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ABSTRACT

To examine the nature of forward saccadic eye movements in reading, eye movement records were collected from college students as they read a short passage. Forward saccades from this data set were analyzed to determine factors influencing the likelihood of any given letter in the text being the recipient of the next fixation. Data indicated that the likelihood of forward saccades taking the eyes to a particular letter position is a function not only of the distance of that position from the prior fixation, but also of the word length and the letter position in the word being read. The analysis suggests that in reading the eyes are simply sent to the next unidentified word with location preferences in the word being a complex function of length and distance. (Graphs of the data are included.) (MM)

CENTER FOR THE STUDY OF READING

Technical Report No. 310

EYE MOVEMENT CONTROL DURING READING:
THE EFFECT OF WORD UNITS

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Abstract

This paper deals with the control of forward saccadic eye movements in reading. Currently there is some controversy both about the nature of the information used in deciding where to send the eyes next and how soon the information can be brought to bear on influencing where the eyes will be sent. Analyses of a set of eye movement data that deals with the interplay between eye guidance and word pattern information are described. The conclusion is that the likelihood of forward saccades taking the eyes to a particular letter position is a function not only of the distance of that position from the prior fixation, but also of the word length and the letter position in the word which that position occupies. An hypothesis is advanced which suggests that, in reading, the eyes are simply sent to the next unidentified word with location preferences in the word being a complex function of length and distance.

Eye movement control during reading:

The effect of word units

In recent years psychologists have shown a renewed interest in eye movement research in reading (see reviews by Levy-Schoen & O'Regan, 1979; McConkie, 1983; Rayner, 1978a). This work has been motivated by more than a simple curiosity about the nature of eye movement control. Rather, eye movement data are regarded as having the potential for testing theories about the ongoing perceptual and language processing taking place during reading. As people read a great deal of variability is exhibited in how far they move their eyes, and in how long their eyes remained centered on different locations in the text. There is a general faith in, and some evidence for, the notion that this variability reflects differences in the nature of the perceptual and cognitive processes occurring at different locations in the text. It is assumed that if we could discover the ways in which mental processes influence eye movement behavior, then we would be able to use eye movement records to infer the nature of the processing occurring at different places in the text. In effect, the eye movement pattern would then become a language by which the brain communicates some of its activities to the psychologist. The hope that this can be achieved is a strong motivator for research on eye movement control in reading (Just & Carpenter, 1980; McConkie, Hogaboam, Wolverton, Zola, & Lucas, 1979).

During reading the eyes execute a rapid series of saccadic movements averaging within a range of about six to ten letter positions in length. They occur at the rate of three or four per second, with each saccade taking the eyes to a different location and providing the reader with a clear perception of a new region of text. How the mind decides where to send the eyes on each saccade has been a matter of speculation among psychologists for decades (i.e., Dodge's (1907) argument for the involvement of peripheral vision). For some time it was believed that learning to establish a regular rhythm of saccadic movement was an oculomotor skill which contributed to skilled reading. However, attempts to improve reading through oculomotor training proved fruitless.

Hochberg (1970) gave strong credence to the distinction between foveal and peripheral vision in his formulation of a dual eye guidance system. He postulated a peripheral search guidance mechanism that communicates information to the oculomotor system about where the eyes must be moved for clearest visibility of detail, and a cognitive search guidance mechanism that affords hypotheses about where to look in order to gain further needed information for reading. Recent research has provided clear evidence that readers use some peripheral information in determining where the next fixation will be located (McConkie & Rayner, 1975; O'Regan, 1980; Rayner, 1978b; Zola, 1981). O'Regan (1981, see also, Rayner, 1979), in attempting to account for where the eyes are sent during reading, stated the "Convenient Viewing Position Hypothesis," suggesting that the eyes tend to go to centers of words, and, if that fails, corrective action is sometimes required, taking the eyes to a more optimal position. Rayner and McConkie (1976) described a range of alternative ways in which the guidance of eye movements might occur during reading and argued for a moment-to-moment control in response to ongoing mental processes taking place. Shebilske (1975) opted for a more delayed form of control, one reflecting the amount of buffered information available from prior fixations. Finally, Levy-Schoen (1981) has suggested that eye guidance in reading is based on a learned oculomotor routine which moves the eyes in a basic left-to-right pattern along one line of text and on to the next. However, this routine can be influenced and even overridden by momentary mental events occurring during reading. Such modulation would lead to the variability seen in eye movement records.

Thus, at present there is controversy both about the nature of the information used in deciding where to send the eyes next (i.e., visual information from fovea or periphery, central information from a basic oculomotor pattern, information concerning the contents of a buffer, and hypothesis about upcoming text and/or information from other ongoing processes involved in the perception and comprehension of the text) and how soon the information can be brought to bear on influencing where the eyes will be sent.

In order to gain further insights into the nature of eye movement control in reading, we have collected eye movement records from a number of college students as they read a short passage about the early history of Alaska. For the present paper, forward saccades from this data set were analyzed to yield descriptive information about the influences of three variables on the likelihood of any given letter in the text being the recipient of the next fixation:

1. how far the letter was from the prior fixation,

2. the length of the word the letter is in,

3. and the letter's serial position in the word.

(Dodge, 1907; Hochberg, 1970; Levy-Schoen, 1981; O'Regan, 1981; Rayner & McConkie, 1976; Rayner, 1979; Shebilske, 1975)

A Set of Eye Movement Data

As subjects have come to our laboratory to participate in other studies, we have typically had them read a 417-word passage taken from a high-school level encyclopedia. Its readability is estimated at 10th grade. Thus, it was relatively easy reading for the college students who have participated in our research. However, they were told that they would be given questions after reading the passage, suggesting implicitly that they should read carefully.

The text was displayed on a Cathode-ray Tube (CRT) one line at a time in normal upper and lower case type. The subject was able to call for each successive line by pressing a button which changed the text within a few msec. The CRT was about 68 cm from the subjects' eyes, a distance at which 4 letter positions occupied one degree of visual angle. Maximum line length was 73 letter positions. As subjects read, their eye position was monitored every millisecond using a SRI Dual-

Purkinje Eyetracker.

The analyses to be described were based on the data from 51 subjects providing a total of nearly 20,000 saccades. From these data we selected each forward saccade which was preceded by a forward saccade, where these movements did not represent a rereading of the line or part of the line of text, and where neither saccade nor the fixation between them were contaminated by eyetracking failures (i.e., blinks, or loss of track). This procedure resulted in a reduced data set of approximately 9,200 forward saccades.

Relationships to prior eye movement events

The degree to which individual saccades are independently controlled was explored by correlating the length of each saccade in the data set with the length of the preceding forward saccade. The correlation of $r = .21$ proved to be due almost entirely to individual differences in average saccade length. The average correlation within subjects was $r = .05$. In addition, the correlation between the length of a saccade and the duration of the prior fixation was $r = -.0001$. These data are in agreement with prior reports (Andriessen & deVoogd, 1973; Rayner & McConkie, 1976) and argue for independent control of individual eye movements. Such data give encouragement to the notion that each saccade reflects stimulus or processing characteristics present at the time immediately preceding that saccade, rather than more general influences existing over longer periods of time.

Distribution of saccade length

Data concerning saccadic eye movements can be conceptualized in either of two ways: either as the likelihood of making saccades of different lengths, or as the likelihood of the eyes going to different locations in the text. In this paper, we have adopted the second perspective, and explore the effects of the three variable listed above on the locus of the next fixation. Our strategy has been to examine the effect of each of these variables while controlling for the others and to allow for some indication of their possible interaction.

A frequency distribution of saccade lengths in the selected data set is shown in Figure 1. The mean saccade length is 7.20 character positions, and the standard deviation of the distribution is 2.90. The distribution also has a median value of 6.87. This distribution gives a general indication of the likelihood of fixating a letter next which lies different distances from the present fixation location. The interpretation of this distribution, however, depends upon the view one takes of the nature of eye movement control. For example, it might be taken as indicating the result of oculomotor learning: the average distance that readers have learned to cast their eyes and the normal variability induced by various cognitive factors (Levy-Schoen, 1981). Or it might be taken to indicate the range of distances to words that are anticipated in reading and must be fixated next in order for visual confirmation to occur (Hocnberg, 1970). Or it might be taken as indicating the range of distances at which perception or identification fail, and thus, added visual clarity is required for reading to continue (McConkie, 1979; O'Regan, 1979). Thus, the proper interpretation of this distribution is an issue which has not yet been resolved.

The Importance of Words

Word-unit influences

The most perceptually obvious structure in the stimulus array of a page of text is its arrangement in lines and the subdividing of lines into words. A very important question asks whether visual characteristics of a word influence the likelihood of the next fixation being attracted to letter positions in the word. There is some evidence that this information is used in determining future fixation location: there are fewer fixations in large blank regions (Abrams & Zuber, 1972-73) and spaces between sentences (Rayner, 1975), and more fixations on the centers of words than on their beginnings and ends (O'Regan, 1981; Rayner, 1979; Zola, 1981).

In order to more accurately assess the degree to which the eyes tend to be attracted to certain letter positions in a word, we partitioned our data according to the location of the fixation with respect to different letter positions in words of different length. For instance, all fixations were found which were located three or four letter positions to the left of the first letter of a 5-letter word. Then the proportion of times that the following fixation fell on that letter was calculated. A similar proportion was obtained for each of the other letter positions of a 5-letter word; in each case, this statistic represented the likelihood that the letter would be fixated immediately following a fixation lying three or four character positions to the left of it. These proportions are graphically presented in Figure 2. This figure also shows similar proportions when the prior fixation was five or six letter positions to the left of each letter position. Thus, there curves indicate the degree to which letter position in a word influences the likelihood that a given letter will be fixated next when distance and word length are held constant. Figure 3 presents similar data for 3-, 5- and 7-letter words when the prior fixation was five or six character positions prior to the letter. Figure 4 presents the same data when the prior fixation was nine or ten character positions in front of the current fixation.

The curves show a strong influence of word position. If a letter position is within 8 to 10 letter positions of the present fixation location, it is most likely to be fixated next if it is slightly left of the center of a 5- or 7-letter word. Letter positions further away than this are benefited more by being closer to the beginning of the word. When 3-letter words are involved, however, the likelihood of a letter being fixated is greater if it lies immediately to the right of the word with a general favoring of end letters over beginning letters, even if the letter lies as much as 9 to 10 positions to the right of the prior fixation location.

While some letter positions are clearly preferred, it is equally important to notice that there are still many fixations at other positions, including the space before or after a word. These observations raise two questions. First, why are certain letter positions preferred over others? And second, why aren't more of the fixations drawn to those locations?

In response to the first question, certain positions could be preferred because of an eye movement control algorithm that seeks these locations (i.e., go slightly left of center in the next word), or because some other determiner of fixation location correlates with word position (e.g., relative perceptibility of letters or larger sub-word units).

How one regards the second question concerning the spread of fixation locations depends on the answer given to the first. If the eye movement control system seeks to center the eyes at certain word locations, the existence of fixations at other locations must indicate either that there is error in the control or that the region sought is sufficiently large that a relatively broad region represents a hit, or both (Rayner, 1979). On the other hand, if the real basis for eye movement guidance simply correlates with word position, then the fact that this correlation is not perfect is the basis for a spread of fixation locations. This latter possibility then serves to motivate further research aimed at seeking a more fundamental basis for eye movement control. At present, we can only conclude that a model of eye movement guidance must predict a greater likelihood of fixating certain locations in words than others, and that the pattern varies with distance of those locations from the present fixation location.

Word length effects

Several effects of word lengths on eye movement control have previously been documented: saccades are larger when either originating in or going to longer words (O'Regan, 1979) and are shorter when the space between words lying in peripheral vision are filled with other letters (McConkie & Rayner, 1975). In the present data, word length effects are seen in Figures 2, 3 and 4. For example, Figure 3 indicates that the second letter of a 5-letter word is most likely to attract the eyes, while the third letter of a 7-letter word is, even when distance from the prior fixation is controlled. It seems difficult to attribute this shift of where the eyes are sent to anything other than an influence of the location of the beginning and the end of a word. Also, the nature of the influence of different letter positions is quite different for 3-letter words than for 5- or 7-letter words, with greater attraction for letter positions at the end and following the word than in the middle of it. From these observations, we conclude that a model of eye movement control in reading must be able to account for a fairly complex pattern of effects related to word length.

Word identification effects

In addition to such stimulus configuration factors as word length and letter position, previous research has also demonstrated that factors related to the identifiability of words influence where the eyes go. Erroneous letters in words to the right of the fixation location can shorten saccades (McConkie & Rayner, 1975; O'Regan, 1980; Rayner, 1975b; Zola, 1981), though this occurs in a relatively narrow region (McConkie & Underwood, manuscript in preparation). Also, there is a tendency to fixate the word "the" (thought to be more perceptible due to its high frequency in the language) less than other 3-letter words (O'Regan, 1979; O'Regan, 1979b).

In the present data there are patterns which seem most easily explained by assuming that whether a word is previously identified or not influences the likelihood of letters in the word receiving the next fixation. For example, Figure 5 presents the frequency distribution of making saccades of different lengths from fixations located one letter position prior to a word. When fixating immediately prior to words of length 5 and 7, the distribution of saccade lengths appears to be bimodal. The dip between the modes comes at about the region between the words in these two cases. The results suggest that at times the word immediately to the right of the fixation was identified, in which case the eyes were sent to the next word beyond it. At other times, the word to the right was not identified, and was then the locus of the next fixation. Interestingly, this bimodality disappears when the words lie just three letter positions to the right of the fixation (see Figure 6). The data suggest that most of the time the word to the right was not identified on that fixation, thus requiring it to be fixated next.

Another finding is that the likelihood of fixating a letter position is much lower if it lies in the presently fixated word than if it lies in the next word when distance of the letter from the present fixation is controlled. Apparently the fixated word is usually identified and thus does not require a second fixation; whereas the next word to the right is often not identified and is much more likely to require a fixation.

Toward a model of eye movement control in reading

At present, it appears that the likelihood of sending the eyes next to some particular letter position to the right of the fixation point is influenced by stimulus factors (i.e., its distance from the present fixation, the length of the word it is in, and the letter position it occupies within the word) and a cognitive factor (i.e., whether or not the word it is in has been identified). Thus, an initial model of eye movement control in reading would suggest that the eyes are simply sent to the next unidentified word while reading carefully. Furthermore, where the eyes are sent is strongly influenced by location preferences that are a complex function of word length and distance.

This simple model appears to be capable of accounting for most present observations about forward saccades made during reading. Still, it leaves many questions unanswered. For instance, is there any psychological significance to where in a word the eyes are sent? Are fixations on the first letter of a 7-letter word placed there for some purpose, or are they there simply because there is some chance distribution in where the eyes go, given that an attempt was made to fixate a word? What factors influence the likelihood of identifying a word, thus influencing the likelihood that letters in it will be the locus of the next fixation? The fact that the word "the" is fixated less often suggests that word frequency might have an effect. A study by Zola (1981) failed to find an influence of language constraint on the distribution of fixations on a word, though constraint did influence the duration of those fixations. Finally, is a given saccade determined by information on the immediately prior fixation, or on fixations before that, too?

Another important set of questions concerns whether the factors included in this simple model are sufficient, or whether there are important influences on where the eyes go which must be added to the model and which will change its basic structure. Are there higher-level cognitive or language factors that will be found to have an influence in some way other than influencing the likelihood of identifying words? Such factors might include buffers, anticipations of upcoming text, or syntactic structures.

Finally, nothing has been said here about the control of regressive saccades, of forward saccades during rereading of the text, or of the factors determining how long the eyes will remain in a location before moving on. Even less is known about these aspects of eye movement control in reading. They all require much more investigation.

Our message here is quite simple. Eye movements in reading reflect the moment-by-moment brain state changes induced by an interaction of the stimulus pattern and the task of comprehending. The underpinnings for a model of control of forward movements in reading involve influences due to word identification, word length and letter position the word, and distance from the current location. Our current hypotnesis suggests that the reader may simply send his eyes to the next unidentified word with positioning in that word based upon its length and its distance from the point of fixation. It is from this perspective that we will continue our efforts to understand the eye guidance system in reading.

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Figure Captions

Figure 1. Frequency distribution of the lengths of selected forward saccade in character positions.

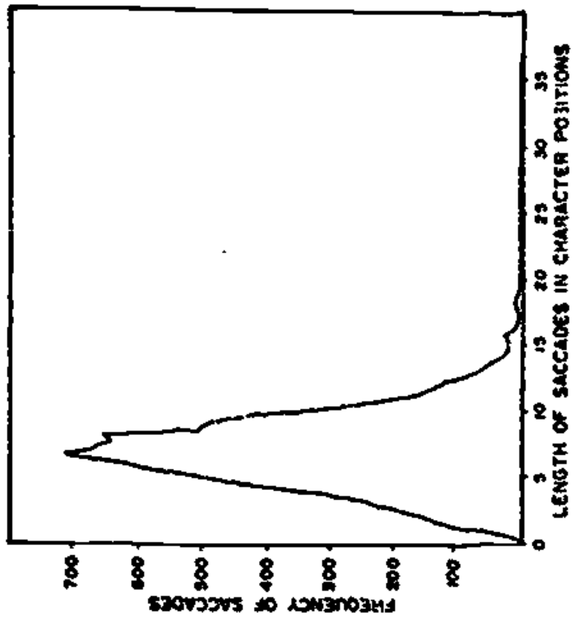
Figure 2. Likelihood of fixating different letter positions of a 5-letter word when the distance of the saccade was 3 or 4 and 5 or 6 letter positions respectively.

Figure 3. Likelihood of fixating different letter positions of 3-, 5- and 7-letter words when the distance of the saccade was 5 or 6 letter positions.

Figure 4. Likelihood of fixating different letter positions of 3-, 5- and 7-letter words when the distance of the saccade was 9 or 10 letter positions.

Figure 5. Frequency distribution of length of saccades following fixations one letter position prior to 5- and 7-letter words respectively.

Figure 6. Frequency distribution of length of saccades following fixations three letter position prior to 5- and 7-letter words respectively.


LENGTH OF SACCADES IN CHARACTER POSITIONS
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200
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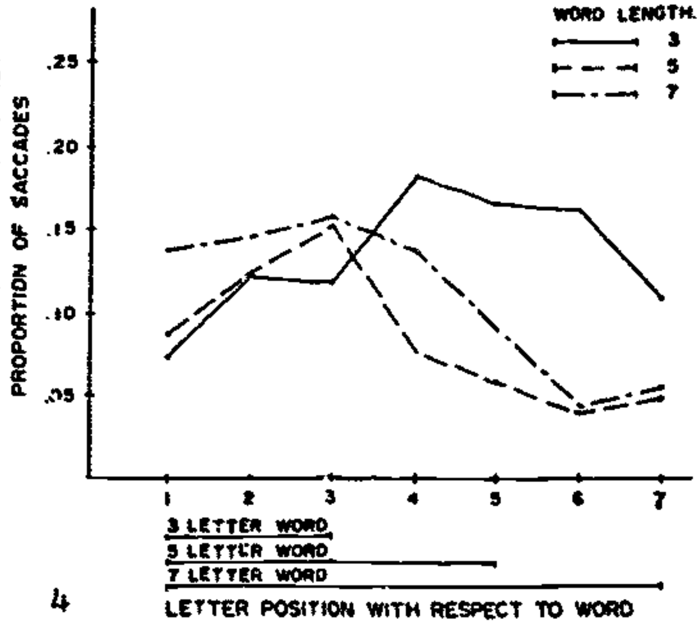
WORD LENGTH
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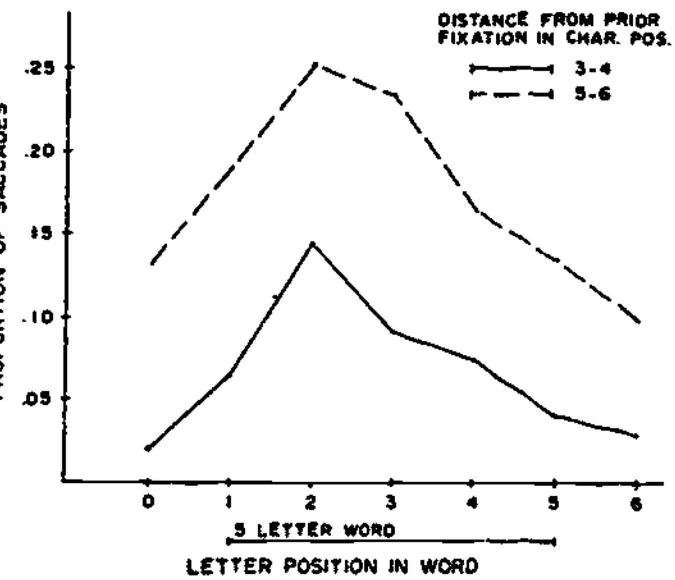
LETTER POSITION WITH RESPECT TO WORD

4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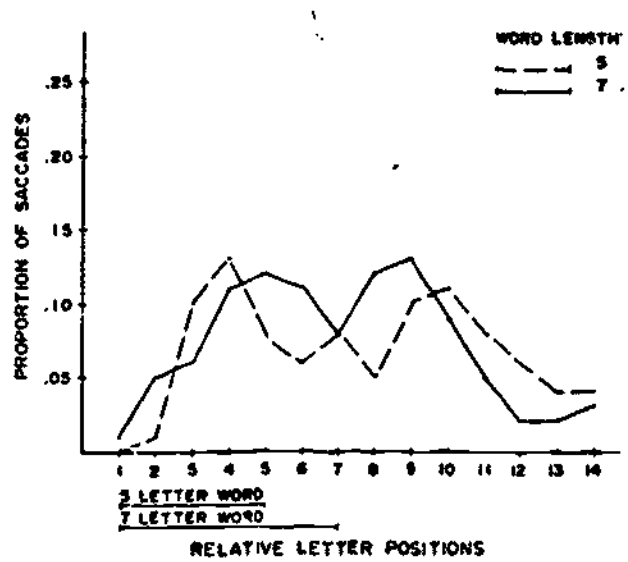
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3 LETTER WORD
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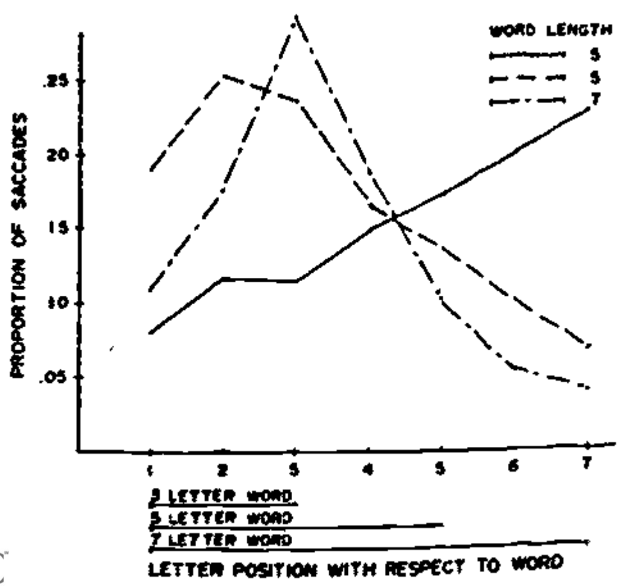
RELATIVE LETTER POSITIONS

5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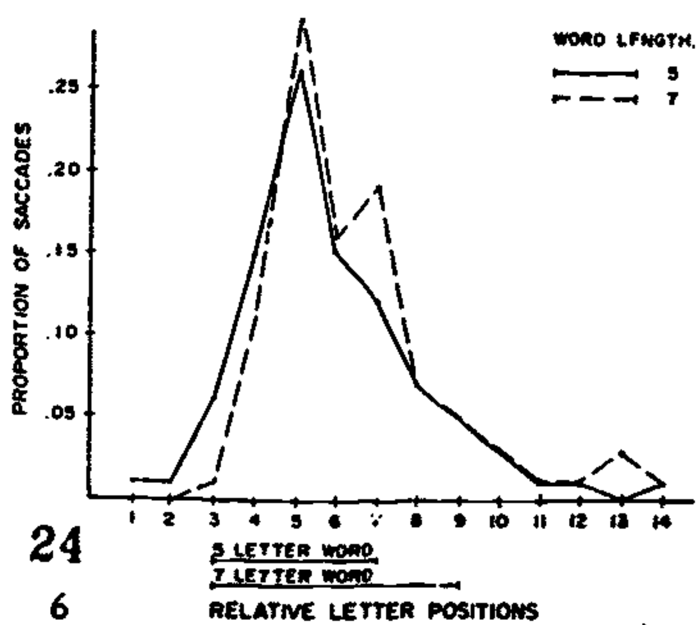
LETTER POSITION WITH RESPECT TO WORD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RELATIVE LETTER POSITIONS

6