

Visual Factors and Eye Movements in Reading

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The effects on oculomotor behavior of variations of physical attributes of text, both typographical and psychophysical parameters, and similar effects from physical (visual as opposed to semantic) word cues processed in the reader's parafoveal vision are discussed. It is concluded that the reliability of such effects underscores the primary nature of visual discrimination in reading. Furthermore, sets of data generated from typographically different stimuli suffer a serious confounding.

Psychologists have long been fascinated by the movements of the eyes in reading and have examined readers' oculomotor behavior in an attempt to elucidate the processes underlying fluent reading. The class of oculomotor acts observed during reading are well known. The eyes execute a series of jerky (saccadic) movements followed by pauses during which the eyes are held relatively stable (fixations). Since stimulation obtained during a fixation suppresses the activity due to stimulation obtained during the saccadic movement (Matin, Clymer, & Matin, 1972) it is only during fixations that the reader is able to abstract information from text. Fixations average around 200-250 msec and consume 90-95% of the total reading time (Tinker, 1965). Saccades that are executed in a forward direction (i.e., left-to-right for English readers) serve the function of bringing new information into foveal vision.¹ On the average, each forward saccade covers about 8-9 character spaces (Rayner, 1978). Saccades which are executed to a text location that has already been read are referred to as regressions and account for 10-20% of the saccades (Rayner, 1978). Right-to-left saccades that intervene between the final fixation of a line and the initial fixation of a new line are return sweeps. Frequently, the return sweep under-shoots the beginning of a new line and the reader performs a compensatory regression to the beginning of the line after a relatively short initial fixation

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(Rayner, 1978). The return sweep can also be inaccurate in a vertical direction, causing fixation of the wrong line and a disruption of reading (Tinker & Paterson, 1955). Forward saccades, regressions, and return sweeps are voluntary eye movements and are ballistic movements whose trajectories cannot be influenced once the movement has been initiated.

Although the average values mentioned above are repeatedly reported, the oculomotor behavior in reading shows a considerable amount of variability, both within and between readers. Fixations for individual readers may range from 100 to more than 500 msec, saccade size may range from less than 1 character space (microsaccades) to about 20 character spaces, and the percent of regressions can vary from 0 to 40% (Huey, 1908; Rayner, 1978; Woodworth, 1938). Distributions of fixation duration and saccade length for college-aged readers are given in Figure 1.

There is accumulating evidence that the variability in the different eye movement measures is not due to random fluctuations of a "noisy" oculomotor system. Comprehensive reviews of eye movement data in reading (Huey, 1908; Rayner, 1978; Tinker, 1965; Woodworth, 1938) repeatedly stress systematic changes in oculomotor behavior occurring as a result of text (e.g., typographical factors, text difficulty) and/or reader characteristics (e.g., reading ability). There is evidence that the effects are not the result of a general tuning of the oculomotor system to global text characteristics or motivation levels. Rayner and McConkie (1976) reported no correlation between successive fixation durations or between the size of successive saccades as one would expect if the reader's eye behavior reflected a general tuning. Also, there was no correlation between fixation duration and subsequent saccade size, a result also reported by Walker (1938).

This suggests that the eye movement patterns are sensitive to the moment-to-moment processing activities of a reader (Rayner, 1977; Rayner & McConkie, 1976). Since visual inspection of the text is an obligatory part of reading, the perceptual salience of text should also affect eye behavior on a moment-to-moment basis. Indeed it has been well demonstrated that static characteristics of the text and reading situation (character size, contrast, illumination) and physical characteristics of what is available in parafoveal vision (word length, beginning letters) can alter the eye movement pattern of a reader (Rayner, 1979; Tinker, 1963). In the following pages we will proceed to analyze the effects of visual factors on eye movements in reading.

Effects of typography

Between 1927 and 1965 Miles Tinker and his colleagues conducted comprehensive investigations of the physical characteristics of the reading situation which affect reading speed (Tinker, 1963; Tinker, 1965). Tinker explored the

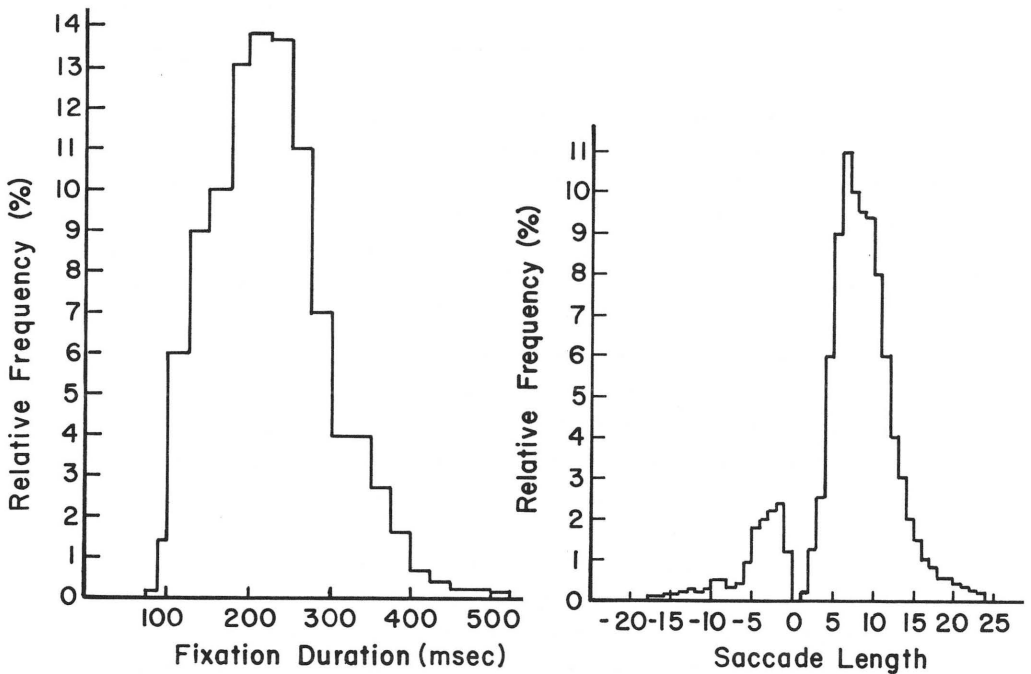


Figure 1. Frequency distributions of fixation duration (left) and saccade length for eight college-age readers. Return sweeps of the eye have been excluded from the distribution. Short fixations following the return sweep which are followed by corrective saccades have also been excluded. Reprinted with permission from Rayner and Inhoff (in press). Copyright The Chemical Rubber Co., CRC Press, Inc.

effects of typeface, type size, line width, leading (i.e., the amount of blank space between successive lines of type set text), illumination, contrast, color, and many other variables (see Tinker, 1963, for a bibliography of this work).² By using a check on reading comprehension to maintain a constant level of high comprehension from subjects, Tinker was able to use speed-of-reading as an operational definition of legibility of text. Legibility values were reported as percent changes in reading speed from that achieved with some standard in any given experiment. Comparisons of the magnitude of these values are valid only between conditions within the same experiment, not across experiments. In addition, readers' eye movements were photographed to determine what oculomotor changes were occurring to cause text to be read faster or slower. As Tinker's data is based on experiments involving over 30,000 subjects, it remains some of the most extensive research on the subject of legibility and how eye behavior is modified by different text parameters. His findings will be summarized in the remainder of this section.

Tinker argued that more legible (more quickly read) text allows readers a wider perceptual span which requires fewer fixations and allows longer saccades. The perceptual span is defined as the amount of textual material which the reader effectively processes during an individual fixation (Paterson & Tinker, 1947). He divided the words or characters constituting a text by the number of fixations made to obtain an average measure of the perceptual span (in words per fixation or characters per fixation). Although recent evidence (McConkie & Rayner, 1975; Rayner, 1975) argues against the assumption underlying this computation, namely that the perceptual spans of successive fixations are contiguous and do not overlap; the assumption that a more legible text allows for a wider perceptual span and generally requires fewer fixations is not disputed.

Hence, although Tinker's words per fixation measure is not to be taken literally, we assume it bears a monotonic relationship to the mean width of the perceptual span. Furthermore, mean saccade length should also be strictly correlated with mean perceptual span size, and thus bear a monotonic relationship to the words per fixation measure. That is, when fewer fixations are made (more words per fixation) they must be more widely spaced, on the average (longer mean saccade length).³ Reviewing Tinker's data we shall attempt to infer the effects of legibility manipulations on mean saccade length.

Tinker asserted that fixation duration is a function of the ease of discrimination of the characters within the fovea. Reading speed then is primarily a function of: fixation frequency – the direct correlate of perceptual span and saccade length – as affected by parafoveal discriminability; and fixation duration, as affected by foveal discriminability. (Regression frequency and duration also influence reading speed.)

The authors could find no mention by Tinker of an attempt to rigidly control viewing distance nor of a need to in order to get reliable rankings of relative legibility. Presumably subjects selected the distance which most comfortably allowed them to perform the comprehension task Tinker used which involved crossing out an inappropriate word. For any subject this distance would be fixed with a head rest in Tinker's eye movement monitoring apparatus but was probably allowed to vary between subjects.

Although changes in viewing distance might be critically important if letters to be identified were at threshold size (for that distance), it doesn't seem that it would have an overwhelming effect in a reading task in determining the relative legibilities of type sizes that are all well above threshold size (when presented foveally). Parafoveal acuity limitations on the perceptual span would seem to be the major source of legibility differences. Of course there is an inverse relationship between viewing distance and retinal image size. Re-

ducing the distance increases retinal image size, but this means a constant unit of print, such as a word, extends into more eccentric retinal areas. Because of the linear decrease in acuity with increasing eccentricity (e.g., Anstis, 1974) small changes in viewing distance may have little effect on the perceptual span. (See Anstis for a demonstration of stimuli which "have the unusual property of being equally readable at any viewing distance" [1974, p. 590]). In any event, Tinker apparently found that relative legibilities of different typographies were reliable over moderate changes within the range of normal reading distances (i.e., within arm's length) and his conclusions generalize to such situations accordingly.

One of the most interesting facts discovered by Tinker is that factors which make alphabetic stimuli, both single letters and words, most readable in a number of threshold determination paradigms (for example distance, eccentricity in peripheral vision, or exposure duration thresholds) do not make them most legible in a normal reading situation. In fact, they may actually reduce legibility of text. For example, all-capital letters have a greater threshold distance than lowercase letters of the same nominal point size because they are actually larger. But they are less legible (reading speed decreased by 11.8%) in a reading situation (Paterson & Tinker, 1947; Tinker, 1963). ALTHOUGH FIXATION DURATIONS WERE SHORTER WHEN READING TEXT IN CAPITALS THAN WHEN READNG LOWERCASE (FROM A MEAN OF 230 MSEC TO 210 MSEC), 12.4% MORE FIXATIONS WERE NECESSARY ON THE CAPITALS AND TOTAL READING TIME WAS INCREASED. MEAN CHARACTERS PER FIXATION WENT FROM 8.1 FOR LOWERCASE TEXT TO 7.0 FOR CAPITALIZED TEXT. SINCE REGRESSION FREQUENCY DID NOT CHANGE, WE INTERPRET THIS AS A DECREASE IN MEAN FORWARD SACCADE LENGTH (IN TERMS OF CHARACTERS TRAVERSED). SURPRISINGLY, THE SACCADES WERE PHYSICALLY LARGER. SINCE CAPITALIZED TEXT OCCUPIES A 35% GREATER PAGE AREA, THE MEAN PICAS PER FIXATION INCREASED FROM 3.2 TO 4.3 (A 34% INCREASE IN PHYSICAL LENGTH), YET FEWER CHARACTERS OCCUPIED THIS DISTANCE. APPARENTLY THE PERCEPTUAL SPAN IS DECREASED FOR UPPERCASE TEXT EVEN THOUGH THE HORIZONTAL EXTENT OF THE SACCADES (IN TERMS OF DISTANCE OR VISUAL ANGLE) INCREASED IN THIS SITUATION. THE LARGER SIZE OF THE CAPITALS MAKES THEM PERCEPTIBLE TO A GREATER ECCENTRICITY IN PERIPHERAL VISION BUT NOT BY ENOUGH TO EQUAL THE INCREASED VISUAL ANGLE THAT A GIVEN CHARACTER STRING WILL SUBTEND. CAPITALIZED TEXT ALSO LACKS WORD SHAPE CUES WHICH COULD CONTRIBUTE TO THE DIMINISHED PERCEPTUAL SPAN.

A similar trend was seen with very large type (14-point versus a 10-point standard). Reading speed, hence legibility, was reduced by 6.4%. Though mean fixation duration was decreased for the larger type (from 230 to 210 msec), fixation frequency increased by 21% (regression frequency did not change significantly). Note that the size manipulation is not confounded with word shape – both sizes are in lowercase. Assuming the larger type would be perceptible to a greater eccentricity in peripheral vision, it is conceivable that saccades would cover more picas to traverse an equal number of characters. This was not so. Again, as with capitalized text, the mean picas per fixation were greater for the larger type (4.9 vs. 3.9), yet characters per fixation decreased (8.5 vs. 10.1). Readers did make physically somewhat longer saccades but these traversed fewer characters. There are two possible explanations for this, however. The study had used both 10-point and 14-point type in 19-pica line widths. The larger type had fewer characters in a line. Perhaps this constrained the perceptual span and not type size per se.

The study was replicated, this time keeping constant not the line width but the number of characters per line. Although the effect was diminished, the 14-point type was still less legible (by 3.3%). Apparently the 10-point type was inherently more legible than the larger (14-point) type – a rather unintuitive finding considering research on recognition thresholds for single letters. There seems to be a trade-off between size of type and decreasing parafoveal acuity which makes a moderate size most legible. At some point, the greater perceptibility of the larger type is offset by the further extension into areas of poorer parafoveal acuity by a given character string. It is also clear that any factors which affect legibility – type size, line width, etc. – interact with each other such that all variables not under experimental manipulation must be controlled in order to draw valid conclusions about independent variables.

Legibility is also reduced by very small type. Comparing 6-point type with a 10-point standard, legibility decreased by 5.8% when printed in constant 19-pica line widths and 6.0% when equated for number of characters per line. Eye movement records showed that when reading the smaller type total fixation frequency significantly increased even though the text occupied less area in this case. Regression frequency increased only slightly; thus the frequency of forward fixations (total fixation frequency minus regression frequency) increased. This implies by our previous reasoning that mean saccade size decreased, in this case both in terms of distance (from 3.5 to 2.7 picas) and characters per fixation (from 9.0 to 8.5). In addition, mean fixation duration was significantly increased for the 6-point type (240 msec) compared with the 10-point standard (230 msec). Thus, foveal processing took longer due to reduced perceptibility of the small characters, and the perceptual span was slightly reduced.

There has existed some uncertainty in the literature as to whether it is more appropriate to talk about saccade length in absolute terms of visual angle or in terms of character spaces (O'Regan, 1980; Rayner, 1978). Tinker's data, showing that a physically longer saccade can cover fewer characters of a less legible text arrangement (i.e., one with larger type) suggests that characters per saccade may be the more useful measure, for a couple of reasons. First, it is invariant over changes in viewing distance for saccades covering equivalent chunks of information; visual angle is not. Second, it is also invariant, for such equivalent-chunk saccades, over texts of different typographies, allowing comparisons between them. Consider the same text printed in two different type sizes. As noted above, more visual angle may be covered by saccades while reading the text of larger type. But without intervening calculations we don't know whether they cover more or fewer characters than the comparatively shorter eye movements made on the smaller sized type. It is not directly evident from a consideration of visual angle whether the perceptual span has increased or decreased with the large type. In addition, mean characters per saccade data will indicate the number of fixations made on a passage (of n characters) without having to adjust mean visual angle per saccade by the number of characters per degree of visual angle at a certain viewing distance. Of course, the number of characters per degree of visual angle in a study should always be reported anyway.

Tinker also determined the optimal line width, in picas, for various type sizes. Generally, a range of widths proves equally legible for a given type size. Larger type sizes are most legible in long lines, smaller types are most legible in short lines.

For 10-point type the optimal line widths ranged from 17 to 27 picas, and performance peaked at 19 picas, which results in a line of approximately 52 characters. Surprisingly, no constant ratio of optimal line width to type size was found. This means that the optimal line width for all type sizes did not result in an equal number of characters per line. An analysis of eye movements revealed why lines shorter and longer than the optimum for a given type size were less legible. For example, for 10-point type, a short line (9-picas) increased fixation frequency by 15.7% over a 19-pica standard.⁴ Tinker concluded that short lines, having fewer characters per line, prevent the full utilization of non-foveal vision. Mean fixation duration increased by 20 msec (to 240) as well. A common pattern observed in the reading of lines of optimal width is a decrease in mean fixation duration over the

last half of a line, presumably because the text has been glimpsed repeatedly in parafoveal vision during earlier fixations on the line (Dearborn, 1906; Tinker & Paterson, 1955). Text in short lines prevents this. Seemingly then, the longer the lines are, the better. However, a different factor decreases legibility for line widths beyond the optimum. Regression frequency dramatically increases (by 56.7% for 10-point type in a 43-pica line compared to a 19-pica standard). With very long lines Tinker found an increased incidence of compensatory regressions at the beginning of the line to correct undershootings and “inaccuracies” in executing the return sweep—one on practically every line! (Paterson & Tinker, 1940). Besides undershooting on lines that are too long, inaccuracies in the vertical plane can cause the wrong line to be fixated. Smaller sized type should be more susceptible to these errors, by demanding a more precise (vertically) return sweep, and restrict the upper limit on optimal line width more. In fact, this is what Tinker found—larger type has optimal width with longer lines than smaller type. In addition to more regressions, text in line widths longer than the optimum show slight yet significant increases in fixation duration (10 msec). The locus of this effect is also the trouble spot at the beginning of a line (Paterson & Tinker, 1940). Therefore, the only problem with long lines is an inability to make accurate return sweeps, and the corresponding disruption of reading.

Leading, or blank space between lines, has the general effect of expanding the acceptable range of line widths for any type size (Tinker, 1963). The increased blank area above and below words probably reduces lateral masking⁵ and widens the perceptual span. Although eye movements were not recorded for the experiments on leading, short lines are probably read with fewer fixations of shorter mean duration than when the text is set solid (without any leading). The improved legibility of very long lines with leading probably results from a less drastic increase in regression frequency. Presumably vertical inaccuracies on the return sweep are more tolerable when lines are spaced farther apart. Tinker found one or two points of leading to be optimal.

Since all the typographical features of a text interact in determining legibility, definitive experiments on the relative legibilities of type sizes necessitates each size being printed in its empirically determined optimal line width and leading. When this was done there were no significant differences between 9, 10, 11, and 12 point type. Smaller sizes, 6 and 8 point, were still less legible (Tinker, 1963). Unfortunately, sizes larger than 12 point were not used. Tinker (1965) recommends 10, 11 or 12 point type.

⁵10-point type, 43-pica measure, set solid and leaded gradually 1, 2, 3, and 4 points.

Effects of contrast and illumination

Brightness contrast between page and print can drastically affect speed-of-reading. Legibility is high if the reflectance of the page is 70% or greater and the reflectance of the characters is 10% or less. Less brightness contrast than this can severely reduce legibility. Tinker investigated the effect of colored prints and backgrounds and found that legibility differences for these stimuli were strictly a function of the brightness contrast between print and page. Color, per se, had no effect. Combinations with low brightness contrast, such as red print on green, were extremely illegible (e.g., there was a 39.5% drop in reading speed). Low contrast typographies increased fixation duration, regression frequency, and total fixation frequency.

Illumination is much less critical than might be expected, provided that legible text of adequate brightness contrast is being read. Tinker states, "Lighting specifications based upon visual acuity or visibility data overestimate the requirement for reading" (1963, p. 251). Illuminating engineers recommend 70 footcandles of illumination for reading (cited in McCormick, 1976, p. 323), but much less is sufficient, provided the reader is adapted to that level. Tinker found that subjects prefer illumination equaling that to which they are momentarily adapted. When adaptation was controlled, his subjects read 10-point type at maximum speed with only 3.1 footcandles of illumination. Actually, very strong illumination may be detrimental if it increases the effects of any glare already present. It is more important that the illumination be well diffused to avoid these effects (Tinker, 1963).

Tinker (1963) recommended illumination (20-30 footcandles) above the limits he empirically determined to be necessary, in order to provide a "margin of safety." Although there may be no decrement due to low illumination when typography is optimal, any non-optimal typographical feature, even one which alone does not cause a significant decrease in legibility, will have a combined effect in the presence of other conditions of marginal legibility, resulting in a significant drop in legibility. Furthermore, combinations of conditions which do individually reduce legibility will have a pooled effect, resulting in extreme drops of legibility – by increasing fixation frequency, fixation duration, and regression frequency. The combined decrement is less than the sum of the individual decrements.

There are other influences upon oculomotor behavior in reading such as text difficulty and changes in reading strategy (e.g., skimming vs. reading for detail). These are not physical properties of the reading task and have not been discussed. At issue were the well documented effects of purely visual phenomena on eye movements. To recapitulate, Tinker demonstrated that alterations of physical parameters of printed text cause significant differences

in legibility due to reliable changes in one or more of the usual oculomotor indices – fixation frequency, fixation duration, and/or regression frequency. Fixation duration is sensitive to the perceptibility of the characters in foveal vision, and also line width. It is a function of type size and line width. Fixation frequency, and inversely, saccade length, reflects the perceptual span a text allows or its perceptibility in extra-foveal vision. It varies as a function of type size, line width, and leading. Changes in regression frequency generally reflect the ease of making accurate return sweeps. It varies primarily as a function of line width, but also type size and leading. Poor contrast, poor illumination, or combinations of many non-optimal typographical features will inflate all three indices. The high reliability of these data emphasize the crucial and compulsory role of visual discrimination in reading.

Effects of parafoveal word characteristics

In addition to the factors discussed by Tinker, there has been recent evidence that visual word cues obtained from parafoveal vision influence readers' oculomotor behavior. The recent experiments have not dealt with typographical variations as the earlier work has. Factors such as type size and line width have been held constant while on-line eye movement monitoring techniques are employed to investigate the fixation-to-fixation processing of the textual stimulus in parafoveal vision and its effects on fixation duration and saccade length. In the following section, the effects of word length, word shape, and boundary (i.e., beginning and ending) letters will be discussed.

Effects of word length

Dodge (1907), and more recently, Dunn-Rankin (1978) used an afterimage technique to determine spontaneous fixation locations for single words. Dunn-Rankin had observers look at a small light source until the light appeared to shimmer and a grey afterimage appeared whenever observers moved their eyes. The afterimage was a bright spot which was superimposed on the perceived material at the focal point. Hence, observers could fixate single words and, at the same time, see a light spot which indicated their focal point. Dunn-Rankin found that observers tend to fixate around the center of short and average length words. In addition, there was a slight tendency for some observers to adjust the focal point to the left on longer words. Rayner (1979) monitored fixation locations in a reading situation and found the same fixational pattern. Readers tended to fixate around the central character of short and medium length words, and again, there was a trend to the left for longer words (see Figure 2). If a word received more than one fixation, there was a tendency for an initial fixation near the beginning and a second fixation

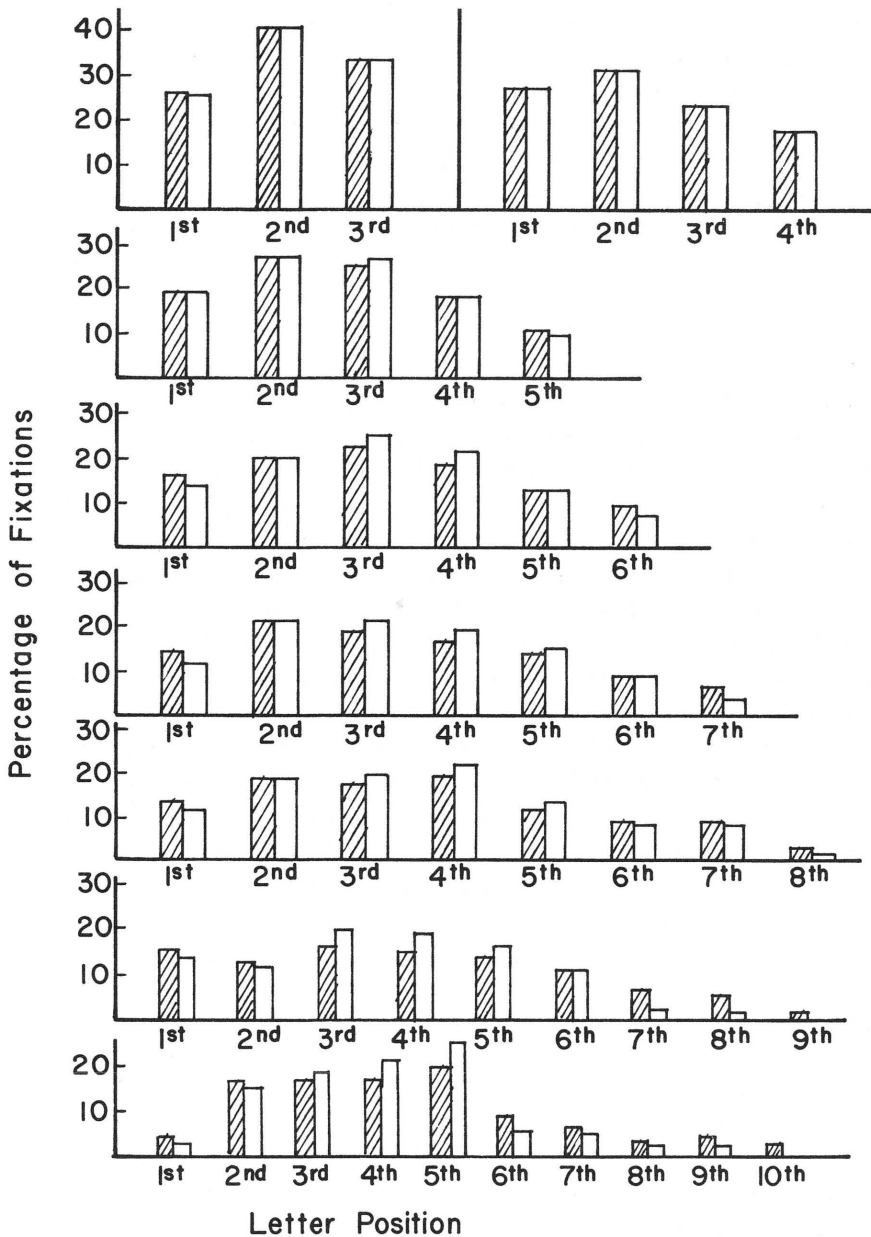


Figure 2. Histograms of percentage of time different letter positions of words of varying lengths were fixated in a forward fixation. Hatched bars indicate instances in which there was more than one forward fixation on a word; the open bars indicate the percentage of time that saccades landed on a word when the word was fixated only once. Reprinted with permission from Rayner (1979). Copyright 1979 by Pion, Ltd.

near the end of the word. Hence, word length was an effective cue in determining the reader's selection of a particular fixation position (i.e., saccade length). It should be pointed out that word length information must be sampled on fixation n if it is to determine the fixation location of fixation $n + 1$. That is, word length has to be identified with parafoveal vision.

Rayner (1979) also calculated the conditional probabilities with which particular words were fixated in reading. The probability was relatively low that one of two short words appearing in succession received a fixation. On the other hand, as either of the two words increased in length, so also did the probability that one of the words received a fixation. Rayner (1979) and also O'Regan (1980) concluded that saccade length was primarily a function of the length of the word to the right of fixation. McConkie and Rayner (1975) investigated the size of the perceptual span readers had for information about the length of words (in order to guide saccades). This, of course, reduces to the question, "What is the perceptual span for blank spaces between words?" They had subjects read computer-generated text (4 characters per degree of visual angle) displayed on a cathode-ray tube (CRT). An eye-tracking system monitored the reader's eye position and fed this information to the computer, which in turn could modify the text display around the readers fixation point in various ways dictated by the experimental manipulations. For example: The computer initially displayed a passage of mutilated text.⁶ However, as soon as the reader fixated a line an area of normal text was symmetrically displayed around the reader's fixation point. Both the size of this "window" and the type of information outside the window were manipulated (see Figure 3). If the window was very large, larger than the perceptual span, say, reading was not disrupted nor were subjects aware of the mutilated text pattern outside of the window. If the window was small enough to constrain the perceptual span though, reading was disrupted – mean fixation frequency and duration increased and mean saccade length decreased – but by different amounts depending on what characteristics of the original text pattern were preserved in the mutilated text outside of the window (these are apparently still perceived). Selectively eliminating visual characteristics of the original text from the mutilated text, such as word length and word shape, allowed the investigators to determine separate perceptual spans for those specific kinds of information. In some conditions ([XS], [CS], or [NCS], Figure 3) readers were provided with word length information outside the window. This was removed in other conditions by inserting letters into the blank spaces between the nonwords (conditions [XF], [CF], and [NCF]). It was found that saccade length was influenced by the presence or absence of word length information outside the window. When word length cues were removed,

Text Graphology means personality diagnosis from hand writing. This is a
 XS XXXXXXXXXXXX XXXXX XXXXonality diagnosis XXXX XXXX XXXXXXXX. XXXX XX a
 XF XXXXXXXXXXXXXXXXXXXXXXXXonality diagnosisXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
 CS Cnojkaiazp wsorc jsnconality diagnosis tnav kori mnlflra. Ykle le o
 CF CnojkaiapawSORcajsnconality diagnosisatnawakoriAmnlflrqaaaYklealeao
 NCS Hbfxwysyvo tifdl xiblONality diagnosis abyT wfdn hbemedv. Awel el f
 NCF HbfxwysyvoatifdlaxiblONality diagnosisaabyTawfdnahbemedvaaaAwelaelaf

Figure 3. An example of a line of text and the various peripheral text patterns derived from it. On each line a window of size 17 is shown, assuming the reader is fixating the letter *d* in *diagnosis*. Reprinted with permission from McConkie and Rayner (1975). Copyright 1975 by The Psychonomic Society, Inc.

mean saccade length decreased. This difference between spaced and filled text was found up to window sizes of 25 and 31 character spaces (symmetrically around the fixation point). Hence, it was concluded that word length cues are perceived out to about 12–15 character spaces into the parafovea during a single fixation. Since a reader's saccade length averages around 8-9 character spaces, word length is acquired far enough from the fixation point to influence the selection of the next fixation location. Rayner and Bertera (1979) and Rayner, Inhoff, Morrison, Slowiaczek, and Bertera (1980), using a similar technique to that used by McConkie and Rayner (1975), have recently confirmed that word length cues are obtained about 15 characters to the right of fixation.

Rayner and Pollatsek (1981) did the definitive study showing that saccadic guidance based on parafoveally acquired word length information operates on a fixation-to-fixation basis as has been sketched. In the previous studies, window size had been varied between sentences or groups of sentences: The reader encountered the same window size throughout a sentence. It could be argued that saccade length was adjusted on a delayed basis, once window size had been determined following a couple of normal length saccades. To test this, Rayner and Pollatsek (1981) also varied window size within sentences, randomly from one fixation to the next. This would make a delayed strategy useless. The data showed the usual pattern – saccade size was a function of window size, smaller windows causing shorter saccades – with no difference between the random and blocked window size conditions. Hence, the visual information available during each fixation affects the oculomotor behavior immediately, or on a moment-to-moment basis.

Effects of word shape and specific letters

McConkie and Rayner (1975) also manipulated the availability of word shape information outside of the window by constructing mutilated text wherein each letter was either visually confusable or nonconfusable with the original text. It was found that graphical similarity of the mutilated text with the original text (conditions [CS] and [CF], Figure 3) resulted in shorter fixation durations than the conditions in which the word shape cues were not provided (conditions [NCS] and [NCF]). This difference was observed up to a window size of 21 character spaces. It was concluded that word shape information is acquired as far as 10 letter spaces from the point of fixation and influences fixation duration. Similar results were reported by Rayner (1975). Word shape was also reported to be an effective parafoveal cue in a naming task. Rayner, McConkie, and Ehrlich (1978) instructed readers to move their eyes to a parafoveal location which was occupied by various mutilations of a word. During the course of the eye movement, the initial, mutilated stimulus was replaced with the "base" word. The results seemed to indicate that prior availability of word shape information is an effective cue in parafoveal vision; i.e., response time to name the base word decreased if readers were initially provided with word-shape preserving mutilations. However, this was shown to be false in later studies.

Rayner, McConkie, and Zola (1980) found that facilitation due to word shape was a by-product of specific letter information. In the Rayner, McConkie, and Ehrlich (1978) experiment facilitating word-shape conditions also had some of the same letters as the base word. Shape preserving mutilations which shared no common letters with the base word had produced little facilitation. Rayner, McConkie, and Zola (1980) used stimuli printed in alternating case and reversed the case of each letter to derive the mutilated alternatives. For example, the stimulus "cHaRt" might appear in parafoveal vision, followed by the base word "ChArT" after the eye movement. This condition, devoid of normal word shape information and totally reversing the shape of the stimulus during the saccade, produced the most facilitation. Apparently some letters are identified or encoded into an abstract code from parafoveal vision and this facilitates processing of the base word in the fovea. McConkie and Zola (1979) showed the same effect during fluent reading. It appears that there is no effect of word shape information per se, but only of the identification of specific letters in the word. The letters most likely to be identified in parafoveal vision are presumably the beginning and ending letters of a word which suffer less from lateral masking because they are adjacent to a blank space.

That boundary letters are particularly prominent cues in word perception has been repeatedly demonstrated. For example, Oleron and Danset (1963) presented single words in a tachistoscope and blurred either the initial, middle, or final part of the words. Four levels of blur were used; at each level, the order of accuracy was the same: initial letters were reported best, final letters next, and medial letters poorest. Reaction time measures mimicked that order, with initial letters having shortest latencies.

Boundary letter information is particularly salient in parafoveal word presentations, although the most eccentric letter was found to be more perceptible than the inward-most (closest to the fovea) letter (Bouma, 1973). In addition, boundary letters are better identified to the right of fixation than to the left (Bouma, 1973). Boundary letters have also been hypothesized to control readers' eye movement behavior (e.g., Hochberg, 1970).

To explore the effect of boundary letters upon readers' eye behavior, Rayner (1975) controlled the availability of such cues. More specifically, it was possible to compare conditions in which a parafoveal nonword stimulus did or did not contain the boundary letters of a base word subsequently perceived in the fovea. The results showed that initial and final letters affected fixation durations on the base in a reading situation. That is, parafoveal word mutilations which preserved boundary letter information reduced subsequent fixation durations on the base word. Similarly, Rayner et al. (1978) showed that parafoveally available boundary letter information reduced response time for a subsequently fixated base word in a naming task. Unlike the data reported by Bouma (1973), these results showed that the initial letter in a word to the right of fixation, not the last (most eccentric) letter, had the strongest effect. It was concluded that specific letters, especially the initial letters of words, can be identified in parafoveal vision and allow shorter fixation durations when the words are fixated. This may account for the tendency of readers to have shorter mean fixation durations towards the end of a line than the beginning of a line (Dearborn, 1906; Tinker, 1965).

To summarize, recent research has shown that word length and the identity of specific letters (especially initial letters of words) in parafoveal vision affect oculomotor behavior. Word length primarily determines saccade length, while specific letter identification affects fixation duration.

Conclusion

The research surveyed provides evidence that the typographical features of text are determinants of the perceptual span in reading and thus affect eye movement measures such as fixation frequency and saccade length. Regression frequency and fixation duration are also affected by these purely

visual factors. Although comprehension requirements (e.g., skimming, reading for detail) and text difficulty may also have effects on eye movement measures within readers, and despite wide differences in eye behavior between individuals, the oculomotor effects of the physical characteristics of text are undeniable and should not be ignored.

Paradigms which use oculomotor measures (e.g., fixation frequency) as indices of text processing difficulty must control the effects of typography to avoid confounds. Absolute comparisons of eye movement data between studies utilizing different typographies will generally be invalid. Control groups yielding baseline data under typographical conditions identical to experimental groups are necessary to allow relative comparisons between experiments utilizing different typographies.

Oculomotor consequences of typography and visual word cues identified in parafoveal vision underscore the fundamental nature of visual discrimination in reading, including "normal" fluent adult reading. Reading depends upon the encoding of information physically represented in print. The speed of this process can be limited by characteristics of the print which impede the visual processing, particularly the efficiency of parafoveal information extraction. The availability of parafoveal word cues, such as word length and initial letters, may be crucial for fluent reading.

1. The fovea is a small, indented region of the human retina which extends about 2° of visual angle. The fovea contains the region of highest acuity although there is considerable drop-off even within the fovea (Riggs, 1965). Acuity continues to decrease beyond the fovea, both for the parafoveal region, which extends about 10° around fixation, and the peripheral region, which covers the remainder of the retinal system. Many experimenters have found that a number of visual acuity thresholds increase linearly with retinal eccentricity up to 30° (Anstis, 1974).
2. A point is a typographer's unit of vertical distance approximately equal to $\frac{1}{72}$ of an inch. Nine-point type (these lines) means that the vertical extent allowed a line of characters including the ascending and descending parts is approximately $\frac{9}{72}$ of an inch. A pica is a unit of horizontal distance approximately equal to $\frac{1}{6}$ of an inch.
3. This is necessarily true only if regressive fixations are removed from the fixation frequency before words per fixation is calculated. Although Tinker did not remove regressions (Tinker, 1955, p. 176), he does report regressive fixation frequency separately. Often the regressive fixation frequency shows no significant difference with legibility manipulations in Tinker's data. Significant changes in words per fixation in these instances are interpreted as real differences in mean forward saccade length.
4. Although Tinker's fixation frequency data include regression frequency, the increase must be solely due to an increase in the number of forward fixations, as regression frequency actually decreased or did not change on very short lines.

5. Lateral masking refers to the decreased perceptibility of stimuli when surrounded by adjacent contours. The effect is especially noticeable when letters to be identified in non-foveal vision are presented in isolation or amidst laterally adjacent letters. Performance decreases drastically in the latter condition (Mackworth, 1965).
6. In mutilated text each character is replaced with a different character, resulting in a passage of nonwords.

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