Reading Without a Fovea

Abstract. *A visual mask moving in synchrony with the eye obliterated foveal vision during reading under certain conditions. When foveal vision was masked, reading became difficult. In another condition, a window of readable text moved in synchrony with the eye, and parafoveal vision was masked on each fixation. The results point out the importance of foveal and parafoveal vision in reading.*

In normal reading, a horizontal line of text projected on the reader's retina can be divided into three major regions: foveal, parafoveal, and peripheral. The fovea is the area of clear visual acuity extending 2° across the fixation point. Beyond the fovea, the parafoveal region extends 10° around the fixation point, and the remainder is the peripheral region. The functional significance of this distinction is that acuity drops off markedly as a stimulus is presented farther from the fovea; the ability to identify a word or letter decreases dramatically as it is presented outside the fovea and at increasing distances from a central fixation point (*1*). In order to bring words into foveal vision for detailed analysis as we read, we make saccadic eye movements at the rate of four or five per second (*2*). The saccade is a rapid ballistic movement typically covering seven to nine characters in reading. For normal reading material, three or four characters equal 1° of visual angle for text held at a normal reading distance; saccades thus appear to bring a given region of text into foveal vision so that the reader can perceive clear visual detail of the words to be read. Between saccades, the eye is relatively still in a fixation pause, during which it gathers information. Our experiments dealt with the extent to which readers obtain different types of information from different regions. If the information necessary for making semantic identifications is limited to foveal vision, reading rate will be much more limited than if this information can be obtained from a larger area extending well into parafoveal vision.

In order to determine the size of the effective visual field during reading, McConkie and Rayner (*3*) controlled the amount of information available to the reader during each fixation. Subjects' eye movements were monitored by a computer and the information about eye position was fed into a computer controlling the cathode-ray tube (CRT) from which the subject was reading. Changes were made on the CRT on the basis of the location of the reader's gaze. For example, a passage of mutilated text was initially presented on the CRT with every letter from the original text replaced by an *x*. However, wherever the reader fixated, a region around the fixation point changed into readable text. This window area moved in synchrony with the eye movements so that wherever the reader fixated, the real text was exposed, but everywhere outside the window area the mutilated text remained. By varying the size of the window area, it was possible to estimate the effective visual field in reading.

We have used a technique similar to that of McConkie and Rayner (*3*) and others (*4*) to determine the extent to which readers can obtain enough information outside foveal vision to identify the meaning of words. We excluded foveal and parafoveal information from the reader on each fixation. Subjects in experiment 1 were asked to read sentences on a CRT as their eye movements were monitored. The eye movement system (*5*) sampled the position of the eye every 4 msec, and a visual mask (*6*) was superimposed over the text, under certain conditions, to completely obliterate the text in foveal vision. The size of the mask varied, but always moved in synchrony with the eye. After the subjects (*7*) completed reading, they reported as much as they could from the sentence. The sentence disappeared from the CRT either when the subject pushed a button indicating that the sentence had been read or after 100 eye movements had been made.

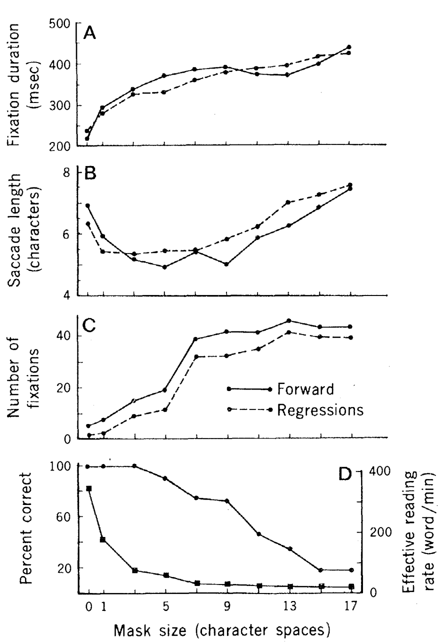

Fig. 1. Foveal masking study. (A) Mean fixation duration, (B) saccade length, (C) number of fixations per sentence, and (D) number of words correctly reported per sentence (●) and effective reading rate (■).

As mask size increased, the mean fixation increased significantly (Fig. 1A) (*8*). In general, data on saccade length and number of fixations suggest that as mask size increased, reading became increasingly difficult (Fig. 1, B and C).

When subjects could read the sentence (as with small masks), they had no trouble reporting the sentence verbatim (Fig. 1D) (*9*). As mask size increased, however, the percentage of words from the sentence correctly reported decreased dramatically. On 18 percent of the trials when the mask was of 13 to 17 characters, subjects could report nothing from the display even though they were asked to guess. They were aware of words in the parafovea and periphery, but they were unable to report what they were. With the largest masks, often the only words correctly reported were short words (fewer than four characters), particularly when they were at the beginning or end of the sentence (*10*). Although longer words were occasionally read correctly, in general they were extremely difficult to gain information from. As the mask size increased so that foveal vision

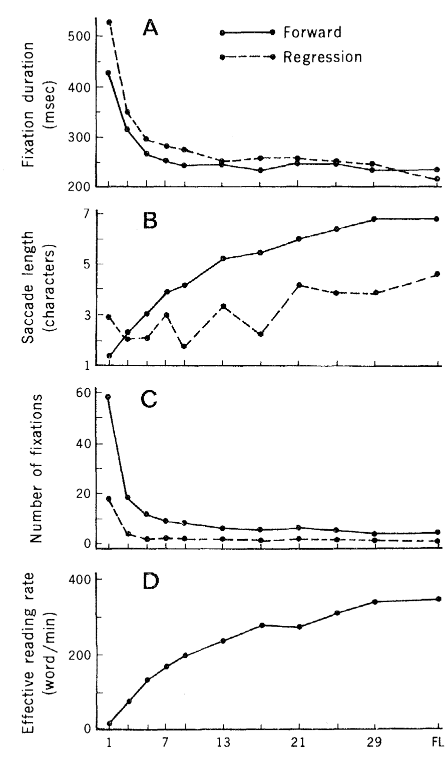

Fig. 2. Window study. (A) Mean fixation duration, (B) saccade length, (C) number of fixations per sentence, and (D) effective reading rate; *FL*, control condition in which the sentence was presented without a mask.

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was completely masked, the type of errors made was consistent with the visual information that could be obtained. For example, the sentence "The pretty bracelet attracted much attention" was read as "The priest brought much ammunition" with a mask size of 7; "Their profits doubled in the first year" was read as "Their politics doubled in the first war" with a mask size of 9; and "The banner waved above the stone monument" was read as "The banker watched the snow mountain" with a mask size of 13. Errors of the following types were very common: *fliers* was misread as *fires, fuzzy* as *funny, stereo* as *store, recruits* as *relatives, popular* as *people, customer* as *cashier, rusted* as *raised, lightly painted* as *greatly pleased, frosty* as *family*, and *satisfaction* as *accommodation*. In short, the errors made when foveal vision was completely masked indicated that readers were obtaining information about the beginning letters (and sometimes ending letters) of words in parafoveal vision, as well as word shape and word length information, and trying to construct coherent sentences out of the information available (*11*).

Reading speed was drastically affected by the presence of the masks. Reading speed in the control, no-mask condition was 332 words per minute. The one-character mask cut reading rate in half to 165 word/min. When the mask covered the three or five characters in the center of vision, reading rate was 55 and 42 word/min, respectively. The estimated effective reading rate was computed by multiplying the percentage of words correctly reported by the reading rate (Fig. 1D). When the mask was seven characters or larger, the effective reading rates were less than 10 word/min and only 2 word/min with mask sizes 15 and 17 (*12*).

We also repeated the McConkie and Rayner study (*3*) in which a window moved in synchrony with the eye across the text (*13*). Whereas the smallest window size used by McConkie and Rayner was 13 characters, we decreased the size of the window to one character. Reading performance improved with increasing window size (Fig. 2). When the window was 29 characters, performance was similar to performance when the entire line was visible. McConkie and Rayner (*3*) also reported that the field of useful vision during an eye fixation is about 12 to 15 characters to the right of the fixation point (*14*). With the smallest window sizes, reading was difficult although possible. When the window was only one character, subjects reported that they had to resort to spelling the words out, but they were able to report 90 percent of the words. At all other window sizes, subjects were virtually 100 percent accurate in reporting the words from the sentences. With window sizes of 7 or smaller, the mean saccade length brought the window to an area that was the beginning of the mask region on the prior fixation. For window sizes of 9 and larger, mean saccade length centered the window on text that had been visible on the prior fixation. Thus, information overlapped on most fixations as has been implied previously (*3, 4, 15*).

The window study allowed us to compare reading performance when the parafovea was masked with that when the fovea was masked. Masking the fovea resulted in more severe problems in reading than masking the parafovea. Both experiments are consistent with previous findings (*3, 15*) that information necessary for semantic identification is obtained from the foveal and near parafoveal region, whereas other more gross types of information are obtained from the parafovea.

The subjective experience of the subjects in the experiment seemed consistent with the experience of people with a scotoma of the retina resulting in the loss of foveal vision and thus making it difficult to read (*16*). Although it is difficult to obtain information necessary for semantic identification from the parafovea, information available there is useful in reading and guiding eye movements to the next location as we read.

KEITH RAYNER

JAMES H. BERTERA

Department of Psychology, University of Massachusetts, Amherst 01003

References and Notes

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5. Eye movements were recorded with a dual Purkinje eyetracker (Stanford Research Institute) and a computer (Hewlett-Packard 2100). The eyetracker has a resolution of 10′ of arc, and the output is linear over the visual angle (14°) occupied by the sentences. Subjects' heads were fixed by a bite bar.
6. A visual mask varied in size to cover 1 to 17 characters on the line. A mask size of 11 meant that the letter in the center of vision and five characters to the left and right of that central fixation point were covered by the mask. The mask consisted of an interlaced square-wave grating slightly brighter than the letters making up the sentences. A CRT (Hewlett-Packard) with a P-31 phosphor controlled by the computer presented the stimuli. Removing a character resulted in a drop to 1 percent of maximum brightness in 0.25 msec. Photoelectric testing indicated that the display change (or movement of the mask) was accomplished within 2 to 10 msec after the saccade ended, and the phenomenological experience was that the mask moved in perfect synchrony with the eye.
7. Four subjects participated in the experiment. They all had normal, uncorrected vision and had had practice reading under the masking conditions before the experiment began. The subject's eye was 46 cm from the CRT; three characters equaled 1° of visual angle. At the beginning of the experiment, the subjects read some warm-up sentences with various mask sizes.
8. All four of the subjects showed the same pattern of results. Trend analyses were conducted on the group data on forward (left-to-right) eye movements. For fixation duration, the linear component accounted for 73 percent of the variance ($P < .001$), the quadratic component accounted for an additional 12 percent ($P < .05$), and the cubic an additional 14 percent ($P < .05$). For saccade length, 77 percent of the variance was accounted for by the quadratic component ($P < .001$) and an additional 14 percent was accounted for by the cubic component ($P < .05$). For number of fixations, the linear component accounted for 84 percent of the variance ($P < .001$) and the quadratic accounted for an additional 8 percent ($P < .05$). Regressive eye movements mirrored forward eye movements (Fig. 1) primarily because subjects constantly looked right and then left in an attempt to obtain information from outside the mask area.
9. Instructions to the subjects emphasized that they could either report the sentence verbatim or paraphrase it. Since the sentences were six to eight words long, subjects had no trouble reporting the sentence in its exact form and most of the time did so. Errors that were paraphrases were counted as correct, although such instances were extremely rare.
10. The function word *the* was correctly reported 77 percent of the time when it was the first word in the sentence compared with 33 percent when it occurred in another location in the sentence. Three-letter content words were correctly reported 35 percent of the time.
11. Much of the time, the errors preserved the syntactic structure of the sentence, mainly because subjects seemed to pick up information from some words and realize that only certain classes of words can follow. For example, if the function word *the* is identified, the subject knew an adjective or noun would follow. Subjects' introspective reports were consistent with this account. Thus, once a word had been identified, subjects used the visual information as well as their knowledge of language in trying to identify the next word. All subjects reported that once they reached a tentative interpretation for a word, they were committed to it and had difficulty abandoning it.
12. Practice reading under the foveal masking conditions did not improve performance noticeably. Some of our subjects have repeated the experiment with large masks three or four times without improvement.
13. The four subjects who participated in experiment 1 also participated in experiment 2. A mask identical to that used in experiment 1 covered the sentence except for the window area. When the eye moved from one location to another, the window moved with the eye so that the text was always exposed around the fixation point for the specified window size. Again, the display change (or movement of the window) associated with each eye movement was accomplished in 2 to 10 msec. A trend analysis on the data for effective reading rate revealed that the linear component accounted for 86 percent of the variance ($P < .001$).
14. In a study in which the window was either symmetric or asymmetric around the fixation point, readers obtained information mainly to the right of fixation [G. W. McConkie and K. Rayner, *Bull. Psychonom. Soc.* **8**, 365 (1976)].
15. K. Rayner, *Cognit. Psychol.* **7**, 65 (1975).
16. H. Teuber, W. S. Battersby, M. E. Bender, *Visual Field Defects after Penetrating Missile Wounds of the Brain* (Harvard Univ. Press, Cambridge Mass., 1960); J. Dessoff, *Arch. Ophthalmol.* **58**, 452 (1957). The extent of the reading difficulty is determined by the size of the central scotoma and by whether the foveas of both eyes are affected. We have interviewed two people with central scotomas in one eye. They both reported that when the good eye is occluded they can identify short words in parafoveal vision as well as beginning letters of the nearest words. Their introspective reports seemed to be consistent with the performance of our subjects in experiment 1.

17. Supported by National Institute of Child Health and Human Development grant HD12727.

16 July 1979