fixation locations and visual acuity restrictions affect the model's word recognition performance.
2. There is some dispute concerning the influence of "higher order" variables on where readers fixate. For example, Lavigne, Vitu, and d'Ydewalle (2000) reported that the eyes moved further into a word when that word was both high frequency and predictable from the prior context. However, Rayner et al. (2001) and Vonk, Radach, and van Rijn (2000) found no such effect. In addition, Underwood, Clews, and Everatt (1990; see also Hyönä, Niemi, & Underwood, 1989) reported that the eyes moved further into words when the informative part of the word was at the end of the word. However, Rayner and Morris (1992) and Hyönä (1995) were unable to replicate this finding. On the other hand, there appears to be general agreement that an orthographically irregular letter cluster at the beginning of a word results in the eyes' initial landing position deviating toward the beginning of the word (Beauvillain & Doré, 1998; Beauvillain, Doré, & Baudouin, 1996; Hyönä, 1995).
3. We (Reichle et al., 1998) have previously argued that the last version of our model, E-Z Reader 5, is superior to an earlier version, E-Z Reader 3, even though the latter model provided a slightly better aggregate fit to the Schilling et al. (1998) data. This claim was based primarily on a qualitative argument: In E-Z Reader 5 (but not E-Z Reader 3), the rate of lexical processing decreases as the disparity between the word being processed and the fovea increases. Although this feature of E-Z Reader 5 makes the model more psychologically plausible, the counter argument could be made that the lack of an improvement of the model's overall performance does not warrant the additional of two parameters. However, Salvucci and Anderson (in press) recently found additional evidence supporting our claim. Briefly, Salvucci and Anderson first replicated the Schilling et al. experiment with a different subject population, and then used several different eye-movement protocol algorithms to determine how well E-Z Readers 3 and 5 could account for the eye movement data of individual subjects. They also examined how well the models could account for two sequential measures: (1.) the proportions of saccades of each given length; and (2.) the proportions of saccades of each given length following saccades of various lengths. The results of these analyses indicated that E-Z Reader 5 fit all three measures better than did E-Z Reader 3, and that E-Z Reader 5 in fact provided a better account of the finer-grained, sequential aspects of the observed eye-movement data.
4. These results are open to alternative interpretations because the task was not natural reading, and thus did not actually require eye movements. Instead, subjects were required to read text on a computer monitor that was displayed through a stationary nine-character "window." The text was

manually advanced via pressing keys that moved the text forward (1-9 character spaces) or backwards (1-3 character spaces), and a mask (covering 1, 3, or 5 character spaces) was placed over the center of the viewing window to occlude letters in the scotomata conditions.

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References

- Altarriba, J., Kambe, G., Pollatsek, A., & Rayner, K. (2001). Semantic codes are not used in integrating information across eye fixations in reading: Evidence from fluent Spanish-English bilinguals. *Perception & Psychophysics*, in press.
- Altarriba, J. Kroll, J.F., Sholl, A., & Rayner, K. (1996). The influence of lexical and conceptual constraints on reading mixed language sentences: Evidence from eye fixation and naming times. *Memory & Cognition*, 24, 477-492.
- Anderson, J.R., & Lebiere, C. (1998). *The atomic components of thought*. Erlbaum.
- Andrews, S., Miller, B., & Rayner, K. (2001). Eye fixation measures of morphological segmentation of compound words: There is a mouse in the mousetrap. Submitted for publication.
- Balota, D. A., Pollatsek, A., & Rayner, K. (1985). The interaction of contextual constraints and parafoveal visual information in reading. *Cognitive Psychology*, 17, 364-390.
- Bavelier, D., Corina, D., Jezzard, P., Padmanabhan, S., Clark, V. P., Karni, A., Prinster, A., Braun, A., Lalwani, A., Rauschecker, J. P., Toner, R., & Neville, H. (1997). Sentence reading: A functional MRI study at 4 Tesla. *Journal of Cognitive Neuroscience*, 9, 664-686.
- Beauvillain, C., & Doré, K. (1998). Orthographic codes are used in integrating information from the parafovea by the saccadic computation system. *Vision Research*, 38, 115-123.
- Beauvillain, C., Doré, K., & Baudouin, V. (1996). The "center of gravity" of words: Evidence for an effect of the word-initial letters. *Vision Research*, 36, 589-603.
- Becker, W. & Jürgens, R. (1979). An analysis of the saccadic system by means of double step stimuli. *Vision Research*, 19, 967-983.
- Binder, J. R., Frost, J. A., Hammeke, T. A., Cox, R. W., Rao, S. M., & Prieto, T. (1997). Human brain language areas identified by functional magnetic resonance imaging. *The Journal of Neuroscience*, 17, 353-362.
- Binder, K.S., Pollatsek, A., & Rayner, K. (1999). Extraction of information to the left of the fixated word in reading. *Journal of Experimental Psychology: Human Perception and Performance*, 25, 1162-1172.
- Binder, K. S. & Rayner, K. (1998). Contextual strength does not modulate the subordinate bias effect: Evidence from eye fixations and self-paced reading. *Psychonomic Bulletin & Review*, 5, 271-276.
- Blanchard, H.E., Pollatsek, A., & Rayner, K. (1989). The acquisition of parafoveal word information in reading. *Perception & Psychophysics*, 46, 85-94.
- Bookheimer, S. Y., Zeffiro, T. A., Blaxton, T., Malow, B. A., Gaillard, W. D., Sato, S., Kufta, C., Fedio, P., & Theodore, W. H. (1997). A direct comparison of PET activation and electrocortical stimulation mapping for language localization. *Neurology*, 48, 1056-1065.
- Bouma, H., & de Voogd, A.H. (1974). On the control of eye saccades in reading. *Vision Research*, 14, 273-284.
- Brown, P. (1991). DEREK: The direct encoding routine for evoking knowledge. In D. Besner & G. W. Humphreys (Eds.), *Basic processes in reading: Visual word recognition* (pp. 104-147). Hillsdale, NJ: Erlbaum.
- Brysbaert, M. & Vitu, F. (1998). Word skipping: Implications for theories of eye movement control in reading. In G. Underwood (Ed.), *Eye guidance in reading and scene perception* (pp. 125-147). Oxford: Elsevier.
- Bullinaria, J. A. (1997). Modeling reading, spelling, and past tense learning with artificial neural networks. *Brain and Language*, 59, 236-266.
- Byrne, M.D., & Anderson, J.R. (1998). Perception and action. In J.R. Anderson and C. Lebiere (Eds). *The atomic components of thought*. Erlbaum.
- Caplan, D., Alpert, N., & Waters, G. (1999). PET studies of syntactic processing with auditory sentence presentation. *NeuroImage*, 9, 343-351.
- Caplan, D.A. (1992). *Language: Processing and disorders*. Cambridge: MIT Press
- Carpenter, P. A. & Just, M. A. (1983). What your eyes do while your mind is reading. In K. Rayner (Ed.), *Eye movements in reading: Perceptual and language processes* (pp. 275-307). New York: Academic Press.
- Churchland, P.S. (1986). *Neurophilosophy: Toward a unified science of the mind-brain*. Cambridge: MIT Press.
- Churchland, P.S., & Sejnowski, T.J. (1992). *The computational brain*. Cambridge: MIT Press.
- Clark, J. J., & O'Regan, J. K. (1999). Word ambiguity and the optimal viewing position in reading. *Vision Research*, 39, 843-857.
- Cohen, L., Dehaene, S., Naccache, L., Lehéricy, S., Dehaene-Lambertz, G., Hénaff, M.-A., & Michel, F. (2000).

- The visual word form area: Spatial and temporal characterization of an initial stage of reading in normal subjects and posterior split-brain patients. *Brain*, 123, 291-307.
- Corbetta, M. (1998). Frontoparietal cortical networks for directing attention and the eye to visual locations: Identical, independent, or overlapping neural systems? *Proceedings of the National Academy of Sciences*, 95, 831-838.
- Corbetta, M., Miezin, F. M., Schulman, G. L., & Petersen, S. E. (1993). A PET study of visuospatial attention. *Journal of Neuroscience*, 13, 1202-1226.
- DenBourman, R., Boersma, T., & Gerrissen, J.F. (1981). Eye movements and the perceptual span in reading. *Reading Research Quarterly*, 16, 227-235.
- Deutsch, A., & Rayner, K. (1999). Initial fixation location effects in reading Hebrew words. *Language and Cognitive Processes*, 14, 393-421.
- Dopkins, S., Morris, R. K., & Rayner, K. (1992). Lexical ambiguity and eye fixations during reading: A test of competing models of lexical ambiguity resolution. *Journal of Memory and Language*, 31, 461-477.
- Duffy, S. A., Kambe, G., & Rayner, K. (2001). The effect of prior disambiguating context on the comprehension of ambiguous words: Evidence from eye movements. In D. Gorfein (Ed), *Lexical ambiguity*. In press.
- Duffy, S. A., Morris, R. K., & Rayner, K. (1988). Lexical ambiguity and fixation times in reading. *Journal of Memory and Language*, 27, 429-446.
- Ehrlich, S.F., & Rayner, K. (1981). Contextual effects on word perception and eye movements during reading. *Journal of Verbal Learning and Verbal Behavior*, 20, 641-655.
- Engbert, R., & Kliegl, R. (2001). Mathematical models of eye movements in reading: exact numerical simulations. Submitted for publication.
- Felleman, D. J. & Van Essen, D. C. (1991). Distributed hierarchical processing in the primate cerebral cortex. *Cerebral Cortex*, 1, 1-47.
- Francis, W. N. & Kucera, H. (1982). *Frequency analysis of English usage: Lexicon and grammar*. Boston: Houghton Mifflin.
- Frazier, L. & Rayner, K. (1982). Making and correcting errors during sentence comprehension: Eye movements in the analysis of structurally ambiguous sentences. *Cognitive Psychology*, 14, 178-210.
- Gautier, V., O'Regan, J.K., & LaGargasson, J.F. (2000). 'The skipping' revisited in French: programming saccades to skip the article 'les'. *Vision Research*, 40, 2517-2531.
- Goldberg, M. E. (1994). The cortical control of saccadic eye movements. In J. Ygge & G. Lennerstrand (Eds.), *Eye movements in reading*. Oxford, England: Pergamon Press.
- Goodale, M. A. & Milner, A. D. (1992). Separate visual pathways for perception and action. *Trends in Neurosciences*, 15, 20-25.
- Grill-Spector, K., Kushnir, T., Hendler, T., Edelman, S., Itzchak, Y., & Malach, R. (1998). A sequence of object-processing stages revealed by fMRI in the human occipital lobe. *Human Brain Mapping*, 6, 316-328.
- Haarmann, H., Just, M. A., & Carpenter, P. A. (1997). Aphasic sentence comprehension as a resource deficit: A computational approach. *Brain and Language*, 59, 76-120.
- Henderson, J. M. & Ferreira, F. (1990). Effects of foveal processing difficulty on the perceptual span in reading: Implications for attention and eye movement control. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 16, 417-429.
- Henderson, J.M., & Ferreira, F. (1993). Eye movement control during reading: Fixation measures reflect foveal but not parafoveal processing difficulty. *Canadian Journal of Experimental Psychology*, 47, 201-221.
- Hoffman, J.E., & Subramaniam, B. (1995). The role of visual attention in saccadic eye movements. *Perception & Psychophysics*, 57, 787-795.
- Horwitz, B., Rumsey, J. M., & Donohue, B. C. (1998). Functional connectivity of the angular gyrus in normal reading and dyslexia. *Proceedings of the National Academy of Science*, 95, 8939-8944.
- Hyönä, J. (1995). Do irregular letter combinations attract readers' attention? Evidence from fixation locations in words. *Journal of Experimental Psychology: Human Perception and Performance*, 21, 68-81.
- Hyönä, J., Niemi, P., & Underwood, G. (1989). Reading long words embedded in sentences: Informativeness of word halves affects eye movements. *Journal of Experimental Psychology: Human Perception and*

- Performance*, 15, 142-152.
- Hyönä, J., & Olson, R.K. (1995). Eye movement patterns among dyslexic and normal readers: Effects of word length and word frequency. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 21, 1430-1440.
- Hyönä, J. & Pollatsek, A. (1998). Reading Finnish compound words: Eye fixations are affected by component morphemes. *Journal of Experimental Psychology: Human Perception and Performance*, 24, 1612-1627.
- Hyönä, J. & Pollatsek, A. (2000). Processing of Finnish compound words in reading. In A. Kennedy, R. Radach, D. Heller, & J. Pynte (Eds.), *Reading as a perceptual process*. (pp. 65-87). Oxford, England: Elsevier.
- Ikeda, M., & Saida, S. (1978). Span of recognition in reading. *Vision Research*, 18, 83-88.
- Inhoff, A.W. (1984). Two stages of word processing during eye fixations in the reading of prose. *Journal of Verbal Learning and Verbal Behavior*, 23, 612-624.
- Inhoff, A.W., & Briehl, D. (1991). Semantic processing of unattended text during selective reading: How the eyes see it. *Perception & Psychophysics*, 49, 289-294.
- Inhoff, A.W., & Liu, W. (1998). The perceptual span and oculomotor activity during the reading of Chinese sentences. *Journal of Experimental Psychology: Human Perception and Performance*, 24, 20-34.
- Inhoff, A.W., Pollatsek, A., Posner, M.I., & Rayner, K. (1989). Covert attention and eye movements during reading. *Quarterly Journal of Experimental Psychology*, 41A, 63-89.
- Inhoff, A.W. & Radach, R. (1998). Definition and computation of oculomotor measures in the study of cognitive processes. In G. Underwood (Ed.), *Eye guidance in reading and scene perception* (pp. 29-53). Oxford, England: Elsevier.
- Inhoff, A.W., & Rayner, K. (1986). Parafoveal word processing during eye fixations in reading: Effects of word frequency. *Perception & Psychophysics*, 40, 431-439.
- Inhoff, A.W., Starr, M., & Shindler, K.L. (2000). Is the processing of words during eye fixations in reading strictly serial? *Perception & Psychophysics*, 62, 1474-1484.
- Inhoff, A.W., & Topolski, R. (1992). Lack of semantic activation from unattended text during passage reading. *Bulletin of the Psychonomic Society*, 30, 365-366.
- Ishai, A., Ungerleider, L. G., Martin, A., Schouten, J. L., & Haxby, J. V. (1999). Distributed representation of objects in the human ventral visual pathway. *Proceedings of the National Academy of Science*, 96, 9379-9384.
- Just, M. A. & Carpenter, P. A. (1980). A theory of reading: From eye fixations to comprehension. *Psychological Review*, 87, 329-354.
- Just, M. A. & Carpenter, P. A. (1987). *The psychology of reading and language comprehension*. Boston: Allyn and Bacon.
- Just, M. A. & Carpenter, P. A. (1992). A capacity theory of comprehension: Individual differences in working memory. *Psychological Review*, 99, 122-149.
- Just, M. A., Carpenter, P. A., Keller, T. A., Eddy, W. F., & Thulborn, K. R. (1996). Brain activation modulated by sentence comprehension. *Science*, 274, 114-116.
- Kambe, G., Rayner, K., & Duffy, S.A. (2001). Global context effects on processing lexically ambiguous words: Evidence from eye fixations. *Memory & Cognition*, in press.
- Kennedy, A. (1998). The influence of parafoveal words on foveal inspection time: Evidence for a processing trade-off. In G. Underwood (Ed.), *Eye guidance in reading and scene perception* (pp. 149-179). Oxford, England: Elsevier.
- Kennedy, A. (2000). Parafoveal processing in word recognition. *Quarterly Journal of Experimental Psychology*, 53A, 429-455.
- Kennedy, A. Radach, R., Heller, D. & Pynte, J. (2000). *Reading as a perceptual process*. Oxford: Elsevier.
- Kennison, S. M. & Clifton, C. (1995). Determinants of parafoveal preview benefit in high and low working memory capacity readers: Implications for eye movement control. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 21, 68-81.
- Kim, Y.-H., Gitelman, D. R., Nobre, A. C., Parrish, T. B., LaBar, K. S., & Mesulam, M. M. (1999). The large-scale neural network for spatial attention displays multifunctional overlap but differential asymmetry. *NeuroImage*, 9, 269-277.

- Klitz, T. S., Legge, G. E., & Tjan, B. S. (2000). Saccade planning in reading with central scotomas: Comparison of human and ideal performance. In A. Kennedy, R. Radach, D. Heller, & J. Pynte (Eds.), *Reading as a perceptual process* (pp. 667-682). Oxford, England: Elsevier.
- Kolers, P.A. (1976). Buswell's discoveries. In R.A. Monty & J.W. Senders (Eds), *Eye movements and psychological processes*. Hillsdale, NJ: Erlbaum.
- Kowler, E. (1990). The role of visual and cognitive processes in the control of eye movement. In E. Kowler (Ed), *Eye movements and their role in visual and cognitive processes* (pp 1-70). Elsevier.
- Laberge, D. A. (1990). Attention. *Psychological Science, 1*, 156-162.
- Lavigne, F., Vitu, F., & d'Ydewalle, G. (2000). The influence of semantic context on initial eye landing sites in words. *Acta Psychologica, 104*, 191-204.
- Legge, G. E., Klitz, T. S., & Tjan, B. S. (1997). Mr. Chips: An ideal-observer model of reading. *Psychological Review, 104*, 524-553.
- Leigh, R. J. & Zee, D. S. (1994). *The neurology of eye movements*. New York: Oxford University Press.
- Lima, S.D. (1987). Morphological analysis in sentence reading. *Journal of Memory and Language, 26*, 84-99.
- Lima, S.D., & Inhoff, A.W. (1985). Lexical access during eye fixations in reading: Effects of word-initial letter sequences. *Journal of Experimental Psychology: Human Perception and Performance, 11*, 272-285.
- Luna, B., Thulborn, K. R., Strojwas, M. H., Mcurtain, B. J., Berm an, R. A., Genovese, C. R., & Sweeney, J. A. (1998). Dorsal cortical regions subserving visually guided saccades in humans: An fMRI study. *Cerebral Cortex, 8*, 40-47.
- Maunsell, J. H. R. & Newsome, W. T. (1987). Visual processing in monkey extrastriate cortex. *Annual Review of Neuroscience, 10*, 363-401.
- McClelland, J. L. (1986). The programmable blackboard model of reading. In McClelland, J. L., Rumelhart, D. E., & the PDP Research Group. (1986). *Parallel distributed: Explorations in the microstructure of cognition, vol. 2: Psychological and biological models*. Cambridge, MA: MIT Press.
- McClelland, J. L. & Rumelhart, D. E. (1981). An interactive activation model of context effects in letter perception: Part I. An account of basic findings. *Psychological Review, 88*, 375-407.
- McClelland, J. L., Rumelhart, D. E., & the PDP Research Group. (1986). *Parallel distributed: Explorations in the microstructure of cognition, vol. 2: Psychological and biological models*. Cambridge, MA: MIT Press.
- McConkie, G.W. (1979). On the role and control of eye movements in reading. In P.A. Kolers, M.E. Wrolstad, & H. Bouma (eds.), *Processing of visible language* (pp 37-48). New York: Plenum.
- McConkie, G. W. & Dyre, B. P. (2000). Eye fixation durations in reading: Models of frequency distributions. In A. Kennedy, R. Radach, D. Heller, & J. Pynte (Eds.), *Reading as a perceptual process* (pp. 683-700). Oxford, England: Elsevier.
- McConkie, G. W., Kerr, P. W., & Dyre, B. P. (1994). What are 'normal' eye movements during reading: Toward a mathematical description. In J. Ygge & G. Lennérstrand (Eds.), *Eye movements in reading* (pp. 315-328). Oxford, England: Pergamon Press.
- McConkie, G. W., Kerr, P. W., Reddix, M. D., & Zola, D. (1988). Eye movement control during reading: I. The location of initial eye fixations on words. *Vision Research, 28*, 1107-1118.
- McConkie, G. W., Kerr, P. W., Reddix, M. D., Zola, D., & Jacobs, A. M. (1989). Eye movement control during reading: II. Frequency of re-fixating a word. *Perception & Psychophysics, 46*, 245-253.
- McConkie, G. W. & Rayner, K. (1975). The span of the effective stimulus during a fixation in reading. *Perception & Psychophysics, 17*, 578-586.
- McConkie, G. W. & Rayner, K. (1976). Asymmetry of the perceptual span in reading. *Bulletin of the Psychonomic Society, 8*, 365-368.
- McConkie, G.W., & Zola, D. (1984). Eye movement control during reading: The effect of words units. In W. Prinz & A.F. Sanders (eds.), *Cognition and motor processes* (pp 63-74). Berlin: Springer-Verlag.
- McConkie, G. W., Zola, D., Grimes, J., Kerr, P. W., Bryant, N. R., & Wolff, P. M. (1991). Children's eye movements during reading. In J. F. Stein (Ed.), *Vision and visual dyslexia* (pp. 251-262). London: Macmillan Press.
- Mesulam, M. M. (1990). Large-scale neurocognitive networks and distributed processing for attention, language, and memory. *Annals of Neurology, 28*, 597-613.

- Mesulam, M. M. (1998). From sensation to cognition. *Brain*, *121*, 1013-1052.
- Morris, R.K., Rayner, K., & Pollatsek, A. (1990). Eye movement guidance in reading: The role of parafoveal letter and space information. *Journal of Experimental Psychology: Human Perception and Performance*, *16*, 268-281.
- Morrison, R. E. (1984). Manipulation of stimulus onset delay in reading: Evidence for parallel programming of saccades. *Journal of Experimental Psychology: Human Perception and Performance*, *10*, 667-682.
- Morrison, R.E. & Rayner, K. (1981). Sacca de size in reading depends upon character spaces and not visual angle. *Perception & Psychophysics*, *30*, 395-396.
- Müller, R.-A., Rothermel, R. D., Behen, M. E., Muzik, O., Mangner, T. J., & Chugani, H. T. (1997). Receptive and expressive language activations for sentences: a PET study. *Neuroreport*, *8*, 3767-3770.
- Niswander, E. Pollatsek, A., & Rayner, K. (2000). The processing of derived and inflected suffixed words during reading. *Language and Cognitive Processes*, *15*, 389-420.
- O'Regan, J.K. (1979). Eye guidance in reading: Evidence for linguistic control hypothesis. *Perception & Psychophysics*, *25*, 501-509.
- O'Regan, J.K. (1980). The control of saccade size and fixation duration in reading: The limits of linguistic control. *Perception & Psychophysics*, *28*, 112-117.
- O'Regan, J. K. (1990). Eye movements and reading. In E. Kowler (Ed.), *Eye movements and their role in visual and cognitive processes* (pp. 395-453). Amsterdam: Elsevier.
- O'Regan, J. K. (1992). Optimal viewing position in words and the strategy-tactics theory of eye movements in reading. In K. Rayner (Ed.), *Eye movements and visual cognition: Scene perception and reading* (pp. 333-354). New York: Springer-Verlag.
- O'Regan, J. K. & Lévy-Schoen, A. (1987). Eye movement strategy and tactics in word recognition and reading. In M. Coltheart (Ed.), *Attention and performance, XII: The psychology of reading* (pp. 363-383). Hillsdale, NJ: Erlbaum.
- O'Regan, J.K., Levy-Schoen, A., Pynte, J., & Brugailière, B. (1984). Convenient fixation location within isolated words of different length and structure. *Journal of Experimental Psychology: Human Perception and Performance*, *10*, 250-257.
- Osaka, N. (1992). Size of saccade and fixation duration of eye movements during reading: Psychophysics of Japanese text processing. *Journal of the Optical Society of America A*, *9*, 5-13.
- Paap, K. R., Newsome, S. L., McDonald, J. E., & Schvaneveldt, R. W. (1982). An activation-verification model for letter and word recognition: The word-superiority effect. *Psychological Review*, *89*, 573-594.
- Peterson, S. E., Fox, P. T., Posner, M. I., Mintun, M., & Raichle, M. E. (1989). Positron emission tomographic studies of the cortical anatomy of single-word processing. *Nature*, *331*, 585-589.
- Peterson, S. E., Fox, P. T., Snyder, A. Z., & Raichle, M. E. (1990). Activation of extrastriate and frontal cortical areas by visual words and word-like stimuli. *Science*, *249*, 1041-1044.
- Plaut, D. C., McClelland, J. L., Seidenberg, M. S., & Patterson, K. (1996). Understanding normal and impaired word reading: Computational principles in quasi-regular domains. *Psychological Review*, *103*, 56-115.
- Poldrack, R. A., Desmond, J. E., Glover, G. H., & Gabrieli, J. D. E. (1998). The neural basis of visual skill learning: An fMRI study of mirror reading. *Cerebral Cortex*, *8*, 1-10.
- Pollatsek, A., Bolozky, S., Well, A. D., & Rayner, K. (1981). Asymmetries in the perceptual span for Israeli readers. *Brain and Language*, *14*, 174-180.
- Pollatsek, A., Hyönä, J., & Bertram, R. (2000). The role of morphological constituents in reading Finnish compound words. *Journal of Experimental Psychology: Human Perception and Performance*, *26*, 820-833.
- Pollatsek, A., Lesch, M., Morris, R. K., & Rayner, K. (1992). Phonological codes are used in integrating information across saccades in word identification and reading. *Journal of Experimental Psychology: Human Perception and Performance*, *18*, 148-162.
- Pollatsek, A., Raney, G.E., LaGasse, L., & Rayner, K. (1993). The use of information below fixation in reading and in visual search. *Canadian Journal of Experimental Psychology*, *47*, 179-200.
- Pollatsek, A., & Rayner, K. (1982). Eye movement control in reading: The role of word boundaries. *Journal of Experimental Psychology: Human Perception and Performance*, *8*, 817-833.
- Pollatsek, A. & Rayner, K. (1990). Eye movements and lexical access in reading. In D. A. Balota, G. B. Flores d'

- Arcais, & K. Rayner (Eds.), *Comprehension processes in reading* (pp. 143-164). Hillsdale, NJ: Erlbaum.
- Pollatsek, A., & Rayner, K. (1999). Is covert attention really unnecessary? *Behavioral and Brain Sciences*, 22, 695-696.
- Pollatsek, A., Rayner, K., & Balota, D.A. (1986). Inferences about eye movement control from the perceptual span in reading. *Perception & Psychophysics*, 40, 123-130.
- Pollatsek, A., Rayner, K., Fischer, M. H., & Reichle, E. D. (1999). Attention and eye movements in reading. In J. Everatt (Ed.), *Reading and dyslexia: visual and attentional processes* (pp.179-209).London: Routledge.
- Posner, M.I.(1980). Orienting of attention. *Quarterly Journal of Experimental Psychology*, 32, 3-25.
- Posner, M. I., Aldullaev, Y. G., McCandliss, B. D., & Sereno, S. C. (1999a). Anatomy, circuitry and plasticity of word reading. In J. Everatt (Ed.), *Reading and dyslexia: Visual and attentional processes* (pp. 137-162). New York, NY: Routledge.
- Posner, M.I., Abdullaev, Y.G., McCandliss, B.D., & Sereno, S.C. (1999b). Neuroanatomy, circuitry and plasticity of word reading. *NeuroReport*, 10, R12-R23.
- Posner, M. I. & Raichle, M. I. (1997). *Images of mind*. New York: Scientific American Library.
- Price, C. J. (1997). Functional anatomy of reading. In R. S. J. Frackowiak, K. J. Friston, C. D. Frith, R. J. Dolan, & J. C. Mazziotta (Eds.), *Human brain function* (pp. 301-328). San Diego: Academic Press.
- Pugh, K. R., Mencl, W. E., Shaywitz, B. A., Shaywitz, S. E., Fulbright, R. K., Constable, R. T., Skudlarski, P., Marchione, K. E., Jenner, A. R., Fletcher, J. M., Liberman, A. M., Shankweiler, D. P., Katz, L., Lacadie, C., & Gore, J. C. (2000). The angular gyrus in developmental dyslexia: Task-specific differences in functional connectivity with posterior cortex. *Psychological Science*, 11, 51-56.
- Radach, R., & Kempe, V. (1993). An individual analysis of initial fixation positions in reading. In G. d'Ydewalle & J. Van Rensbergen (eds.), *Perception and cognition: Advances in eye movement research* (pp 213-226). Amsterdam: North Holland.
- Radach, R. & McConkie, G. W. (1998). Determinants of fixation positions in words during reading. In G. Underwood (Ed.), *Eye guidance in reading and scene perception* (pp.77-100). Oxford, England: Elsevier.
- Rafal, R. & Robertson, L. (1995). The neurology of visual attention. In M. S. Gazzaniga (Ed.), *The cognitive neurosciences* (pp. 625-648). Cambridge, MA: MIT Press.
- Raney, G.E., & Rayner, K. (1995). Word frequency effects and eye movements during two readings of a text. *Canadian Journal of Experimental Psychology*, 49, 151-172.
- Rayner, K. (1975). The perceptual span and peripheral cues in reading. *Cognitive Psychology*, 7, 65-81.
- Rayner, K. (1977). Visual attention in reading: Eye movements reflect cognitive processes. *Memory & Cognition*, 4, 443-448.
- Rayner, K. (1978). Eye movements in reading and information processing. *Psychological Bulletin*, 85, 618-660.
- Rayner, K. (1979). Eye guidance in reading: Fixation locations within words. *Perception*, 8, 21-30.
- Rayner, K. (1986). Eye movements and the perceptual span in beginning and skilled readers. *Journal of Experimental Child Psychology*, 41, 211-236.
- Rayner, K. (1998). Eye movements in reading and information processing: 20 years of research. *Psychological Bulletin*, 124, 372-422.
- Rayner, K., Balota, D.A., & Pollatsek, A. (1986). Against parafoveal semantic preprocessing during eye fixations in reading. *Canadian Journal of Psychology*, 40, 473-483.
- Rayner, K. & Bertera, J.H. (1979). Reading without a fovea. *Science*, 206, 468-469.
- Rayner, K., Binder, K.S., Ashby, J., & Pollatsek, A. (2001). Eye movement control in reading: Word predictability has little influence on initial landing positions in words. *Vision Research*, in press.
- Rayner, J. & Duffy, S. A. (1986). Lexical ambiguity and fixation times in reading: Effects of word frequency, verb complexity, and lexical ambiguity. *Memory & Cognition*, 14, 191-201.
- Rayner, K. & Duffy, S. A. (1988). On-line comprehension processes and eye movements in reading. In M. Daneman, G. E. MacKinnon, & T. G. Waller (Eds.), *Reading research: Advances in theory and practice* (pp. 13-66). New York: Academic Press.
- Rayner, K., & Fischer, M.H. (1996). Mindless reading revisited: Eye movements during reading and scanning are different. *Perception & Psychophysics*, 58, 734-747.

- Rayner, K., Fischer, M.H., & Pollatsek, A. (1998). Unspaced text interferes with both word identification and eye movement control. *Vision Research*, 38, 1129-1144.
- Rayner, K. & Frazier, L. (1989). Selection mechanisms in reading lexically ambiguous word. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 15, 779-790.
- Rayner, K., & McConkie, G.W. (1976). What guides a reader's eye movements. *Vision Research*, 16, 829-837.
- Rayner, K., & Morris, R.K. (1992). Eye movement control in reading: Evidence against semantic preprocessing. *Journal of Experimental Psychology: Human Perception and Performance*, 18, 163-172.
- Rayner, K. & Morrison, R. E. (1981). Eye movements and identifying words in parafoveal vision. *Bulletin of the Psychonomic Society*, 17, 135-138.
- Rayner, K., & Pollatsek, A. (1981). Eye movement control during reading: Evidence for direct control. *Quarterly Journal of Experimental Psychology*, 33A, 351-373.
- Rayner, K. & Pollatsek, A. (1989). *The psychology of reading*. Englewood Cliffs, NJ: Prentice Hall.
- Rayner, K., & Raney, G.E. (1996). Eye movement control in reading and visual search: Effects of word frequency. *Psychonomic Bulletin & Review*, 3, 238-244.
- Rayner, K., Reichle, E. D., & Pollatsek, A. (1998). Eye movement control in reading: An overview and model. In G. Underwood (Ed.), *Eye guidance in reading and scene perception* (pp. 243-268). Oxford: Elsevier.
- Rayner, K., Reichle, E. D., & Pollatsek, A. (2000). Eye movement control in reading: Updating the E-Z Reader model to account for initial fixation locations and refixations. In A. Kennedy, R. Radach, D. Heller, & J. Pynte (Eds.), *Reading as a perceptual process* (pp. 701-719). Oxford, England: Elsevier.
- Rayner, K. & Sereno, S. C. (1994). Eye movements in reading: Psycholinguistic studies. In M. Gernsbacher (Ed.), *Handbook of psycholinguistics* (pp. 57-82). New York: Academic Press.
- Rayner, K., Sereno, S. C., Morris, R. K., Schmauder, A. R., & Clifton, C. (1989). Eye movements and on-line language comprehension processes. *Language and Cognitive Processes*, 4, [Special issue] 21-49.
- Rayner, K., Sereno, S. C., & Raney, G. E. (1996). Eye movement control in reading: A comparison of two types of models. *Journal of Experimental Psychology: Human Perception and Performance*, 22, 1188-1200.
- Rayner, K., Slowiaczek, M.L., Clifton, C., & Bertera, J.H. (1983). Latency of sequential eye movements: Implications for reading. *Journal of Experimental Psychology: Human Perception and Performance*, 9, 912-922.
- Rayner, K., & Well, A.D. (1996). Effects of contextual constraint on eye movements in reading: A further examination. *Psychonomic Bulletin & Review*, 3, 504-509.
- Rayner, K., Well, A.D., & Pollatsek, A. (1980). A symmetry of the effective visual field in reading. *Perception & Psychophysics*, 27, 537-544.
- Rayner, K., Well, A.D., Pollatsek, A. & Bertera, J.H. (1982). The availability of useful information to the right of fixation in reading. *Perception & Psychophysics*, 31, 537-550.
- Reichle, E.D., Hart, L., & Perfetti, C.A. (2001). The neural bases of eye movement control in reading: Using ERP to evaluate the E-Z Reader model. In preparation.
- Reichle, E. D., Pollatsek, A., Fisher, D. L., & Rayner, K. (1998). Toward a model of eye movement control in reading. *Psychological Review*, 105, 125-157.
- Reichle, E.D., & Rayner, K. (2001). Cognitive processes and models of reading. In G. Hung and K. Ciuffreda (Eds.), *Models of the visual system*. In press
- Reichle, E. D., Rayner, K., & Pollatsek, A. (1999). Eye movement control in reading: Accounting for initial fixation locations and refixations within the E-Z Reader model. *Vision Research*, 39, 4403-4411.
- Reilly, R. (1993). A connectionist framework for modeling eye-movement control in reading. In G. d'Ydewalle & Van Rensbergen (Eds.), *Perception and cognition: Advances in eye movement research* (pp. 191-212). Amsterdam: North Holland.
- Reilly, R. & O'Regan, J. K. (1998). Eye movement control in reading: A simulation of some word-targeting strategies. *Vision Research*, 38, 303-317.
- Rumelhart, D. E., Hinton, G. E., & Williams, R. J. (1986). Learning internal representations by error propagation. In D. E. Rumelhart, J. L. McClelland, & the PDP Research Group (Eds.), *Parallel distributed processing: Explorations in the microstructure of cognition, vol. 1: Foundations* (pp. 318-362). Cambridge, MA: MIT Press.

- Rumelhart, D. E., McClelland, J. L., & the PDP Research Group. (1986). *Parallel distributed processing: Explorations in the microstructure of cognition, vol. 1: Foundations*. Cambridge, MA: MIT Press.
- Sagi, D. & Julesz, B. (1985). "Where" and "what" in vision. *Science*, 228, 1217-1219.
- Salvucci, D. D. (2000). An interactive model-based environment for eye-movement protocol visualization and analysis. In *Proceedings of the Eye Tracking Research and Applications Symposium* (pp. 57-63). New York: ACM Press.
- Salvucci, D. D. (2001). An integrated model of eye movements and visual encoding. *Cognitive Systems Research*.
- Salvucci, D. D. Anderson, J. R. (1998). Tracing eye movement protocols with cognitive process models. *Proceedings of the Twentieth Annual Conference of the Cognitive Science Society* (pp. 923-928). Hillsdale, NJ: Erlbaum.
- Salvucci, D. D. & Anderson, J. R. (2000). Intelligent gaze-added interfaces. *Human Factors in Computing Systems: CHI 2000 Conference Proceedings* (pp. 273-280). New York: ACM Press. Manuscript in press.
- Salvucci, D. D. & Anderson, J. R. (2001). Automated eye-movement protocol analysis. *Human Computer Interaction*.
- Schilling, H. E. H., Rayner, K., & Chumbley, J. I. (1998). Comparing naming, lexical decision, and eye fixation times: Word frequency effects and individual differences. *Memory & Cognition*, 26, 1270-1281.
- Schlösser, M. J., Aoyagi, N., Fulbright, R. K., Gore, J. C., & McCarthy, G. (1998). Functional MRI studies of auditory comprehension. *Human Brain Mapping*, 6, 1-13.
- Schroyens, W., Vitu, F., Brysbaert, M., & d'Ydewalle, G. (1999). Eye movement control during reading: Foveal load and parafoveal processing. *Quarterly Journal of Experimental Psychology*, 52A, 1021-1046.
- Schustack, M.W., Ehrlich, S.F., & Rayner, K. (1987). The complexity of contextual facilitation in reading: Local and global influences. *Journal of Memory and Language*, 26, 322-340.
- Seidenberg, M. S. (1989). Visual word recognition and pronunciation: A computational model and its implications. In W. Marslen-Wilson (Ed.), *Lexical representation and process* (pp. 25-74). Cambridge, MA: MIT Press.
- Seidenberg, M. S. & McClelland, J. L. (1989). A distributed, developmental model of word recognition and naming. *Psychological Review*, 96, 523-568.
- Sereno, S. C. (1992). Early lexical effects when fixating a word in reading. In K. Rayner (Ed.), *Eye movements and visual cognition: Scene perception and reading* (pp. 304-316). New York: Springer-Verlag.
- Sereno, S.C. (1995). Resolution of lexical ambiguity: Evidence from an eye movement priming paradigm. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 21, 582-595.
- Sereno, S. C., Pacht, J. M., & Rayner, K. (1992). The effect of meaning frequency on processing lexically ambiguous words. *Psychological Science*, 3, 296-300.
- Sereno, S. C., Rayner, K., & Posner, M. I. (1998). Establishing a time-line of processing during reading: Evidence from eye movements and event-related potentials. *NeuroReport*, 9, 2195-2200.
- Somers, D. C., Dale, A. M., Seiffert, A. E., & Tootell, R. B. H. (1999). Functional MRI reveals spatially specific attentional modulation in human primary visual cortex. *Proceedings of the National Academy of Sciences*, 96, 1663-1668.
- Sparks, D. L. & Mays, L. (1990). Signal transformations required for the generation of saccadic eye movements. *Annual Review of Neuroscience*, 13, 309-336.
- Starr, M.S. (2001). Parafoveal information is obtained from both the left and right of fixation during reading. Submitted for publication.
- Stelmach, L.B., Campsall, J.M., & Herdman, C.M. (1997). Attentional and ocular movements. *Journal of Experimental Psychology: Human Perception and Performance*, 23, 823-844.
- Stromswold, K., Caplin, D., Alpert, N., & Rauch, S. (1996). Localization of syntactic comprehension by Positron Emission Tomography. *Brain and Language*, 52, 452-473.
- Suppes, P. (1990). Eye-movement models for arithmetic and reading performance. In E. Kowler (Ed.), *Eye movements and their role in visual and cognitive processes* (pp. 455-477). Amsterdam: Elsevier.
- Suppes, P. (1994). Stochastic models of reading. In J. Ygge & G. Lennerstrand (Eds.), *Eye movements in reading* (pp. 349-364). Oxford, England: Pergamon Press.
- Suppes, P., Cohen, M., Laddaga, R., Anliker, J., & Floyd, H. (1982). Research on eye movements in arithmetic performance. In R. Groner & P. Fraisse (Eds.), *Cognition and eye movements* (pp. 57-73). Amsterdam:

North-Holland.

- Suppes, P., Cohen, M., Laddaga, R., Anliker, J., & Floyd, H. (1983). A procedural theory of eye movements in doing arithmetic. *Journal of Mathematical Psychology*, 27, 341-369.
- Sweeney, J. A., Mintun, M. A., Kwee, S., Wiseman, M. B., Brown, D. L., Rosenberg, D. R., & Carl, J. R. (1996). Positron emission tomography study of voluntary saccadic eye movements and spatial working memory. *Journal of Neurophysiology*, 75, 454-468.
- Tanaka, K. (1996). Inferotemporal cortex and object vision. *Annual Review of Neuroscience*, 19, 109-139.
- Thibadeau, R., Just, M. A., & Carpenter, P. A. (1982). A model of the time course and content of reading. *Cognitive Science*, 6, 157-203.
- Ungerleider, L. G., Courtney, S. M., & Haxby, J. V. (1998). A neural system for human visual working memory. *Proceedings of the National Academy of Science*, 95, 883-890.
- Ungerleider, L. G. & Haxby, J. V. (1994). 'What' and 'where' in the human brain. *Current Opinion in Neurobiology*, 4, 157-165.
- Ungerleider, L. G. & Mishkin, M. (1982). Two cortical visual systems. In D. J. Ingle, M. A. Goodale, & R. J. W. Mansfield (Eds.), *Analysis of visual behavior* (pp. 548-586). Cambridge, MA: MIT Press.
- Underwood, G., Clews, S., & Everatt, J. (1990). How do readers know where to look next? Local information distributions influence eye fixations. *Quarterly Journal of Experimental Psychology*, 42A, 39-65.
- Underwood, N.R., & McConkie, G.W. (1985). Perceptual span for letter distinctions during reading. *Reading Research Quarterly*, 20, 153-162.
- Van Essen, D. C. & De Yoe, E. A. (1995). Concurrent processing in the primate visual cortex. In M. S. Gazzaniga (Ed.), *The cognitive neurosciences* (pp. 383-400). Cambridge, MA: MIT Press.
- Vitu, F. (1991). The influence of parafoveal processing and linguistic context on the optimal landing position effect. *Perception & Psychophysics*, 50, 58-75.
- Vitu, F., O'Regan, J.K., & Mittau, M. (1990). Optimal landing position in reading isolated words and continuous text. *Perception & Psychophysics*, 47, 583-600.
- Vonk, W., Racach, R., & van Rijn, H. (2000). Eye guidance and the saliency of word beginnings in reading text. In A. Kennedy, R. Radach, D. Heller, & J. Pynte (Eds), *Reading as a perceptual process* (pp 269-300). Amsterdam: North Holland.
- Wiley, J., & Rayner, K. (2000). Effects of titles on the processing of text and lexically ambiguous words: Evidence from eye movements. *Memory & Cognition*, 28, 1011-1021.
- Wolverton, G.S., & Zola, D. (1983). The temporal characteristics of visual information extraction during reading. In K. Rayner (ed.), *Eye movements in reading: Perceptual and language processes* (pp 41-52). New York: Academic Press.
- Zola, D. (1984). Redundancy and word perception during reading. *Perception & Psychophysics*, 36, 277-284.

Table 1. Mean Observed and Predicted Gaze Durations (GDs), First-Fixation Durations (FFDs), Single-Fixation Durations (SFDs), and Probabilities of Skipping (Skip), Making a Single Fixation (Single), and Refixating (Refix) for Five Frequency Classes of Words.

Word Frequency		GDs		FFDs		SFDs	
Clas	Range	Obs ^a	Pred ^b	Obs	Pred	Obs	Pred
1	1-10	293	286	248	253	265	272
2	11-100	272	268	234	252	249	263
3	101-1,000	256	247	228	240	243	245
4	1,001-10,000	234	216	223	215	235	217
5	10,000+	214	206	208	206	216	210

Word Frequency		Skip		Single		Refix	
Clas	Range	Obs	Pred	Obs	Pred	Obs	Pred
1	1-10	0.10	0.06	0.68	0.78	0.20	0.17
2	11-100	0.13	0.11	0.70	0.80	0.16	0.09
3	101-1,000	0.22	0.21	0.68	0.74	0.10	0.04
4	1,001-10,000	0.55	0.44	0.50	0.53	0.02	0.03
5	10,000+	0.67	0.64	0.32	0.34	0.01	0.02

Notes:

- a. *Obs* indicates the observed performance, as reported in Reichle et al. (1998). These values were calculated from the Schilling et al. (1998) sentence corpus.
- b. *Pred* indicates the values predicted by E-Z Reader (see Reichle et al., 1999, Table 1). The simulation results were based on the following parameter values: $f_b = 150$; $f_m = 12$; $\beta = 0.85$; $\beta_m = 0.5$; $t(m) = 135$; $t(M) = 50$; $e_1 = 1.09$; $e_2 = 1.13$; $\gamma = 7$; $\beta_b = 0.85$; $\beta_m = 0.11$; $O_b = 7.3$; and $O_m = 4.5$.

Table 2. Mean Observed and Predicted Frequency Effects for Gaze Durations (GDs), First-Fixation Durations (FFDs), and Single-Fixation Durations (SFDs).

Word Frequency	GDs		FFDs		SFDs	
	Obs ^a	Pred ^b	Obs	Pred	Obs	Pred
Low (Mean = 2 per million)	298	298	248	254	261	276
High (Mean = 141 per million)	248	260	216	249	224	253
Frequency Effect (<i>Difference</i>)	50	38	31	6	37	23

Notes:

a. *Obs* indicates the observed values which were calculated from the 48 target words used by Schilling et al. (1998) to examine word-frequency effects in reading (as reported by Reichle et al., 1998). The low-frequency targets had normative frequencies of four or less per million (Mean = 2 per million; Francis & Kucera, 1982); high-frequency targets had frequencies of 46 or more per million (Mean = 141 per million).

b. *Pred* indicates the predicted values, which were based on the following parameter values: $f_b = 195$; $f_m = 17$; $\Delta = 0.70$; $\theta = 0.5$; $t(m) = 150$; $t(M) = 50$; $\epsilon_1 = 1.25$; and $\epsilon_2 = 1.75$ (as reported by Reichle et al., 1998).

Table 3. Mean Observed and Predicted Values for Four Reading-Related Phenomena.

	Spillover Effects ^a	Parafoveal Preview Benefit ^b	Fixation Costs of Word n for Skipping ^c	
			Word $n-1$	Word $n+1$
Observed	20 ms	40-60 ms	50 ms	38 ms
Predicted ^d	22 ms	40 ms	52 ms	173 ms

Notes:

- a. Observed values are typical of those reported in the literature (e.g., Rayner & Duffy, 1986).
- b. Observed values are typical of those reported in the literature (e.g., Balota et al., 1985).
- c. Observed values were calculated from the Schilling et al. (1998) sentence corpus, as reported by Reichle et al. (1998).
- d. Predicted values were based on the following parameter values: $f_b = 195$; $f_m = 17$; $\Delta = 0.70$; $\theta = 0.5$; $t(m) = 150$; $t(M) = 50$; $\epsilon_1 = 1.25$; and $\epsilon_2 = 1.75$ (as reported by Reichle et al., 1998).

Table 4. A Comparison of the Reading Models^a with Respect to Reading-Related Phenomena^b that are Explained by the E-Z Reader Model.

Reading Phenomena	Oculomotor Models			Processing Models		
	Strategy-Tactics	Word Targeting	Minimal-Control	Reader	Attention-Shift	Mr. Chips
Gaussian Landing Site Distributions	Yes	Yes	No	No	Yes	No
Systematic Range Error	Yes	Yes	No	No	No	No
Parabolic Refixation Function	Yes	Ltd	No	No	Yes	Ltd
Means for Word-Based Measures	No	No	Ltd	Ltd	Ltd	No
Word Frequency Effects	No	No	No	Ltd	Ltd	No
Parafoveal Preview Benefit	No	No	Ltd	No	Ltd	Ltd
Spillover Frequency Effects	No	No	No	No	No	No
Fixation Costs for Skipping	No	No	No	No	Ltd	No

Notes:

a. The primary references for the reading models are: (1.) *Strategy-Tactics* (O'Regan, 1990, 1992); (2.) *Word-Targeting* (McConkie et al., 1988; Reilly & O'Regan, 1998); (3.) *Minimal-Control* (Suppes, 1990, 1994); (4.) *Reader* (Just & Carpenter, 1980, 1987, 1992; Thibadeau et al., 1982); (5.) *Attention-Shift* (Reilly, 1993); and (6.) *Mr. Chips* (Legge et al., 1997; Klitz et al., 2000).

b. *Yes* indicates that a model can explain a result; *No* indicates that it does not; *Ltd* indicates that the model's account of a phenomenon is incomplete (e.g., the models predicts parafoveal preview benefit, but the benefit is not modulated by foveal processing difficulty).

Figure Captions

Figure 1. The moving-window paradigm. Panel A shows the positions of three successive fixations (indicated by the asterisks) in a normal line of text. Panels B and C illustrate how a “window” of normal text is displayed contingent upon where the eyes are currently looking. Panel B shows a two-word moving window; that is, both the fixated word and the word to the right of fixation are displayed normally, and all of the letters in the remaining words are replaced by Xs. In Panel C, the window extends four character spaces to the left of fixation and 14 character spaces to the right of fixation.

Figure 2. Landing site distribution as a function of the saccade length between the launch site (word_{n-1}) and intended saccade target (word_n). In all three panels, the launch site and target words are depicted by rectangles, with character spaces represented by numbers (as per convention, the space to the left of word_n is denoted by a zero.) The landing site distributions are approximately Gaussian in shape. Although the distributions are centered near the middle of the saccade targets, the oculomotor system is biased towards making saccades approximately seven character spaces in length. This bias results in a systematic range error; that is, the eyes tend to overshoot close targets and undershoot more distant targets. For example, in Panel B, the intended saccade target is five character spaces from the launch site, so that (on average) the eyes overshoot their intended target, thereby causing the landing site distribution to shift towards the end of word_n . In Panel C, the opposite happens: The eyes undershoot their target, causing the landing site distribution to shift towards the beginning of word_n .

Figure 3. A schematic diagram of the E-Z Reader model (Reichle et al., 1998, 1999). The familiarity check, or initiate stage of word identification, signals the oculomotor systems to begin programming a saccade to the next word, while the completion of lexical access causes attention to shift to the next word. Saccadic programming is thus decoupled from the shifts of attention. Saccadic programming is completed in two stages: The first, labile, stage can be canceled by the initiation of subsequent programs; the second, non-labile stage is not subject to cancellation. Saccades are executed immediately after the non-labile stage of saccadic programming has been completed.

Figure 4. A diagram showing how parafoveal preview benefit is modulated by normative word frequency. The bottom line represents the time required to complete the familiarity check, $t(f_n)$, as a function of the natural logarithm of word_n 's token frequency. The middle line represents the time required to complete lexical access, $t(lc_n)$, on word_n . Finally, the top line represents the saccadic latency, or time required to initiate a saccade from word_n to word_{n+1} . On average, the saccadic latency requires a constant $t(m_{n+1}) + t(M_{n+1})$ ms to complete (starting from the point in time when the familiarity check on word_n has been completed). In E-Z Reader, parafoveal preview begins as soon as word_n has been identified and attention has shifted to word_{n+1} . The parafoveal preview is therefore limited to the duration of the interval (depicted by the shaded area in the figure) between $t(lc_n)$ and $t(m_{n+1}) + t(M_{n+1})$. Notice that, because the relative disparity between $t(f_n)$ and $t(lc_n)$ increases as the frequency of word_n decreases, the duration of the parafoveal preview decreases with the frequency of word_n .

Figure 5. E-Z Reader simulation results (as reported by Reichle et al., 1999). Panel A (top) shows the landing site distributions on five-letter words as a function of saccade length (i.e., the distance between the launch site and the middle of the saccade target). The locations of the

launch sites and landing sites are indicated by numbers (in the legend and along the x-axis, respectively) representing ordinal position, from left to right, with the blank space between the two words being zero. The predicted landing sites are similar to those that have been reported elsewhere (e.g., McConkie et al., 1988; cf. Figs. 2 & 5a); that is, the distributions are approximately Gaussian in shape, with means that shift from near the centers to the beginnings of the target words with increasing saccade length. Panel B (middle) shows how the predicted systematic range error depicted in Panel A is modulated by the launch site fixation durations. As is evident, the systematic range error is attenuated following longer (above average duration) fixations on the launch site words. Finally, Panel C (bottom) shows the predicted probabilities of making refixations on four-, five-, six-, and seven-letter words following initial fixations at different locations. Each curve in Panel C represents a different word length and is centered on the x-axis with the left-most point corresponding to the space preceding the word, the next point corresponding to the first letter in the word, etc. This type of parabolic refixation function is consistent with those reported in the literature (e.g., Rayner et al., 1996).

Figure 6. A schematic diagram of the Attention-Shift model (Reilly, 1993). In the model, visual input is represented by an array of 26 letters that can be in any of 20 different spatial locations (position 8 is the center of the fovea). The core of the model consists of two connectionist networks that work in tandem to identify words and move the eyes. The first network, labeled “Lexical Encoding” in the figure, has as its input the activation values of each letter from the 16 central spatial positions. This information is used to identify individual words, which are represented by the word units as unique 8-bit patterns. The input to the second network, labeled “Saccadic Programming” in the figure, are the maximal values from each spatial position, which is used to compute the direction and amplitude of the saccades. The “Asymptote Detectors” determine when the networks have settled into stable activation patterns, and thus provide an index of processing time. Word identification causes attention to shift, which modifies the visual input by reducing the activation values of unattended spatial input units (this is represented by the thick dashed arrows in the figure). Attention shift also enable saccades, which are executed after the “Saccadic Programming” network has settled into a stable pattern or after a certain time interval (which is determined by the “Timer”). Saccades also modify the visual input by boosting the activation values of the letters in the next word.

Figure 7. A schematic diagram of the Mr. Chips model (Legge et al., 1997; Klitz et al., 2000). The model attempts to compute the saccade length that will minimize the uncertainty about the identity of next unidentified word. It does this using three sources of information: (1.) the relative frequencies with which the words in its lexicon occur in text; (2.) the accuracy of saccades for each possible saccade length; and (3.) visual information from the model’s “retina.” Visual information is encoded from two regions in the retina: a fovea, in which letters can be identified, and a parafovea, in which letters can be discriminated from blank spaces. (In the figure, the retina is presented by a rectangle, with the white and gray areas corresponding to the fovea and parafovea, respectively.) The entropy-minimization algorithm computes the saccade length that will minimize the uncertainty of the next unidentified word, and then an error-prone “Saccade Generator” executes the saccade so that the retina can encode additional letter information.

Figure 8. The time course of cognitive processing (as specified in the E-Z Reader model; Reichle et al., 1998, 1999) as the eyes move from word_n to word_{n+1}. The right side of the figure

shows the neural processes (and their locations within the brain) that may mediate these cognitive processes.

Figure 9. Sagittal views of the left lateral (left side of figure) and medial (right side of figure) cortical, thalamic (i.e., pulvinar nucleus), and mid-brain (i.e., superior colliculus) structures that may mediate the control of eye movements during reading. The letters in the figure correspond to the following brain structures: (1) primary visual cortex (Brodmann's Area [BA] 17); (2) extrastriate cortex (BAs 18 & 19); (3) inferior temporal gyrus (BAs 20 & 37); (4) posterior inferior parietal lobule (i.e., angular gyrus; BA 39); (5) intraparietal sulci (i.e., parietal eye fields; BAs 7 & 40); (6) pulvinar nucleus of the thalamus; (7) superior prefrontal and posterior superior frontal gyri (i.e., frontal eye fields; BAs 6 & 8); (8) superior colliculus; (9) posterior middle and superior temporal gyri (i.e., Wernicke's area; BAs 21 & 22); and (10) the motor circuits of the brainstem which actually execute saccades. (Although the figure only shows the left hemisphere, the right hemisphere homologues of structures 1, 2, 5, 6, and 7 are also components of the visuospatial, attention, and oculomotor networks.)

Figure 1.

A. Normal Text

the link between eye movements and language
*
the link between eye movements and language
*
the link between eye movements and language
*

B. Moving Window: 2 Words

xxx link between xxx xxxxxxxxxx xxx xxxxxxxxxx
*
xxx xxxx between eye xxxxxxxxxx xxx xxxxxxxxxx
*
xxx xxxx xxxxxxxx eye movements xxx xxxxxxxxxx
*

C. Moving Window: 4 Spaces Left & 14 Spaces Right

xxe link between eye xxxxxxxxxx xxx xxxxxxxxxx
*
xxx xxxx between eye movemexxxx xxx xxxxxxxxxx
*
xxx xxxx xxxxxxxn eye movements and xxxxxxxxxx
*

Figure 2.

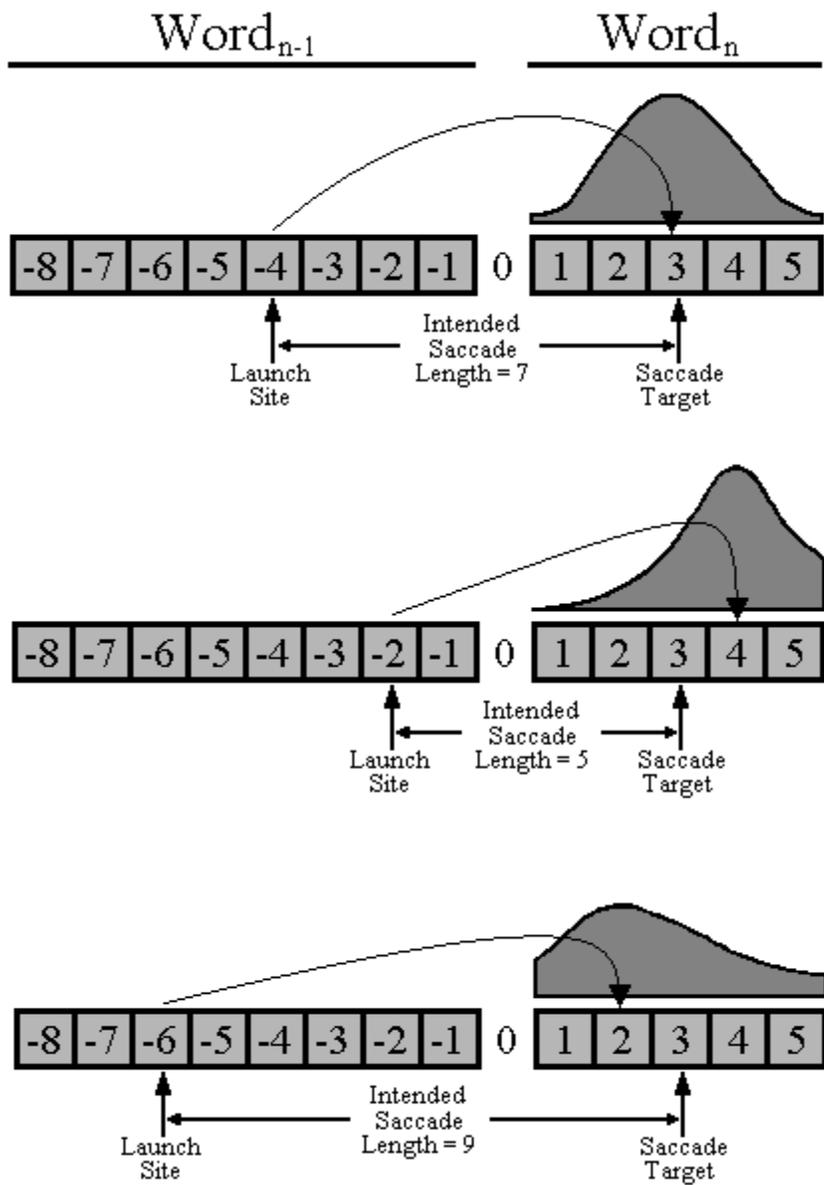
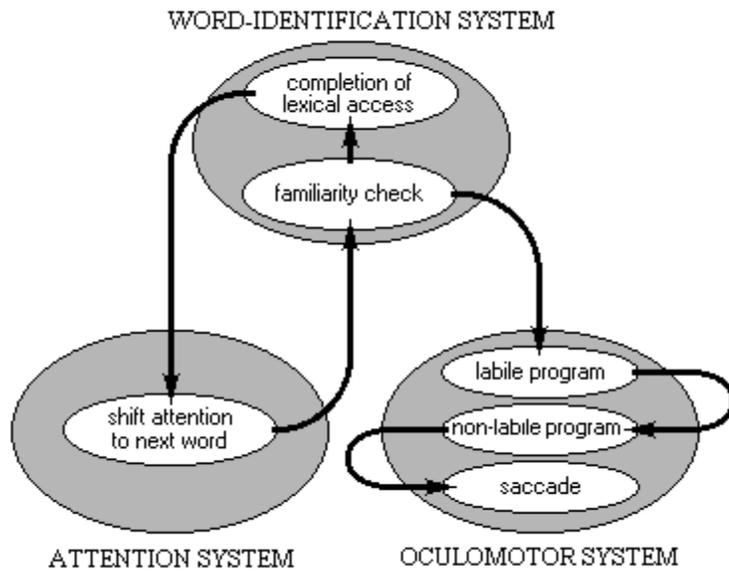


Figure 3.



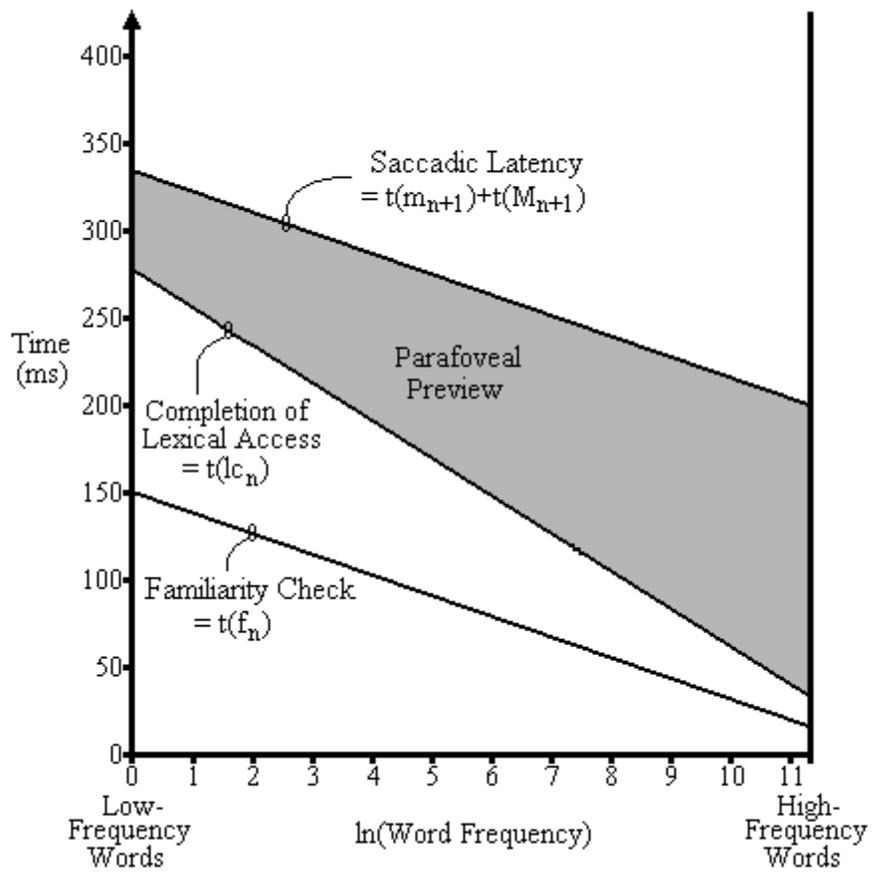
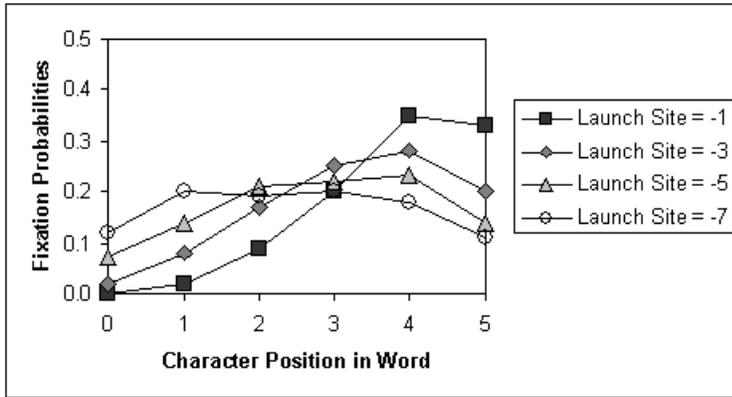


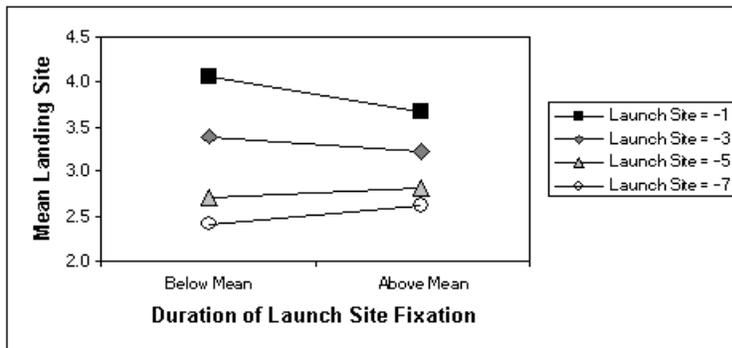
Figure 4.

Figure 5.

A.



B.



C.

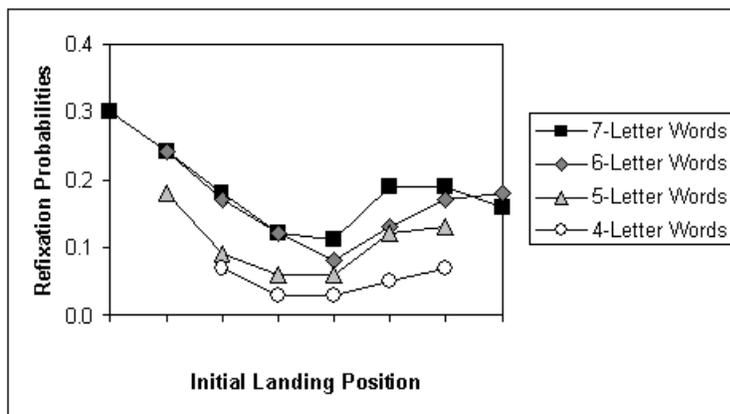


Figure 6.

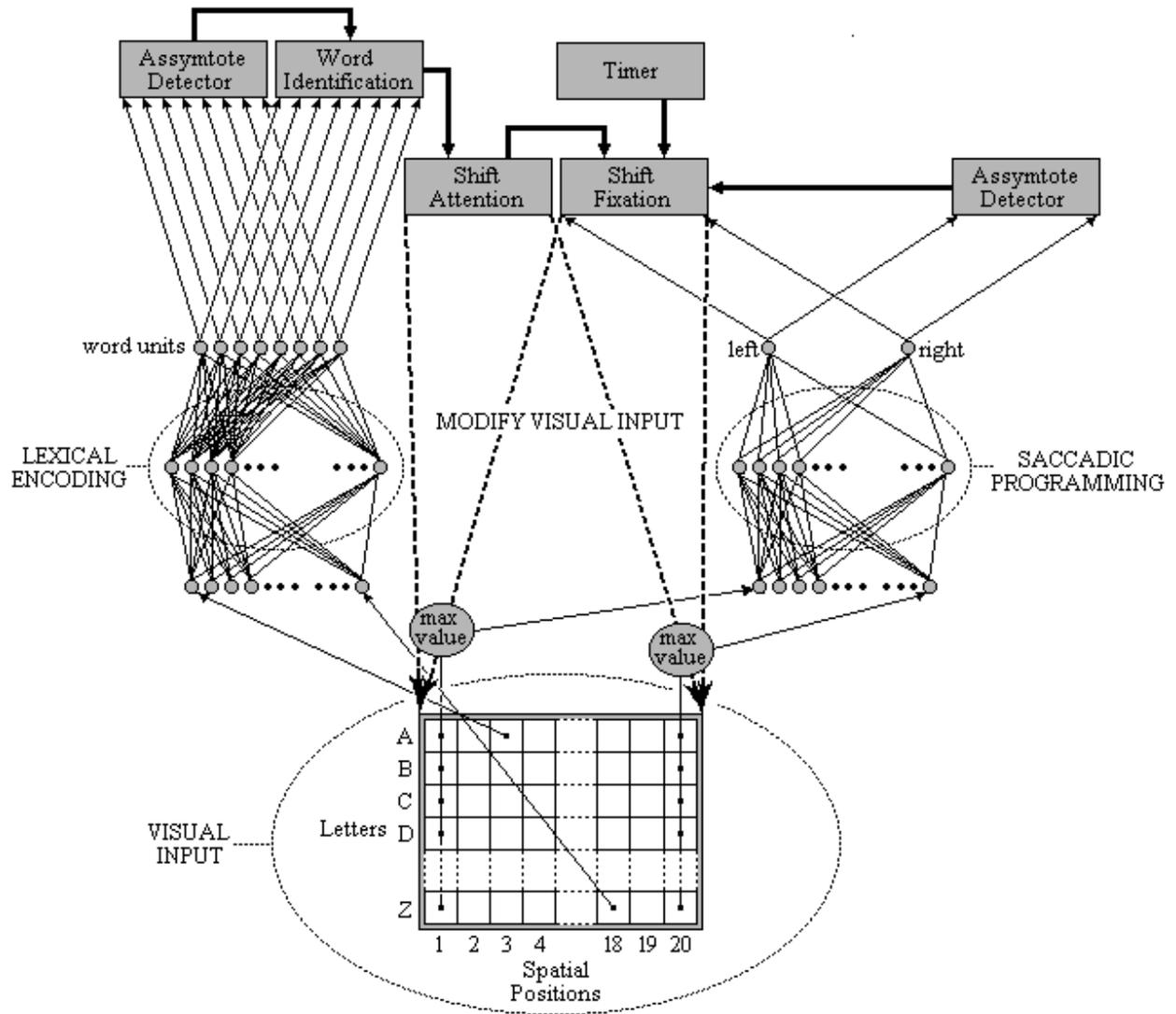


Figure 7.

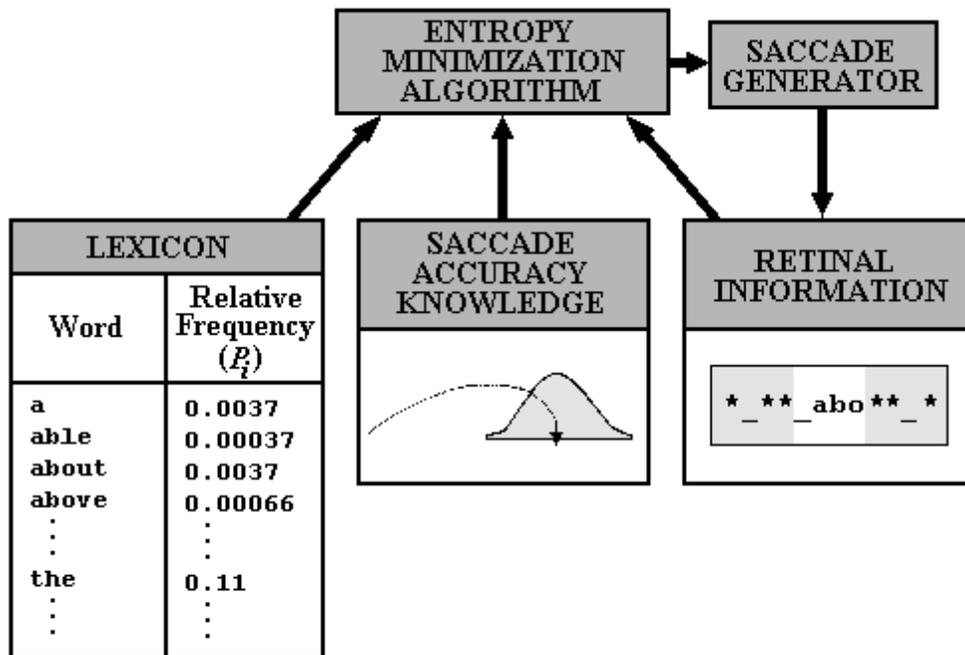


Figure 8.

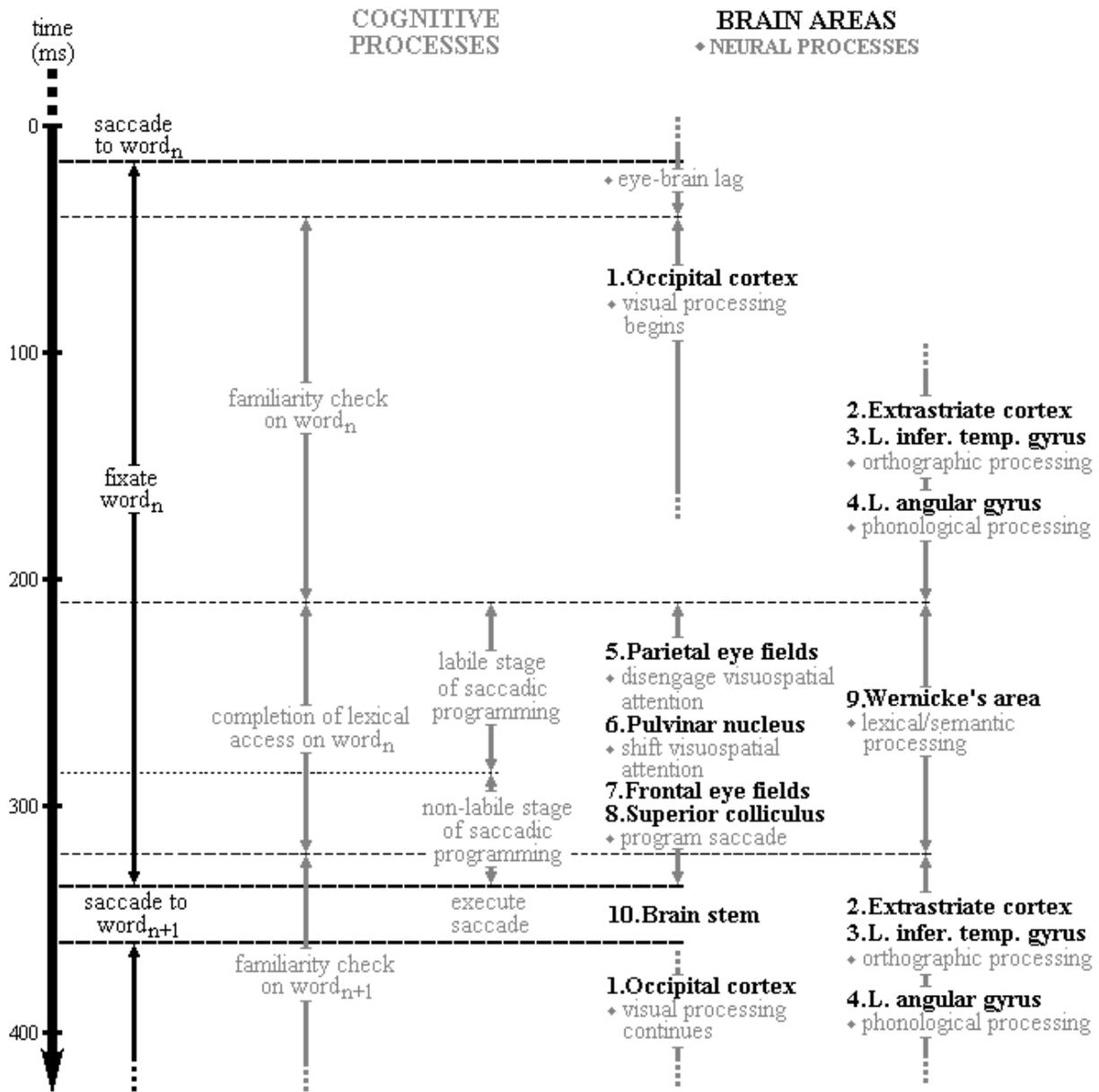


Figure 9.

