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# Understanding Eye Movements in Reading

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The primary characteristics of eye movements during reading are reviewed and 4 areas are summarized: (a) the span of effective vision, (b) integration of information across eye movements, (c) the decision of where to fixation next, and (d) the decision of when to move the eyes. In addition, some current controversies about eye movements and reading are discussed.

In his article, McConkie (this issue) describes some historical and personal reflections on our initial work using eye movements to study the reading process. In this article, I review the major findings that have emerged over the past 25 years of research on eye movements in reading. My own bias is that understanding eye movements during reading is vitally important for understanding the reading process. The results of many studies using eye movement data have placed severe constraints on the direction a theory of reading should go. In addition, eye movement data have proved to be very useful in adjudicating between alternative theoretical accounts of how different processes operate during skilled reading. I shall return at the end of the article to further discuss why understanding eye movement behavior is important in understanding reading.

Research on eye movements during reading over the past 25 years can be divided into two types of efforts: (a) studies that deal with aspects of eye movements per se and (b) studies that use eye movements as a tool or method of investigation for language processing per se. For the most part, in this article, I focus on the former type of study (see Rayner & Sereno, 1994, for a review of the latter types of work). As I hope to document in this article, considerable advances have been made in understanding eye movements during reading. My goal is to review these findings

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and point out where there seems to be some agreement. However, after reviewing some general findings, I discuss some current controversies.

Four major issues are reviewed: (a) the span of effective vision, (b) integration of information across eye movements, (c) the decision about where to fixate next, and (d) the decision about when to move the eyes. Prior to discussing these issues, I first provide a brief overview of some basic facts about eye movements and reading. Then, I discuss issues related to the most appropriate measure of processing time related to eye fixations.

## BASIC FACTS ABOUT EYE MOVEMENTS AND READING

During reading, we make a series of eye movements *(saccades)* in which the eyes move very rapidly. The saccades are separated by periods of time when the eyes are relatively still *(fixations)*. The typical saccade is about six to nine letter spaces; this value is not affected by the size of the print as long as it is not too small or too large (Morrison & Rayner, 1981). Thus, the appropriate metric to use when discussing eye movements in reading is letter spaces, and not visual angle (generally, 3 to 4 letter spaces is equivalent to 1° of visual angle). Because of the high velocity of the saccade, no useful information is acquired while the eyes are moving; readers only acquire information from the text during the fixations (Wolverton & Zola, 1983). The average fixation duration in reading is on the order of 200 to 250 msec. The other primary characteristic of eye movements is that about 10% to 15% of the time readers move their eyes back in the text *(regressions)* to look at material that has already been read.

As text difficulty increases, fixation durations increase, saccade lengths decrease, and regression frequency increases. More important, the values presented for fixation duration, saccade length, and regression frequency are averages and there is considerable variability in all of the measures. Thus, although the average fixation duration might be 225 msec and the average saccade length might be 8 letter spaces for a given reader, for others these values might be somewhat higher or lower. This between reader variability (which also exists for regression frequency) is perhaps not as important as the fact that there is considerable within reader variability. In other words, although a reader's average fixation duration is 225 msec, the range can be from under 100 msec to over 500 msec within a passage of text. Likewise, the variability in saccade length can range from 1 letter space to over 15 letter spaces (though such long saccades typically follow regressions).

Eye movements during reading are necessary because of acuity limitations in the visual system. A line of text extending around the fixation point can be divided into three regions: foveal, parafoveal, and peripheral. In the foveal region (extending 1° of visual angle to the left and right of fixation), acuity is sharpest and the letters can be easily resolved. In the parafoveal region (extending to 5° of visual angle on either side of fixation) and the peripheral region (everything on the line beyond the parafoveal region), acuity drops off markedly so that our ability to identify letters is not very good even in the near parafovea. Thus, the purpose of eye movements is to place the foveal region on that part of the text to be processed next.

## MEASURES OF PROCESSING TIME

One great virtue of eye movement data is that they enable researchers to study moment-to-moment processing activities of readers. One of the hopes that McConkie and I had initially was that eye movements would provide such information, and my belief is that the past 25 years of research has validated this hope.

As indicated earlier, there is quite a bit of variability in how long individual readers fixate and how far they move their eyes. What causes this variability? A great deal of research (discussed later) has demonstrated that much of the variability in fixation time and saccade length is related to cognitive processes associated with comprehension. Indeed, fixation times vary as a function of the ease or difficulty associated with comprehending the words in the text. Thus, it has become important to identify processing time measures for eye movement data in relation to individual words (see Blanchard, 1985). If readers made only one fixation on each word in the text, there would be little problem. Unfortunately, things are not that simple because at least 20% to 30% of the words in text are skipped altogether (i.e., do not receive a fixation) and some words are fixated more than once before the reader moves on to another word.

Because of the skipping and multiple fixation problems, a number of different measures of processing time associated with individual words have been proposed. One measure, *gaze duration* (Just & Carpenter, 1980), is the sum of the total fixation time on a word when it is encountered for the first time. Specifically, all of the fixations on a word, before the reader moves to another word, are summed; regressions back to the word are therefore not included in the gaze duration measure. Likewise, if a reader made one fixation on word *n,* then regressed back to an earlier word *(n* - 2), and then came back to word *n,* only the first fixation on the word would contribute to the gaze duration. Gaze duration is probably the most frequently used measure of processing time for a word. A second measure, *first fixation duration* (Inhoff, 1984), represents the duration of the first and/or only fixation on a word on the first pass, again conditional on the word being fixated. A third measure is the *single fixation duration* (Rayner, Sereno, & Raney, 1996), which is the duration of fixations on words that are fixated exacdy once on the first pass through the text. Obviously, measures of mean second and third fixations on a word can also be obtained. However, because most words are fixated only once, these measures are not commonly examined. Finally, a fourth measure is the *total time* spent on a word. This value includes not only the first pass fixation time included in the gaze duration, but also any additional time spent on the word when regressing back to it.

The aforementioned measures record how long a reader fixates a word given that he or she fixated it. To make the record complete, measures of the probability that a word was fixated or skipped are also usually taken, as well as the probability that a word was skipped initially and later regressed to. My general belief is that as much information as possible should be examined in inferring cognitive activities associated with word processing. Examination of all of the measures discussed earlier provides researchers with a great deal of information to be used to construct a coherent explanation of how words are processed. With these preliminary points behind us, I now turn to a review of some central issues in eye movement research.[1]

## THE SPAN OF EFFECTIVE VISION

What is the size of the *perceptual span* or the *effective visual field* (the area from which readers acquire useful information) during an eye fixation in reading? This basic question has inspired a great deal of research. To investigate this question, George McConkie and I developed what has become known as the *eye-contingent display change* paradigm. As noted by McConkie (this issue), around the same time that we developed the technique, Steve Reder and Kevin O'Regan were also working on developing the technique. In this paradigm, a reader's eye movements are monitored (generally every millisecond) by a highly accurate eye-tracking system. The eyetracker is interfaced with a computer that controls the display monitor from which the respondent reads. The monitor has a rapidly decaying phosphor and changes in the text are made contingent on the location of the reader's eyes. Generally, the display changes are made during saccades and the reader is not consciously aware of the changes.

There are three primary types of eye-contingent paradigms: *the moving window, foveal mask,* and *boundary techniques.* With the moving window technique (McConkie & Rayner, 1975), on each fixation a portion of the text around the reader's fixation is available to the reader. However, outside of this window area, the text is replaced by other letters, or by Xs (see Figure 1). When the reader moves his or her eyes, the window moves with the eyes. Thus, wherever the reader looks, there is readable text within the window and altered text outside the window. The rationale with the technique is that when the window is as large as the region from which a reader can normally obtain information, reading will not differ from when

[1]The summaries presented in the next four sections are adapted (and updated) from Rayner (1995).

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move smoothly across the page of text        Normal
               *


XXXX XXXothlys across the XXXX XX XXXX
               *                              Moving Window

XXXX XXXXXXXX xxxxss the page of teXX



move smoothlXXXXXXXs the page of text
               *                              Foveal Mask

move smoothly acrosXXXXXXXage of text



move smoothly across the date of text
        *       *                             Boundary

move smoothly across the page of text
                          *
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**FIGURE 1** Examples of the moving window, foveal mask, and boundary paradigms. The first line shows a normal line of text with the fixation location marked by an asterisk. The next two lines show an example of two successive fixations with a window of 17 letter spaces and the other letters replaced with Xs (and spaces between words preserved). The next two lines show an example of two successive fixations with a 7 -letter foveal mask. The bottom two lines show an example of the boundary paradigm The first line shows a line of text prior to a display change with fixation locations marked by asterisks. When the reader's eye movement crosses an invisible boundary (the letter *e* in *the),* an initially displayed word *(date)* is replaced by the target word *(page).* The change occurs during the saccade so that the reader does not see the change.

there is no window present. The foveal mask technique (Rayner & Bertera, 1979) is very similar to the moving window paradigm except that the text and replaced letters are reversed. Thus, wherever the reader looks, the letters around the fixation are replaced by Xs whereas outside of the mask area the text remains normal (see Figure 1). Finally, in the boundary technique (Rayner, 1975), an invisible boundary location is specified in the text and when the reader's eye movement crosses the boundary, an originally displayed word or letter string is replaced by a target word (see Figure 1). The amount of time that the reader looks at the target word is computed both as a function of the relation between the initially displayed stimulus and the target word and as a function of the distance that the reader was from the target word prior to launching a saccade that crossed the boundary.

Research using these techniques has been used to determine the size of the perceptual span or area of effective vision during reading. The major findings from the research are as follows:

1. The perceptual span extends 14 to 15 character spaces to the right of fixation (DenBuurman, Boersema, & Gerrisen, 1981; McConkie & Rayner, 1975; Rayner, 1986; Rayner & Bertera, 1979; Rayner, Inhoff, Morrison, Slowiaczek, & Bertera, 1981; Rayner, Well, Pollatsek, & Bertera, 1982).

2. The span is asymmetric and extends further to the right of fixation than to the left for readers of English (and other left-to-right orthographies). To the left of fixation, the span extends to the beginning of the currendy fixated word, or 3 to 4 letter spaces (McConkie & Rayner, 1976; Rayner, Well, & Pollatsek, 1980). For readers of languages printed from right-to-left (such as Hebrew), the span is asymmetric but in the opposite direction from English so that it is larger left of fixation than right (Pollatsek, Bolozky, Well, & Rayner, 1981).

3. No useful information is acquired below the line of text (Inhoff & Briihl, 1991; Inhoff & Topolski, 1992; Pollatsek, Raney, LaGasse, & Rayner, 1993).

4. The word identification span (or area from which words can be identified on a given fixation) is smaller than the total span of effective vision (Rayner et al., 1982; Underwood & McConkie, 1985). The word identification span generally does not exceed 7 to 8 letter spaces to the right of fixation.

5. The size of the span of effective vision and the word identification span is not fixed, but can be modulated by word length. For example, if three short words occur in succession, the reader may be able to identify all of them. If the upcoming word is constrained by the context, readers acquire more information from that word (Balota, Pollatsek, & Rayner, 1985) and if the fixated word is difficult to process, readers obtain less information from the upcoming word (Henderson & Ferreira, 1990; Inhoff, Pollatsek, Posner, & Rayner, 1989; Kennison & Clifton, 1995; Rayner, 1986).

6. Orthography influences the size of the span. Specifically, experiments with Hebrew readers (Pollatsek et al., 1981) suggest that their span is smaller than that

of English readers and experiments with Japanese (Ikeda & Saida, 1978; Osaka, 1992) and Chinese readers (Inhoff & Liu, in press) suggest that their span is even smaller. Hebrew is a more densely packed language than English, and Japanese and Chinese are more densely packed than Hebrew.[2]

7. Reading skill influences the size of the span. Beginning readers (at the end of second grade) have a smaller span than skilled readers (Rayner, 1986) and adult dyslexic readers have smaller spans than skilled readers (Rayner, Murphy, Henderson, & Pollatsek, 1989; Rayner, Pollatsek, & Bilsky, 1995). However, it is most likely the case that a smaller perceptual span in dyslexic readers is due to their difficulty processing fixated words. Thus, the smaller span does not cause their reading problems (Rayner et al., 1995; Underwood & Zola, 1986).

## INTEGRATION OF INFORMATION ACROSS SACCADES

What kind of information is integrated across saccades in reading? Experiments using both the moving window and the boundary technique have demonstrated a preview benefit from the word to the right of fixation; information obtained about the parafoveal word on fixation *n* is combined with information on fixation *n* + 1 to speed identification of the word when it is subsequendy fixated (Blanchard, Pollatsek, & Rayner, 1989; Rayner et al., 1982).

A number of experiments using the boundary paradigm have varied the orthographic, phonological, morphological, and semantic similarity between an initially displayed stimulus and a target word in attempts to determine the basis of the preview effect. The major findings from these studies are as follows:

1. There is facilitation due to orthographic similarity (Balota et al., 1985; Balota & Rayner, 1983; Rayner, 1975; Rayner, McConkie, & Ehrlich, 1978; Rayner et al., 1982; Rayner, McConkie, & Zola, 1980) so that *chest* facilitates the processing of *chart.* However, the facilitation is not strictly due to visual similarity because changing the case of letters from fixation to fixation (so that CAArTbecomes *cHaRt* on the next) has little effect on reading behavior (McConkie & Zola, 1979; O'Regan & Levy-Schoen, 1983; Rayner, McConkie, & Zola, 1980).

2. The facilitation is in part due to abstract letter codes associated with the first few letters of an unidentified parafoveal word (Rayner et al., 1980; Rayner et al., 1982), though there may be some facilitation from other parts of the word to the right of fixation besides the beginning letters (see Inhoff, 1989a; Inhoff & Tousman, 1990). However, the bulk of the preview effect is due to the beginning letters (Briihl & Inhoff, 1995; Rayner et al., 1982). Inhoff s research shows that the effect is not

**[2] *Densely packed* refers to the fact that it takes more characters per sentence in English than Hebrew, for example.**

simply due to spatial proximity because there is farilitation from the beginning letters of words when readers are asked to read sentences from right to left, but with letters within words printed from left to right (Inhoff et al., 1989).

3. There is facilitation due to phonological similarity (Henderson, Dixon, Petersen, Twilley, & Ferreira, 1995; Pollatsek, Lesch, Morris, & Rayner, 1992). Thus, *beech* facilitates *beach* and *shoot* facilitates *chute*, with less facilitation in the latter case.

4. Although morphological factors can influence fixation time on a word (Beauvillain, 1996; Lima, 1987), they don't appear to be the source of the preview benefit (Inhoff, 1987,1989b; Lima, 1987; Lima & Inhoff, 1985).

5. There is no facilitation due to semantic similarity. Thus, *song* as the initial stimulus does not facilitate the processing of *tune,* even though such words yield semantic priming effects under typical priming conditions (Rayner, Balota, & Pollatsek, 1986).

## THE DECISION ABOUT WHERE TO FIXATE NEXT

There are two components to the issue of how eye movements are controlled during reading: (a) where to fixate next and (b) when to move the eyes. It appears that there are separate mechanisms involved in these decisions (Rayner & McConkie, 1976; Rayner & Pollatsek, 1981), and they will accordingly be discussed separately. The primary findings concerning where to fixate next are as follows:

1. Word length seems to be the primary determinant of where to fixate next when moving forward through the text (see Point 8 for regressions). When word length information about the upcoming word is not available (because the spaces are either removed or filled with other letters or letter-like characters), readers move their eyes a shorter distance than when such information is available (McConkie & Rayner, 1975; Morris, Rayner, & Pollatsek, 1990; Pollatsek & Rayner, 1982; Rayner & Bertera, 1979; Rayner & Pollatsek, 1996; Spragins, Lefton, & Fisher, 1976). Also, the length of the word to the right of fixation strongly influences the size of the saccade (O'Regan, 1979,1980; Rayner, 1979).

2. There is a *landing position* effect such that readers tend to fixate about halfway between the beginning and the middle of words (Dunn-Rankin, 1978; McConkie, Kerr, Reddix, & Zola, 1988; O'Regan, 1981; O'Regan, Levy-Schoen, Pynte, & Bragaillere, 1984; Rayner, 1979; Rayner et al., 1996). Rayner (1979) originally termed this prototypical location as the *preferred viewing location.* Subsequently, O'Regan and Levy-Schoen (1987) distinguished between the preferred viewing location and what O'Regan and colleagues now refer to as the *optimal viewing position.* The optimal viewing location is the location in a word at which recognition time is minimized and it is a bit to the right of the preferred viewing location, closer

to the center of the word. Extensive research efforts have examined the consequences of being fixated at locations other than this optimal viewing location (McConkie, Kerr, Reddix, Zola, & Jacobs, 1989; Vitu, 1991; Vitu, O'Regan, & Mittau, 1990) and it has been found that the consequences are more serious when words are presented in isolation than when they are in text. This result suggests either that contextual information overrides low-level visual-processing constraints or that readers are somewhat flexible about where they can acquire information around fixation.

3. There is a launch site effect such that where readers land in a word is strongly influenced by where the saccade came from (McConkie et al., 1988; Rayner et al., 1996). Thus, whereas the most frequent landing position may be near the middle of the word, if the prior saccade was launched some distance (8 to 10 letters) from the target word then the landing position will be shifted to the left of center. Likewise, if the prior saccade was launched close (2 to 3 characters) to the beginning of the target word, the landing position will be shifted to the right of center.

4. Given the two preceding findings, the optimal strategy would be to fixate near the middle of each successive word. However, because short words can often be identified when they are to the right of the currently fixated word, they are often skipped (Blanchard et al., 1989; Rayner, 1979). Factors such as this result in the landing position distribution being spread somewhat due to the launch site effect.

5. Although it has been suggested that semantic information within an as yet-unfixated parafoveal word can influence the landing position in that word (see Everatt & Underwood, 1992; Hyona, Niemi, & Underwood, 1989; Underwood, Bloomfield, & Clews, 1988; Underwood, Clews, & Everatt, 1990), neither Rayner and Morris (1992) nor Hyona (1995) were able to replicate the effect. At this point, it seems safest to conclude that there is no semantic preprocessing effect in which an unidentified parafoveal word influences where the eyes land.

6. On the other hand, if a parafoveal word is identified on the current fixation, the word will typically be skipped and the duration of the fixation prior to the skip is inflated (Hogoboam, 1983; Pollatsek, Rayner, & Balota, 1986). Factors such as word length, word frequency, and predictability influence if a word will be skipped (Rayner et al., 1996).

7. The orthographic regularity of the initial letter clusters in a parafoveal word influence how far into the word the initial saccade goes. Beauvillain, Dore, and Baudouin (1996) and Hyona (1995) found that an irregular letter sequence at the beginning of the parafoveal word results in landing position closer to the beginning of the word than when the sequence is regular.

8. There has not been as much investigation of regressions as there has of forward saccades. Intraword regressions may be due to the eye initially landing in a bad location (O'Regan, 1990), but lexical processes are also involved (Rayner & Pollatsek, 1987). Larger interword regressions back to earlier words or sentences are generally assumed to be due to comprehension failures (Ehrlich & Rayner,

1983). It is interesting that skilled readers are very accurate in regressing to regions of text that were the source of the comprehension problem (Frazier & Rayner, 1982; Murray & Kennedy, 1988).

## THE DECISION ABOUT WHEN TO MOVE THE EYES

A great deal of research indicates that the amount of time a reader fixates on a word or segment of text reveals something about the cognitive processes associated with comprehending that word or segment (although there is some controversy on this point that is discussed in the next section). Some relevant findings are as follows:

1. During reading, information gets into the processing system very early in a fixation (thus leaving a lot of time for processes associated with word recognition and other necessary processes). Experiments using the foveal mask paradigm in which the onset of the mask is delayed following a saccade have demonstrated that if the reader has 50 msec to process the text prior to the onset of the mask then reading proceeds quite normally (Ishida & Dceda, 1989; Rayner et al., 1981; Slowiaczek & Rayner, 1987). If the mask occurs earlier, reading is disrupted. Although readers may typically acquire the visual information needed for reading during the first 50 msec of a fixation, they can extract information at other times during a fixation as needed (Blanchard, McConkie, Zola, & Wolverton, 1984).

2. Although word length strongly effects gaze duration (Kliegl, Olson, & Davidson, 1982; Rayner et al., 1996), it is also influenced by a number of lexical, syntactic, and discourse variables. Furthermore, single fixation duration and first fixation duration have been shown to be influenced by such variables (particularly word frequency). In particular, there are demonstrations that the following variables influence fixation time: (a) word frequency (Henderson & Ferreira, 1993; Hyona & Olson, 1995; Inhoff & Rayner, 1986; Just & Carpenter, 1980; Raney & Rayner, 1995; Rayner, 1977; Rayner & Duffy, 1986; Rayner & Fischer, 1996; Rayner & Raney, 1996; Rayner, Sereno, Morris, Schmauder, & Clifton, 1989; Rayner et al., 1996; Schmauder, 1991); (b) contextual constraint (Altarriba, Kroll, Sholl, & Rayner, 1996; Balota et al., 1985; Ehrlich & Rayner, 1981; Rayner & Well, 1996; Schustack, Ehrlich, & Rayner, 1987; Zola, 1984); (c) semantic relations between words in a sentence (Carroll & Slowiazek, 1986; Morris, 1994; Sereno & Rayner, 1992); (d) anaphora and coreference (Duffy & Rayner, 1990; Ehrlich & Rayner, 1983; Garrod, Freudenthal, & Boyle, 1994; Garrod, O'Brien, Morris, & Rayner, 1990; O'Brien, Shank, Myers, & Rayner, 1988); (e) lexical ambiguity (Binder & Morris, 1995; Doplrins, Morris, & Rayner, 1992; Duffy, Morris, & Rayner, 1988; Folk & Morris, 1995; Rayner & Duffy, 1986; Rayner & Frazier, 1989; Rayner, Pacht, & Duffy, 1994; Sereno, 1995; Sereno, Pacht, & Rayner, 1992); and (f) syntactic disambiguation (Altmann, Garnham, & Dennis, 1992; Altmann, Garn-

ham, & Henstra, 1994; Britt, Perfetti, Garrod, & Rayner, 1992; Clifton, 1993; Ferreira & Clifton, 1986; Ferreira & Henderson, 1990; Frazier & Rayner, 1982; Rayner, Carlson, & Frazier, 1983; Rayner & Frazier, 1987; Rayner, Garrod, & Perfetti, 1992; Trueswell, Tanenhaus, & Kello, 1993).

3. Although the frequency of the fixated word influences fixation time on the word, the frequency of word $n + 1$ does not influence fixation time on word $n$ (Henderson & Ferreira, 1993). Thus, it appears that it is primarily characteristics of the fixated word that influence processing time on the word. However, there is also a spillover effect. Thus, for example, when readers fixate on a low frequency word, the duration of fixation $n$ is longer than when a high frequency word is fixated, but the duration of fixation $n + 1$ is also inflated: The difficulty in processing the low frequency word spills over to the next fixation (Rayner & Duffy, 1986).

## CONTROVERSIES ABOUT EYE MOVEMENTS

For the most part, I have implied that there is quite a bit of consistency in the findings of eye movement research. However, there are also some controversies. In this section, I describe four such controversies. They relate to whether or not (a) eye movements are controlled on a moment-to-moment basis or are due to preexisting oculomotor strategies, (b) the spaces between words are a useful cue in planning and executing eye movements, (c) semantic preprocessing influences where to fixate next, and (d) the eye-contingent display change paradigm yields effects that are due to the display change per se. Each of these controversies are now discussed. But, first a general distinction between different classes of models of eye movement control needs to be made.

There are now quite a few proposals for how eye movements are controlled in reading. For the sake of simplicity, I lump the various proposals into two general categories: (a) processing models (Henderson & Ferreira, 1990; Just & Carpenter, 1980; Morrison, 1984; Pollatsek & Rayner, 1990; Rayner & McConkie, 1976; Rayner & Pollatsek, 1989) in which moment-to-moment comprehension processes (like lexical access of the fixated word) influence the movement of the eyes and (b) oculomotor models (Kowler & Anton, 1987; O'Regan, 1990, 1992; O'Regan & Levy-Schoen, 1987) in which the movement of the eyes is not directly related to ongoing language processing, but is primarily due to oculomotor factors.

According to the processing models, the decision about when to move the eyes is primarily affected by linguistic variables so that fixation times on words reflect moment-to-moment processing complexities of the text. For example, the frequency of the currently fixated word affects how easy the word is to identify, and thus determines the time the eyes spend on the word. Somewhat independendy from this, the decision about Where to move the eyes is affected by perceptual aspects of the forthcoming word, such as its length and distance from the current fixation. The where decision is, however, not directly affected by lexical factors of the forthcoming parafoveal word unless it is identified on the current fixation. Thus, for example, the word frequency (Henderson & Ferreira, 1993) or the informativeness distribution (Rayner & Morris, 1992) of the parafoveal word (word n + 1) does not influence fixation time on word *n* unless it (word *n* + 1) is identified on fixation *n.* If the parafoveal word (word *n* + 1) is identified on fixation *n,* then it will generally be skipped by the ensuing saccade. Word length, word frequency, and predictability all can influence whether or not a parafoveal word is identified on fixation *n.*

According to oculomotor models, the location in a word at which the eyes are initially fixated largely determines how long the eyes remain fixated. Perceptual considerations, such as the strong loss of visual resolution from fovea! to parafoveal vision, have led oculomotor theorists to tightly link the processing of a word to the location at which the word is being fixated. Thus, the decision about when to move the eyes depends on the outcome of the previous decision about where to move the eyes. If the reader fixates at a nonoptimal position in a word (the optimal position is the center of the word), another fixation will need to be made on the word. Lexical factors can have an influence if a single fixation on a word is very long, and they can influence the second of two fixations on a word. Thus, oculomotor factors determine how long readers look at words and fixation times are only rather indirectly influenced by the lexical properties of words.

Thus, there is controversy over the extent to which lexical properties of words influence fixation time on the word. In actuality, there has been a long-standing debate over this issue. Because the reaction time of the eyes in simple oculomotor tasks is known to be at least 175 msec (Rayner, Slowiaczek, Clifton, & Bertera, 1983), it has frequently been argued that the duration of a fixation is too short to permit the reader to process the foveal and parafoveal words, make a decision on the basis of that information where to send the eyes, and then set up the motor program to move the eyes (see Bouma & deVoogd, 1974). However, some of the processing models assume that some of these activities go on in parallel or are independent of each other. Furthermore, it is possible that, for various reasons, the response time to move the eyes in reading is shorter than the estimates obtained from simple oculomotor tasks (see McConkie, Underwood, Zola, & Wolverton, 1985, for one such argument).

In the current controversy, there seems to be acceptance of the fact that characteristics of the fixated word can influence fixation time on that word. What is in dispute seems to be the source of the effect. In support of the idea that oculomotor factors primarily determine when to move the eyes, Vitu, O'Regan, Inhoff, and Topolski (1995) recently reported a study in which respondents either read normal text or they "read" text in which all of the letters had been replaced by zs. Vitu et al. reported that eye movement behavior was quite similar in the two situations; they found that both global characteristics (e.g., the length of saccades, durations of fixations, and the frequency distribution of fixation durations and saccade lengths) and local characteristics (e.g., skipping rates, landing position, and refixation probability) of eye movements were quite similar in the two situations. From this they argued that the similarity in eye movement characteristics in the two situations suggested that predetermined oculomotor strategies are an important element in determining oculomotor behavior during reading.

Rayner and Fischer (1996) extended Vitu et al.'s (1995) study by examining eye behavior with respect to specific target words of high or low frequency when respondents read normal text or z-strings. Globally, they found that the reading condition led to shorter fixations, longer saccades, and less frequent skipping of target strings than did scanning the transformed text. Locally, the manipulation of word frequency affected fixation durations on the target word during reading, but not during scanning. They also found that when readers were asked to search through normal text for a target word, word frequency did not affect fixation time (see also Rayner & Raney, 1996). Rayner and Fischer also found that there were more refixations on target words in reading than in scanning or visual search. Contrary to Vitu et al., we concluded that although there are some surface similarities in eye movements when reading and scanning, that eye movements during reading are strongly influenced by immediate processing demands. It should also be noted that Rayner et al. (1996) showed that single fixations on words are strongly influenced by word frequency, as is the duration of the first of two fixations on a word. Both of these findings are inconsistent with the basic tenets of the oculomotor model. Pynte, Kennedy, and Murray (1991) and Sereno (1992) likewise observed that the duration of the first of two fixations is influenced by the properties of the fixated word. Thus, although oculomotor factors undoubtedly have some influence on eye movement control, the bulk of the evidence is consistent with the processing model.

The second current controversy relates to the usefulness of spaces between words. As noted earlier, a fair amount of research has demonstrated that when space information between words is not available, reading is slowed considerably (by as much as 50%). However, Epelboim, Booth, and Steinman (1994) recently reported a study in which respondents read unspaced text as their eye movements were monitored. Because some of their readers could read unspaced text relatively well and their eye movement patterns were quite similar when reading normal and unspaced text, they argued that unspaced text is relatively easy to read. From this they concluded that the spaces between words are not important in guiding eye movements and that words, not spaces, are the important cues in deciding where to look next. While agreeing that word recognition plays an important role in eye movement control, Rayner and Pollatsek (1996) challenged the conclusion that spaces are not important in reading. They showed that only a couple of Epelboim et al.'s respondents could read unspaced text reasonably well and that the majority of their respondents, like those in other studies, were slowed significantly by the absence of space information. In some recent studies in my lab, we have also found marked differences in local eye movement characteristics when reading spaced and unspaced text. More critically, Kohsom and Gobet (in press) recently demonstrated that when native Thai readers read Thai text with spaces inserted between the words (Thai is normally printed without spaces) that their reading performance is actually facilitated even though they have had no previous experience reading Thai with spaces between the words. Kohsom and Gobet concluded, as did Rayner and Pollatsek (1996), that when spaces are present, they are used to guide eye movements. The bulk of the evidence is thus consistent with the idea that the spaces between words are a useful cue in deciding where to look next.

The third controversy was mentioned earlier in this article. Specifically, Underwood et al. (1990) reported some results that suggest that some type of semantic preprocessing of unidentified (and as yet-unfixated) parafoveal words influences where readers fixate in words. Rayner and Morris (1992) pointed out some theoretical and methodological problems with the research. Furthermore, we were unable to find evidence consistent with such preprocessing effects. Recent studies by Hyona (1995) and Beauvillain (1996) are also consistent with the findings of Rayner and Morris (1992). With respect to this issue, my view is that the weight of the evidence is inconsistent with the semantic preprocessing view.

Finally, there is some controversy with respect to studies that have utilized the eye-contingent display change paradigm. Specifically, it has been suggested that effects found may be due to the display changes per se or to respondents seeing, either consciously or unconsciously, the change (see O'Regan, 1990). Although one always has to be careful in eye-contingent experiments to ascertain that the display changes are taking place at the appropriate time and that the findings are not artifactual in some way, I know of no evidence to suggest that findings from such experiments are due to display changes per se. Indeed, Briihl and Inhoff (1995) recently conducted some analyses examining whether the point at which the display change occurred (provided that it was within a reasonable time window) or the magnitude of the change affected fixation times following the change; they found no evidence that would support the position that display changes per se camouflage effects manifest in fixation times.

## TOWARD A MODEL OF EYE MOVEMENT CONTROL

Hopefully, it is evident from this article that a great deal has been learned about eye movements during reading. Given that we have gained so much knowledge about the characteristics of eye movements during reading, I wondered if it might be possible to predict (a) how long readers would fixate on words and (b) when readers skip words in reading. Thus, over the past couple of years, my colleagues (Erik Reichle, Sandy Pollatsek, and Don Fisher) and I have implemented a simulation model of eye movement control in reading . The model (which is called the E-Z Reader model) does a very good job of predicting fixation time on words and skipping rates for words. Furthermore, it is psychologically plausible and does the job with only a few free parameters. Space limitations preclude any extended discussion of the model (see Reichle, Pollatsek, Fisher, & Rayner, in press), but it does account for a large number of the findings that have been reviewed in this article. At the moment, it does not account for landing position effects (which we think will be relatively easy to implement in the model) nor does it account for higher order effects (which we think will be difficult to implement) such as syntactic or discourse effects. It also does not account for long regressions (short, within word regressions are accounted for by the model). But, it does account for effects of frequency, predictability, the preview effect, spillover effects, and so on.

One important benefit from our modeling work is that the model predicted effects that had not previously been observed. For example, it had previously been reported that when readers skip a word that the duration of the fixation prior to the skip is inflated (Hogaboam, 1983; Pollatsek et al., 1986), and the model accounted for this result. However, it had not previously been reported that when a word is skipped, the duration of the fixation after the skip is also inflated. The model predicted this effect and we found that it was present in the corpus of data we used to compare actual reading performance with the model.

Given the large amount of data that have been collected regarding eye movements during reading, my view is that the time is ripe for the development of formal models that account for the characteristics of eye movements in reading. My guess is that a fair amount of our effort over the next few years will be to refine the model.

## UNDERSTANDING EYE MOVEMENT BEHAVIOR DURING READING

At the beginning of this article, I asserted that understanding eye movements during reading was important for understanding skilled reading. As I indicated there, eye movement data have been very useful in discriminating between different theoretical accounts of reading-related processes (see Rayner & Sereno, 1994). The aim of the research and simulation work in my laboratory has been to give a reasonable account of how cognitive and lexical processing influences the eye movements of skilled readers. This is a necessary and important enterprise for two reasons.

First, as noted earlier in this article, aspects of eye behavior, such as the durations of eye fixations on words or on regions of text, are often used to infer cognitive processes in reading (Just & Carpenter, 1987; Rayner & Pollatsek, 1989). Second, reading is perhaps the most important skill that people acquire for which they may not have been biologically programmed. If we can understand the skill that has been acquired in reading, it might shed light on skill acquisition in general. I have long believed that if we can understand what skilled readers do, it will be advantageous in teaching children the skill in the first place and in providing remediation for those who do not learn it well.

I tend to believe that the facts that we have learned about eye movements in reading and about reading in general from studying eye movements have placed severe constraints on a theory of reading. When George McConkie and I began our research on reading 25 years ago, the view of the skilled reader was one in which reading was only incidentally visual and in which the reader spent most of his or her time generating predictions of upcoming words. Our research, and that of others, has shown that readers are not unsystematically scanning the text looking for the clues to meaning, but rather that they are systematically moving their eyes from left to right across the text fixating on most of the content words (while skipping some function words). We have shown that the region from which readers obtain meaning is rather limited, but that the processing associated with each word is very rapid and that the link between the eyes and the mind is very tight.

## PERSONAL REFLECTIONS

I would like to conclude this article with two points. First, I greatly appreciate the award that was bestowed on George McConkie and myself from the Society for the Scientific Study of Reading. My first professional appointment was in the School of Education at the University of Rochester (with a joint appointment in Psychology). I left Rochester for a position in the Psychology Department at the University of Massachusetts in part because I felt that the work that I was doing was not really appreciated by those interested in reading in the field of education; the work that I was doing seemed to be much better appreciated within the field of cognitive psychology. The fact that McConkie and I were selected as the first recipients of the award by an organization that has typically met in association with the American Educational Research Association suggests that at least some people within the educational field appreciate the nature of the work we have done and I genuinely appreciate this fact.

Second, I want to confirm that setting up an active eye movement laboratory is no small feat and that it takes people who are dedicated to the task. Although I was able to obtain the basic equipment for my lab while still at Rochester, it wasn't until I moved to University of Massachusetts (UMass) that the development of the lab came to fruition. I could never have accomplished the task without the many colleagues at the UMass who have been involved in the lab development. I would specifically like to acknowledge the efforts of Sandy Pollatsek Chuck Clifton, and Jim Bertera in the original hardware and software development in the eye tracking lab at the UMass. And, finally, I would like to thank the many excellent graduate students, post docs, and colleagues that I have collaborated with over the years that I have been at UMass. They have made it exciting and a lot of fun!

As this article hopefully makes clear, I believe that we have learned a lot about reading from the study of eye movements. My best guess is that the bulk of future research will utilize eye movements as a tool to study reading and that not as much of the work will focus on understanding eye movements per se. But, either way, our understanding of reading will benefit from the work.

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