Eye Movements in Reading: Recent Developments

Keith Rayner

When we read, our eyes do not move smoothly across the page of text as our phenomenological impressions imply. Rather, we make a series of eye movements (referred to as *saccades*) separated by periods of time when the eyes are relatively still (*fixations*). Eye movements are necessary during reading because of acuity limitations in the visual system. A line of text extending around the point of fixation can be divided into three regions: foveal, parafoveal, and peripheral. The foveal region is the center of vision (extending 1° of visual angle to the left and right of fixation), where acuity is sharpest, enabling us to resolve the letters in the text easily. In the parafoveal region (extending out 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. The purpose of eye movements in reading is therefore to place the foveal region on that part of the text we wish to process next.

The basic facts about eye movements during reading have been known for some time. The typical saccade is about eight 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. The appropriate metric to use when discussing eye movements during reading is therefore letter spaces, and not visual angle; generally, three to four 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 acquire information from the text during fixations. The average fixation duration is about a quarter of a second (250 ms). The other primary characteristic of eye movements during reading is that about 10% to 15% of the time, we move our eyes back in the text (*regressions*) to look at material that we have already read.

It is also important to note that as text difficulty increases, fixation duration increases, saccade length decreases, and regression frequency increases. More important, the values just presented are averages, and there is considerable variability in the measures, both between and within readers. Thus, although the average fixation duration for a given reader might be 250 ms, for others it could be on the order of 200, 235, 280, or 300 ms. The average saccade length and regression frequency also vary across readers. As far as within-subject variability is concerned, although a reader's average fixation duration might be 250 ms, the range could be from under 100 ms to over 500 ms within a passage of text. Likewise, although the average saccade length for a given reader might be 8 letter spaces, the range could be from 1 letter to over 15 (though such long saccades typically follow regressions). A great deal of recent research has documented that the variability in these measures is related to the ease or difficulty associated with processing the text.

Since the mid-1970s, there has been a resurgence of interest in using eye movement data to study the reading process.[1] Researchers have typically been interested in eye movements during reading for two reasons: (1) to describe the characteristics of the eye movements per se and (2) to use eye movement data to infer something about perceptual and cognitive processes during reading. Because most of the work in my laboratory has focused on the latter issue, the major focus of this article is on processing during reading.

THE EYE-CONTINGENT PARADIGM

A major breakthrough in studying the reading process has been due to the development of the *eye-contingent display change* paradigm.[2] In this paradigm, a reader's eye movements are monitored (generally every millisecond) via an accurate eye-tracking system. The eye-tracker is interfaced with a computer, which, in turn, controls a display monitor (which has a rapidly decaying phosphor) from which the subject reads. Changes in the text are made at precise times contingent on the location of the reader's eyes; sometimes the changes are made during a saccade (so that they are not perceived by the reader), and sometimes the changes are made during a fixation.

Moving-Window Technique

The moving-window technique was developed to investigate the size of the span of effective vision during an eye fixation. With this technique, on each fixation, a portion of the text around the fixation is available to the reader. Outside this window area, the text is replaced by other letters or by xs (see Fig. 1).

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eyes do not move smoothly across the page of text        Normal
                   *
---------------------------------------------------
XXXX XX XXX move smoothly acXXXX XXX XXXX XX XXXX
                   *                                     Moving
                                                         Window
XXXX XX XXX XXXX XXXothly across the XXXX XX XXXX
                            *
---------------------------------------------------
XXXX XX XXX XXXX smoothly acXXXX XXX XXXX XX XXXX        Asymmetric
                   *
cqcr bc maf move smoothly acsarr fbc qoyc at fcvf        Similar-
                   *                                     Letters
XXXXXXXXXXXXmove smoothly acXXXXXXXXXXXXXXXXXXXX         No-Spaces
                   *
XXXX XX XXX XXXX smoothly XXXXXX XXX XXXX XX XXXX        One-Word
                   *
XXXX XX XXX XXXX smoothly across XXX XXXX XX XXXX        Two-Word
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Fig. 1. Examples of the moving-window paradigm. 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. The remaining lines show examples of other types of experimental conditions. In the asymmetric example, the window extends 3 letters to the left of fixation and 8 to the right; in the similar-letters condition, the letters outside the window are replaced by similar letters rather than Xs; in the no-spaces example, all of the spaces between words are filled in outside the window; in the one-word example, only the fixated word is within the window; and in the two-word example, the fixated word plus the word to the right of fixation is available.

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 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 there is no window present.

A number of studies using the moving-window technique have found that the span of effective vision extends about 14 to 15 letter spaces to the right of fixation. However, the span is asymmetric, extending no more than about 4 letters to the left of fixation for readers of English. For readers of right-to-left orthographies, such as Hebrew, the span is asymmetric in the other direction (extending further to the left than to the right). Characteristics of the orthography also influence the size of the span: More densely packed orthographies, such as Chinese and Japanese, yield smaller spans.[3] Another interesting finding is that beginning readers have a smaller span than skilled readers; the span extends only about 11 letters to the right of fixation for children at the end of first grade, but it is asymmetric. Finally, skilled readers do not obtain useful information from below the fixated line, though if the task is visual search, some information is acquired.[4]

Boundary Technique

The boundary technique was developed to determine what type of information is integrated across eye movements in reading. In this technique, a boundary location is specified in the text; when the reader's eye movement crosses the invisible boundary, an originally displayed word or letter string is replaced by a target word (see Fig. 2). The amount of time that the reader looks at the target word is computed both as a function of the relationship 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 the saccade that crossed the boundary.

Experiments using both the moving-window and the boundary techniques have demonstrated a *preview benefit* from the word to the right of fixation. That is, information ob-

eyes do not move smoothly across the date of text Prechange
* * * *

eyes do not move smoothly across the page of text Postchange
*

Fig. 2. 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.

tained about the parafoveal word on fixation n is combined with information on fixation $n + 1$ to speed the identification of the word when it is subsequently fixated.

In a number of different experiments, orthographic, phonological, morphological, and semantic similarity between the initially displayed stimulus and the target word have been varied to determine the basis of the preview effect.[5] The results of these experiments indicate that there is facilitation due to orthographic similarity, 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 *cHaRt* on one fixation would be *ChArT* on the next) has little effect on reading behavior. Thus, the facilitation is due to abstract letter codes associated with the first few letters of an unidentified parafoveal word to the right of fixation.[6] There is also facilitation due to phonological similarity, so that *beech* facilitates *beach* and *chute* facilitates *shoot*, but there is less facilitation in the latter than in the former case. Although morphological factors can influence fixation time on a word, they are not the source of the preview benefit. Finally, there is no facilitation due to semantic similarity: *song* as the initial stimulus does not facilitate the processing of *tune* (though such words yield semantic priming under typical priming conditions).

Masking Technique

The foveal masking technique is quite similar to the moving-window technique, except that a mask moves with the eyes (see Fig. 3). When the mask is larger than seven letters, this situation results in an artificial foveal scotoma for normal readers. Skilled readers find it very difficult, if not impossible, to read when foveal vision is masked.

The results of experiments using the masking technique and the boundary technique suggest that word identification takes place within a rather restricted region during each eye fixation. Readers typically identify the word that they are fixated on. However, when the word to the right of fixation is short, they often identify it as well, and skip over it with the ensuing saccade.

By delaying the onset of the mask, it has also been possible to determine how quickly information is extracted from the text within a fixation. The results of these experiments indicate that if the reader has 50 ms to process the text prior to the onset of a mask, reading proceeds quite normally; earlier masking disturbs reading. Although readers may typically acquire the visual information needed for reading during the first 50 ms of a fixation, other experiments have demonstrated that readers can extract information at other times during the fixation as needed.[7]

Finally, the masking technique has been used to examine eye movement control during reading.[8] For example, by filling in spaces between words at certain points during each eye fixation or by delaying the onset of the text by first presenting a mask, it has been possible to learn a lot about the programming of eye movements. The results of such studies indicate that decisions about where to move the eyes next and when to move are computed separately: Where to move next is based primarily on word length information, and when to move is based on the ease or difficulty associated with processing the fixated word.

Fast Priming Technique

In the fast priming technique, a target word location is identified in the text. The technique is similar to the boundary technique in that a letter string initially occupies the target location to prevent parafoveal preview. When the reader's eyes cross the boundary, a prime word is first presented for a very brief period. During the fixation, the prime is replaced by the target word (see Fig. 4). To date, only one set of studies has been completed using this technique, and semantic priming effects were observed.[9] The technique is now being used to investigate the extent to which phonological codes are automatically activated during eye fixations in reading and to investigate the resolution of lexically ambiguous words during reading.

PERCEPTUAL PROCESSES

Studies using the eye-contingent display change techniques have led to a number of important observations concerning perceptual processes in reading: The region of effective or useful vision in reading is quite small, the span of word iden-

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eyes do not move smoothly across the page of text      Normal
                  *
----------------------------------------------------
eyes do not moveXXXXXXXly across the page of text
                  *                                    Foveal
                                                       Mask
eyes do not move smoothXXXXXXXss the page of text
                           *
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Fig. 3. An example of the foveal-mask paradigm. The lower two lines show two successive fixations with a mask of 7 letter spaces. As in the moving-window paradigm, the mask moves in synchrony with the eyes.

tification is such that on most fixations only the fixated word is identified, information is generally acquired within the first 50 ms of a fixation, and decisions about where to move the eyes and when to move the eyes are computed independently.

The fact that the area from which readers get useful information is small is undoubtedly related to acuity limitations. However, acuity limitations cannot account for this entirely. In particular, it has been demonstrated that how much information a reader gets to the right of fixation is related to the processing difficulty associated with the fixated word: When it is difficult to process (because, e.g., it is a low-frequency word), readers get less information to the right of fixation.[10] It has also been demonstrated that when the parafoveal word is highly predictable, readers obtain more information from the parafovea.[11]

Although the eye-contingent paradigm has yielded a great deal of information about reading, other studies in which eye movements are monitored (without display changes) have also yielded a number of insights. Research examining where readers fixate in words has demonstrated that fixation location in a word is not random: Readers tend to fixate about halfway between the beginning and the middle of the word.[12] Extensive research efforts on this effect have examined the consequences of being fixated at locations other than this optimal viewing location.[13] The general finding has been 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.

COGNITIVE PROCESSES

An important conclusion that has emerged from eye movement research is that the eye–mind span, or the lag between what the eye is fixating and what the mind is processing, is quite tight. For example, effects due to eye-contingent display changes show up immediately on the fixation following a display change, and are not delayed in the eye movement record for a couple of fixations. It has also been demonstrated that low-frequency words yield longer fixation times than high-frequency words, and words that are highly constrained or predictable within a given context are fixated for less time than words that are not so constrained. The point is that increased fixation times show up on the low-frequency word and the unconstrained word. If there were an

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eyes do not move smoothly across the qcpf of text    Prechange
 *       *          *        *
eyes do not move smoothly across the book of text    Prime
                                       *
eyes do not move smoothly across the page of text    Postchange
                                       *
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Fig. 4. An example of the fast priming 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 crosses the invisible boundary location (the letter *e* in *the*), the prime word (*book*) is presented for a brief duration (30 ms) and is in turn replaced by the target word (*page*) for the remainder of the trial. The duration of the prime can be varied, and subjects are usually not aware of its presence if the exposure is less than 50 ms.

appreciable eye–mind lag, the effect would not appear until a couple of fixations later.

The general finding that the area of effective vision and the word identification span are small (so that readers typically identify only the fixated word) coupled with the conclusion that there is no appreciable eye–mind span has led to considerable optimism concerning the use of eye movement data in investigating cognitive processes during reading. In the past 10 years, there has been considerable research using eye movement data to investigate (1) word recognition processes during reading, including the processing of lexically ambiguous words; (2) how readers parse sentences containing temporary syntactic ambiguities; and (3) inferences during reading.

It is beyond the scope of the present article to review all these lines of research.[14] The point that I would simply like to make is that eye movement data have revealed a great deal of important information about moment-to-moment cognitive processes during the reading process. Variations in how long readers look at certain target words or phrases in text have been shown to be due to the ease or difficulty associated with processing those words. Many paradigms used to study the reading process either disrupt the normal processing or are artificial in some way. Because eye movements are a natural part of the reading process, one does not have to worry if task-induced strategies are influencing the pattern of results obtained in an experiment. Indeed, eye movement data have often ended up being the primary source of evidence for adjudicating between alternative theoretical positions. My guess is that this will continue to be the case as more and more researchers find the record left by the movements of the eyes to be an appealing source of experimental data.

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Notes

1. For overviews, see M.A. Just and P.A. Carpenter, *The Psychology of Reading and Language Processing* (Allyn & Bacon, Boston, 1987) and K. Rayner and A. Pollatsek, *The Psychology of Reading* (Prentice Hall, Englewood Cliffs, NJ, 1989).

2. The eye-contingent display change paradigm was developed in the mid-1970s by George McConkie and myself. Around the same time, Steve Reder and Kevin O'Regan developed similar techniques. The paradigm was developed further in my laboratory in collaboration with Alexander Pollatsek, Charles Clifton, and James Bertera. For a comprehensive review of research using this paradigm, see Rayner and Pollatsek, note 1.

3. N. Osaka, 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 (1992).

4. A. Pollatsek, G.E. Raney, L. LaGasse, and K. Rayner, The use of information below fixation in reading and in visual search, *Canadian Journal of Psychology* (in press).

5. For a recent article summarizing this work, see A. Pollatsek, M. Lesch, R.K. Morris, and K. Rayner, 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 (1992).

6. Albrecht Inhoff has conducted a number of studies that show that some information is obtained from other parts of the word to the right of fixation besides the beginning letters; see A.W. Inhoff and S. Tousman, Lexical priming from partial-word previews, *Journal of Experimental Psychology: Human Perception and Performance, 16,* 825–836 (1990). However, it is clear that the bulk of the preview effect comes from the beginning letters. Inhoff's research also shows that the effect is not simply due to spatial proximity because there is facilitation 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.

7. H.E. Blanchard, G.W. McConkie, D. Zola, and G.S. Wolverton, Time course of visual information utilization during fixations in reading, *Journal of Experimental Psychology: Human Perception and Performance, 10,* 75–89 (1984).

8. R.K. Morris, K. Rayner, and A. Pollatsek, Eye movement guidance in reading: The role of parafoveal letter and space information, *Journal of Experimental Psychology: Human Perception and Performance, 16,* 268–281 (1990).

9. S.C. Sereno and K. Rayner, Fast priming during eye fixations in reading, *Journal of Experimental Psychology: Human Perception and Performance, 18,* 173–184 (1992).

10. J.M. Henderson and F. Ferreira, 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 (1990); A.W. Inhoff, A. Pollatsek, M.I. Posner, and K. Rayner, Covert attention and eye movements in reading, *Quarterly Journal of Experimental Psychology, 41A,* 63–89 (1989).

11. D.A. Balota, A. Pollatsek, and K. Rayner, The interaction of contextual constraints and parafoveal visual information in reading, *Cognitive Psychology, 17,* 364–390 (1985).

12. K. Rayner and R.K. Morris, Eye movement control in reading: Evidence against semantic preprocessing, *Journal of Experimental Psychology: Human Perception and Performance, 18,* 163–172 (1992).

13. G.W. McConkie, P.W. Kerr, M.D. Reddix, and D. Zola, Eye movement control during reading: I. The location of initial fixations on words, *Vision Research, 28,* 1107–1118 (1988); F. Vitu, J.K. O'Regan, and M. Mittau, Optimal landing position in reading isolated words and continuous text, *Perception & Psychophysics, 47,* 583–600 (1990).

14. For a summary of this research, see K. Rayner, S.C. Sereno, R.K. Morris, A.R. Schmauder, and C. Clifton, Eye movements and on-line language comprehension processes, *Language and Cognitive Processes, 4* (Special Issue), 21–50 (1989).