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On the role of refixations in letter strings: The influence of oculomotor factors

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Recent studies of reading and word recognition have shown that eye-movement behavior depends strongly on the position in the word that the eye first fixates; the probability of refixating in a word is lowest with the eye near the middle of the word, and it increases as the eye fixates to either side. It has generally been assumed that the cause for this *optimal landing position* phenomenon lies in the very strong drop-off of visual acuity even within the fovea; refixation should be more likely when the eye starts from a noncentral position, because here less information can be extracted during one fixation. It may, however, be the case that the phenomenon is caused not by acuity drop-off, but by differences in within-word oculomotor scanning tactics as a function of the position that the eye initially fixates. To test this, in the present experiment we kept visual information constant while we varied the initial fixation position. We used homogeneous strings of letters of different length. One letter in each string was different from the rest (e.g., kkkkkok), and this was the letter that the subject initially fixated. This target letter had to be identified before saccading to a comparison string. The position of the target letter in the string was varied from trial to trial. If, owing to acuity limitations, refixations reflect insufficient information extraction, then, because the target letter is always directly fixated, the pattern of refixations in this condition should be independent of the first fixation position. However, the obtained refixation probability showed a strong dependence on the position of first fixation. The number of refixations was independent of the absolute length of the letter strings, but it seemed to be influenced by the proportion of the string over which the eye had to pass. The larger this proportion, the higher the probability of refixation. The results suggest that to a certain extent refixations in letter strings (or words) reflect properties of the oculomotor system rather than visual information extraction.

Several studies have confirmed that eye-movement behavior during reading depends strongly on the position in the word that the eye first fixates (McConkie, Kerr, Reddix, Zola, & Jacobs, 1989; O'Regan, 1984, 1989; O'Regan & Lévy-Schoen, 1987; O'Regan, Lévy-Schoen, Pynte, & Brugaillère, 1984; Vitu, O'Regan, & Mittau, 1990). The probability of making more than one fixation and the time that the eye spends on a word reach a minimum when the eye fixates near the middle of the word, and they increase as the eye fixates to either side of this optimal landing position with each letter of deviation from the middle (Figure 1). This effect has been observed both when the word to be recognized was presented in isolation (O'Regan, 1984, 1989; O'Regan & Lévy-Schoen, 1987; O'Regan et al., 1984; Vitu et al., 1990) and during normal reading (McConkie et al., 1989; Vitu et al., 1990), but the probability of refixating a word is much higher when the word is presented in isolation. As Vitu et al. (1990) have pointed out, these differences might be due to reading rhythm involved in the text-reading situation, to linguistic context (cf., e.g., Balota & Rayner, 1983; Vitu, 1990), or to parafoveal preprocessing (Balota, Pollatsek, & Rayner, 1985; Balota & Rayner, 1983; Inhoff & Rayner, 1980; McClelland & O'Regan, 1981; Rayner, McConkie, & Ehrlich, 1978; Rayner, Well, Pollatsek, & Bertera, 1982; Vitu, 1990). The latter two factors facilitate word recognition and thus might decrease the need to refixate words (Balota et al., 1985).

The proportions of refixations in a word, as shown in Figures 1A-1B, manifest a *word refixation curve* that can be specified well with the following equation:

$$Y = A+B(X-C)^2$$

The parameter A indicates the vertical offset of the curve at its lowest point; B is a parameter determining the slope of the curve; and C indicates the *optimal landing position* or the position in the word at which the curve reaches its lowest point. Vitu et al.'s (1990) results show that, for refixation probabilities, the optimal landing position phenomenon is weaker in normal reading than it is in isolated word recognition; that is, the slope of the curves for isolated words is much steeper than the slope for texts (see Figure 1A, bottom). However, when these data are compared with the much larger corpus of data for nor-

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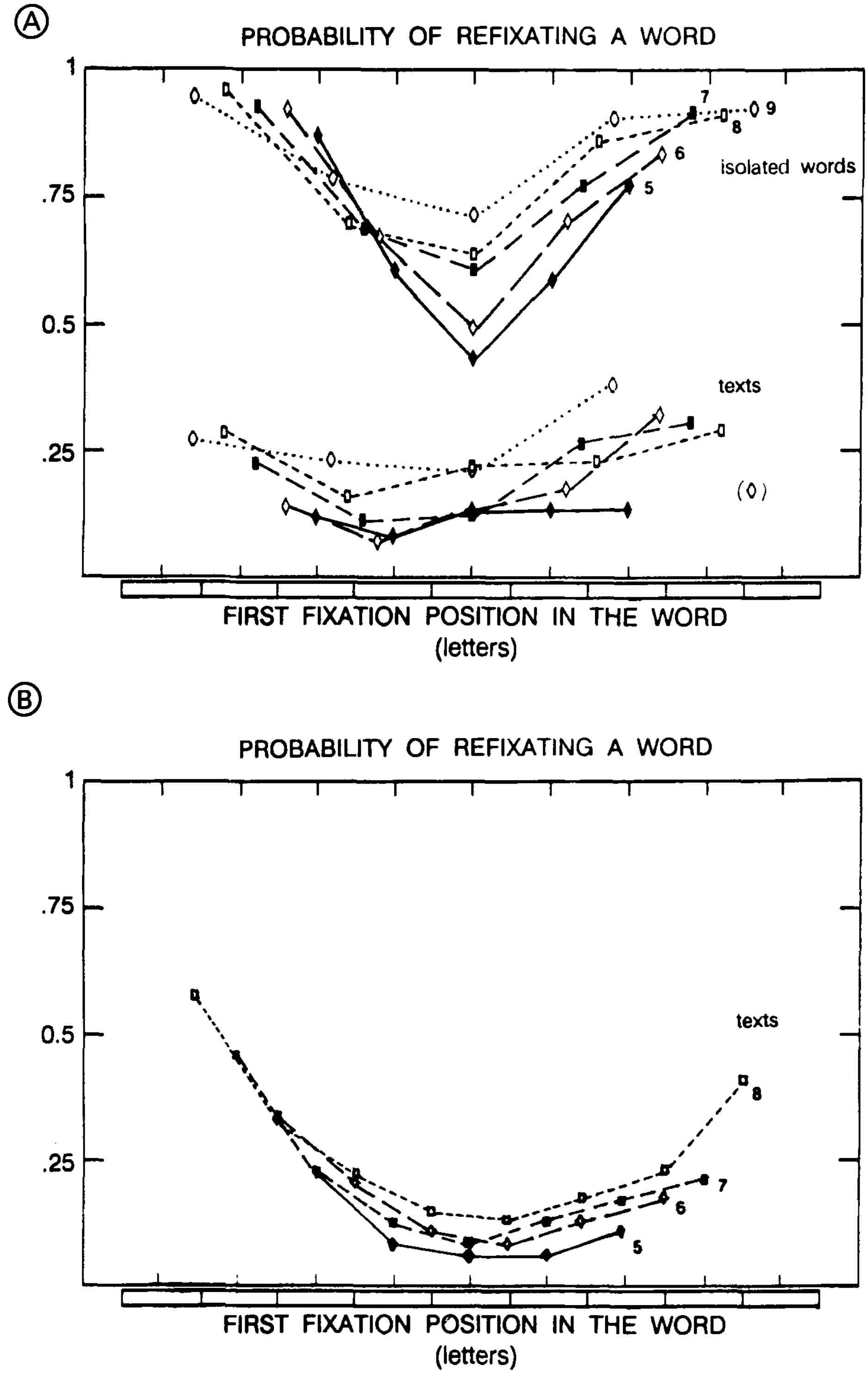


Figure 1. (A) Probability of refixating a word, as a function of the initial fixation position in the word, for five-, six-, seven-, eight-, and nine-letter words. The upper curves show refixations obtained during isolated word recognition, the lower curves, refixations during reading of texts. For all word lengths, the middle of the abscissa corresponds to the middle of the word. (Data obtained by Vitu et al., 1990.) (B) Probability of refixating a word, as a function of the initial fixation position in the word for five-, six-, seven-, and eight-letter words. The curves show refixations obtained during reading of texts. For all word lengths, the middle of the abscissa corresponds to the middle of the word. (Data obtained by McConkie et al., 1989.)

Table 1
Amount of Visual Information Available from Individual Letters in a Seven-Letter Word

Letter Position Fixated in Word	Position of Letter in Seven-Letter Word							Total Visual Information from Word
	1	2	3	4	5	6	7	
1	1	.9	.8	.7	.6	.5	.4	4.9
2	.9	1	.9	.8	.7	.6	.5	5.4
3	.8	.9	1	.9	.8	.7	.6	5.7
4	.7	.8	.9	1	.9	.8	.7	5.8
5	.6	.7	.8	.9	1	.9	.8	5.7
6	.5	.6	.7	.8	.9	1	.9	5.4
7	.4	.5	.6	.7	.8	.9	1	4.9

Note—Assumptions: The amount of visual information from the directly fixated letter is equal to 1; this information drops by .1 for each letter position of eccentricity. Word information is the sum of letter information (see McConkie et al., 1989).

mal reading in McConkie et al. (1989), the difference between the two conditions seems to be mainly one of an overall decrease of refixation probability during normal reading; that is, the vertical offset of the curves for isolated words is much higher than the vertical offset for texts (see Figure 1B). The flattening of McConkie et al.'s curves at the center is probably due to a floor effect. Thus, although the phenomenon of the optimal landing position is more pronounced for isolated words, it still exists in a comparable way during normal reading.

McConkie et al. (1989), as well as O'Regan (1989, 1990), assume that a majority of refixations result from failure to identify the word by the time the following saccade is requested. Although word frequency and other linguistic factors might affect the shape of the refixation curve, these authors see the primary basis of the optimal landing position phenomenon to be the drop-off of peripheral acuity. Since minimum angle of resolution increases as a linear function of the distance from the center of vision (Jacobs, 1979; Olzak & Thomas, 1986), McConkie et al. (1989) have proposed a simple summed letter information model of word identification that can account for the obtained empirical results in both conditions. This model rests on three assumptions: (1) The amount of visual information obtained from a letter decreases as a linear function of its distance from the center of vision; (2) the total amount of visual information available from a word is the sum of the information available for all its letters; and (3) the frequency of identifying a word during the initial fixation on it is a linear function of the amount of visual information available from it. The application of this simple model is illustrated by the data given in Table 1 (example taken from McConkie et al., 1989) and the graph in Figure 2.

Table 1 presents the amount of visual information available from individual letters in a seven-letter word, assuming that the amount of information from the directly fixated letter has the value of 1, and that there is a drop of 10% (an arbitrarily chosen value) in information for each letter-position unit of distance from that location. The total amount of information obtained from a word is the sum of the information obtained from the individual letters. McConkie et al. (1989) concluded that given these assumed parameters, word-identification failure is lowest with the eye at the center of the word, where maximal information can be extracted during one (the initial) fixation (see Figure 2). The more the initial fixation position deviates from the center of the word, the less will be the information extracted. To identify the word correctly, the subject will have to fixate a different part of the word in addition. Thus, this model, which takes into account the

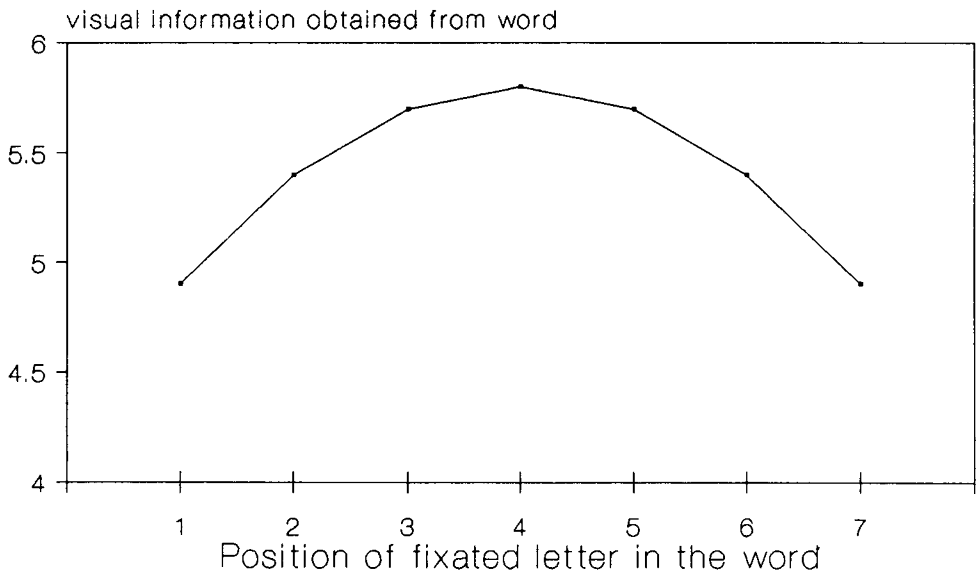


Figure 2. Theoretical distribution of the total amount of visual information obtained from a word, as a function of fixation position (see text).

linear acuity drop-off and a letter-based information extraction, gives rise to the parabolic increase in the frequency of word-identification failure.

The summed letter identification model seems to fit the empirical results perfectly (McConkie et al., 1989; O'Regan, 1989; O'Regan et al., 1984; Vitu et al., 1990). However, it has not been tested directly yet. The major assumption of the model is that the amount of visual information that can be extracted during one fixation differs as a function of the position of the eye on the word, and that refixations are the consequence of insufficient visual information extraction during the initial fixation. However, it might well be that the obtained refixation curves reflect properties other than word-identification failure. Due to some oculomotor constraints, the position of the eye in a letter string itself might affect eye-movement behavior.

If the U-shaped form of the refixation curves is a consequence of differences in the amount of visual information available while one fixates different positions in the word, the curves should become flat when this amount is kept constant. If, however, the probability of refixation does vary as a function of the initial fixation position, it must be assumed that, to some extent, refixations reflect properties of the oculomotor system rather than insufficient visual information extraction.

In the following study, the effect of initial eye position in a letter string was examined, keeping visual information available at each position constant.

So that we could control the amount of visual information available during one fixation, we used strings of homogeneous letters of different length as stimuli, instead of words. One letter in each string was different from the rest (e.g., "kkokkkkk"). This letter was the only target the subject had to identify. The position of the initial fixation in the string was manipulated experimentally (see O'Regan et al., 1984), and simultaneously the position of the target letter was always chosen to coincide with the position of this initial fixation. Thus, although the position of initial fixation in the string varied, the amount of information available from the target letter was the same for each position. If refixations are the consequence of insufficient information extraction, no additional fixations in the string should be necessary, because the only information required to do the experimental task was available immediately at the position of initial fixation. Thus, this method allowed us to test whether the position of the eye in a letter string itself would affect eye-movement behavior.

Probability of refixation and location of refixations were measured as a function of the initial fixation position.

EXPERIMENT 1

Method

Subjects. Eight subjects 20–30 years old participated in the experiment. All had normal vision.

Materials. The stimuli were homogeneous strings of the lower-case letter "k." Four different string lengths were used: 5, 7, 9, and 11 letters. In each of the strings, one of the "k"s was replaced by a target letter. The target letter could be the letter "c," "o," "t," or "f." Except in the 5-letter string, in which the target could be at any of the five letter positions, the position of the target letter was at one of the odd-numbered letter positions in the string. Because the target position coincides with the first fixation position, the given positions also represent the positions of the first fixation.

Design. The experiment contained two identical blocks. In each experimental block, every target letter appeared four times at each one of the possible target positions in each one of the four different string lengths, giving a total of 320 trials per block. The order of the first fixation position in the string as well as the order of string lengths of the string presented during the experiment was randomized. Each block was preceded by 8 training trials. After the first block, there was a short break of about 5 min before the second block started. Thus, in all, there were 640 trials per subject.

Procedure. The subjects sat in an adjustable chair at a distance of 50 cm from the computer screen. Their heads were stabilized by a chin- and forehead rest. The experiment began with a calibration phase, in which the eye-movement recording system was adjusted for perfect correspondence between the recorded fixation position and the fixated stimulus. When calibration was correct, the first trial began. Two vertically aligned lines with a letter-high gap between them appeared at the center of the screen (Figure 3). As soon as the subject fixated in the gap (± ⅛ character from the gap), the fixation lines were replaced by two letter strings of the same length (the test string and a comparison string). The test string appeared at different positions relative to the gap in the fixation lines, so that the directly fixated position in the string was one of the letter positions described above. The target letter appeared always in the gap of the fixation lines—that is, at the fixation point. Whatever the position of the test string relative to the fixation point, the comparison string was always placed to the right of the test string, beginning one character space after the test string. During fixation of the test string, only the letters of this string were visible while the comparison string was masked. When the computer detected that the eye had passed the middle of the space separating the test string and the comparison string, the test string was masked (and remained masked until the end of the trial) and the comparison string became visible. As was the case for the test string, the comparison string was made out of the letter "k," and it contained, at a randomized position, a target letter as well. The target letter in the

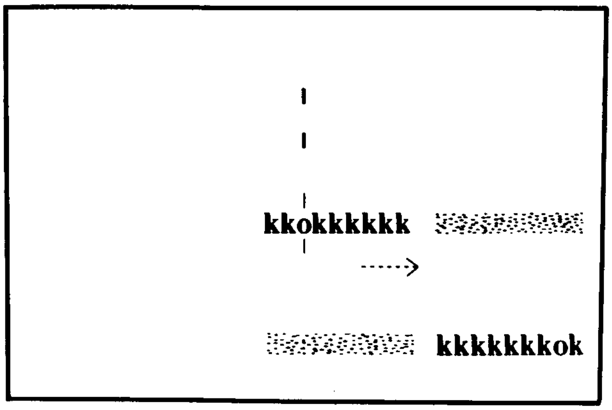


Figure 3. Schematic presentation of the experimental task. First, a fixation point appeared at the center of the screen. After correct fixation, it was removed, and the two letter strings appeared (with the comparison string masked) on the screen. The target letter was always positioned at the fixation point. When the eye had passed the middle of the space separating the two strings, the test string was masked and the comparison string became visible.

comparison string could either be identical or different from the target letter in the test string. The subject's task was to compare the target letter in the test string with the target letter in the comparison string and to determine, by pressing a button, whether the two letters were identical or not.

The total number of fixations, the position of refixations in the test string, and certain temporal aspects of the eye-movement behavior were recorded. Before starting the main experiment, each subject was familiarized with the task to ensure that he or she would be aware of the fact that the position of the eyes on the screen controlled what happened on the screen. The subjects were well informed that the target stimulus in the test string always appeared at the first fixation position.

Apparatus. Eye movements were recorded by a photoelectric, infrared, iris/sclera boundary detection technique. Eye position was sampled by a BBC Master computer every 10 msec. Saccade size and fixation duration were analyzed by the computer in real time. A saccade was defined as a change in eye position of more than one half of the character, taking less than 70 msec and giving rise to a fixation lasting more than 70 msec. The characters were defined in an 8×8 pixel matrix that subtended .3°. The stimuli were presented on a black/white Velec (1614-07) video monitor, refreshed at 50 Hz.

Results

Probability of errors. The probability of an incorrect response to the comparison of the two target letters in the test string and the comparison string averaged only .036 over the whole experiment. Although most subjects reported afterwards that the errors they made were due to confusions of the response keys rather than to comparison failure, these data were excluded from further analysis.

Probability of refixation. Contrary to what would have been predicted if refixations were the consequence of insufficient visual information extraction during the initial fixation, the obtained refixation curves were not flat. Figure 4 gives the proportion of refixations in the test string as a function of the distance of the initial fixation position from the comparison string for the four string lengths. An analysis of variance (ANOVA) performed for each string length to determine whether the probability of refixations depended significantly on imposed fixation location showed that the effect was significant for all four string lengths: 5 letters [$F(4,28) = 38.28$, $p < .01$], 7 letters [$F(3,21) = 25.89$, $p < .01$], 9 letters [$F(4,28) = 12.15$, $p < .01$], and 11 letters [$F(5,37) = 12.66$, $p < .01$]. The curves clearly show that the probability of refixating the string is highest when the eye starts at the beginning of the string, and that it decreases the more the first fixation position is placed toward the end of the string. An analysis of the number of refixations made in the four strings showed that in 86.8% of all cases in which refixations were made, the eye refixated the string only once. In the remaining 13.2%, two or more refixations were made. A general strategy of two or more refixations could have indicated that the subject had not followed the instruction to identify the target at the first fixation position, but instead had searched for it somewhere in the string upon onset of the stimulus.

Thus, although the target letter could be identified immediately at the first fixation position, and although no

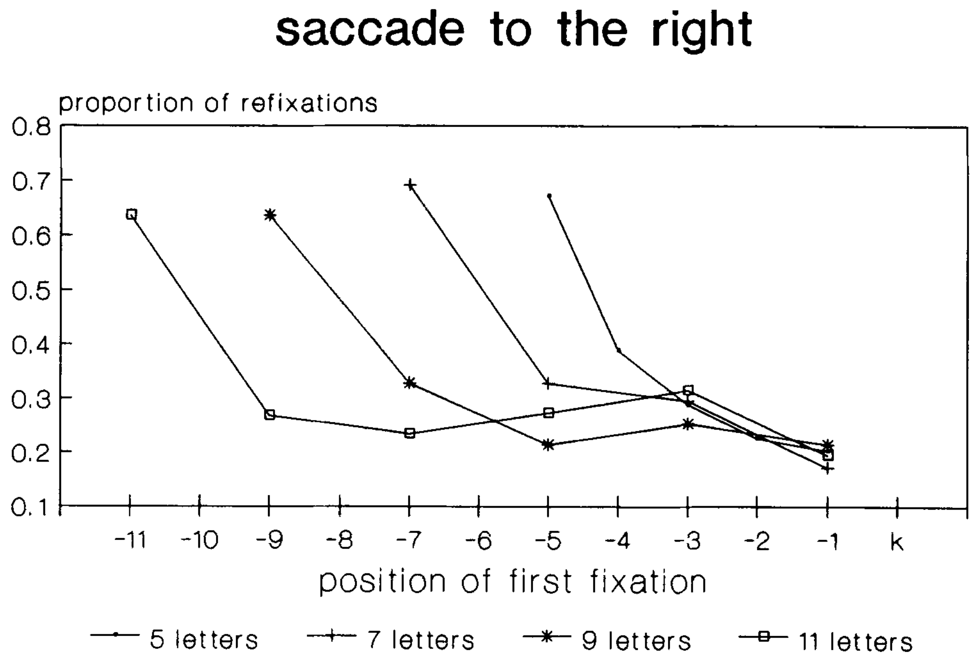


Figure 4. Proportion of refixations in the test string, as a function of the first fixation position for the four string lengths. The letter "k" indicates the beginning of the comparison string. The numbers indicate the distance (in letters) from the first fixation position to the comparison string. Thus, −1 means that the first fixation position is on the last letter in the test string.

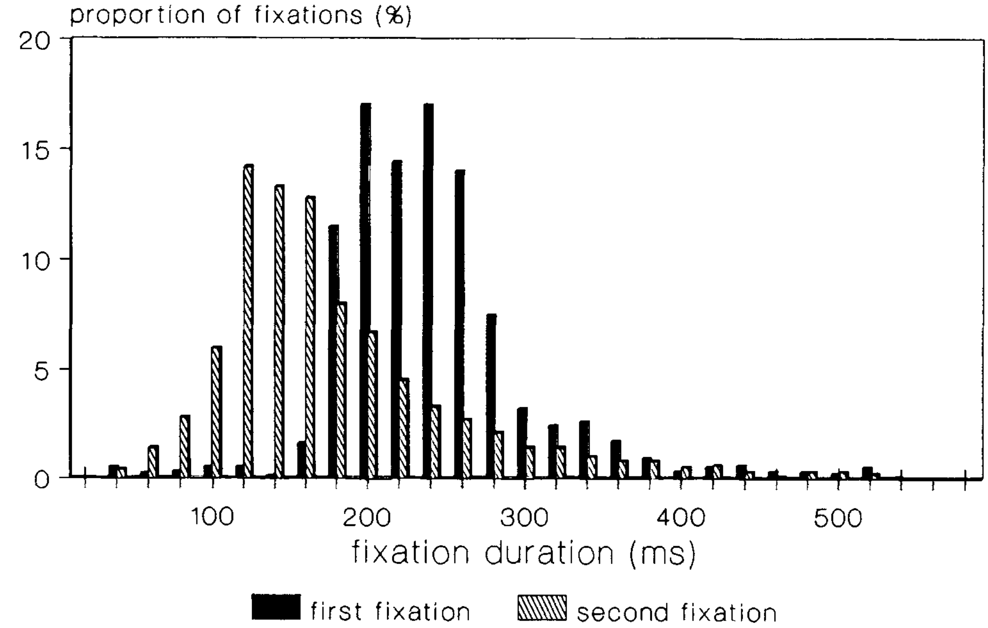


Figure 5. Frequency distribution of first and second fixation durations obtained in Experiment 1 (independently of string length) for the case in which two fixations were made in the string.

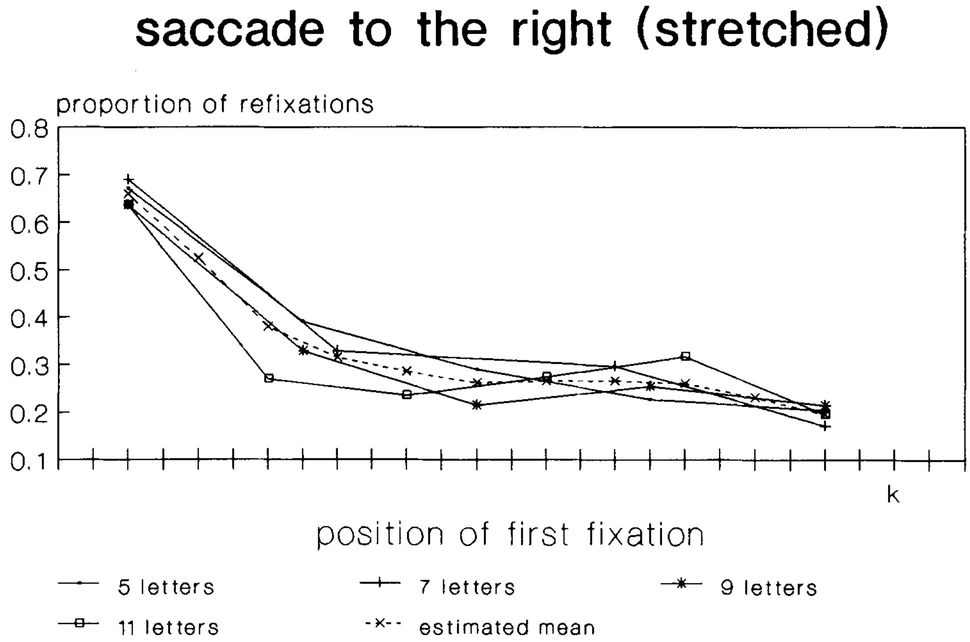


Figure 6. Proportion of refixations in the test string as a function of the first fixation position, presented independently of the absolute length of the four strings. The beginning and the end of each curve fall on the same point. The dashed line is an estimation of the mean of the four curves.

Table 2
Proportion of Refixations as a Function of Its Position Relative to the Initial Fixation Position

Number of Letters	On Parts of the String Over Which the Eye Has to Pass to Reach the Comparison String	On Parts of the String Opposite the Direction in Which the Eye Has to Go
5 letters	.92	.08
7 letters	.93	.07
9 letters	.93	.07
11 letters	.91	.09

additional information (with regard to the task) was obtained during refixations on other parts in the test string, subjects nevertheless tended to refixate the test string before saccading to the comparison string. The observed refixations cannot be explained by drifts of the eye, because the distribution of first and second fixation durations obtained in this task (Figure 5) shows the typical pattern of distribution; there is no accumulation of abnormally short refixations indicative of drifts. Moreover, there is no plausible reason why drifts should appear at one fixation location more frequently than at others.

On first impression, the decreasing proportion of refixations toward the end of the string could have been interpreted in favor of a constant saccade-size strategy made by the subject in order to reach the comparison string. If the size of the saccades made in such a simple task are not larger than a certain limit, such a strategy would produce higher refixation probabilities at the beginning of the string than toward the end, where the distance to the comparison string becomes smaller. However, interestingly, the probability of refixating was independent of the absolute distance (e.g., in letters) between the first fixation position and the comparison string. The proportion of refixations for a distance of five letters to the comparison string was almost .7 in the five-letter string and only about .2–.3 in the longer strings (see Figure 4). In fact, when stretching the curves (see Figure 6) so that the beginning and the end of each curve fall on the same point, the shape of the refixation curves are virtually the same. This means that the refixations obtained in this experiment were caused by the relative position of the eye in the string.

The fact that refixations in the test string had no utility for performance of task, along with the independence of the refixation probabilities with regard to the absolute length of the letter strings, suggests that the refixations obtained in this experiment were caused by properties of the oculomotor system. The position of the eye in the string itself seemed to have influenced the probability of refixation. The decrease of the refixation curves from the beginning toward the end of the string suggests that as the eye saccades over a letter string (in order to reach another string), the proportion of the string over which the eye has to pass determines the refixation probability. The bigger this proportion with regard to the actual string length, the more likely it will be that the eye makes an additional fixation in the string.

Because of the apparent equivalence of the four string lengths, the mean of the four refixation curves was estimated (dashed line in Figure 6). For simplicity, only this curve will be considered in further discussion.

If the refixations were due to the proportion of the string over which the eye had to pass, most of the refixations obtained in this experiment would have to occur somewhere between the initial fixation position and the end of the string, with few between the initial fixation and the beginning of the string. In Table 2, the proportions of the positions of the second fixation (for reasons of simplicity only, the cases where one refixation was made are taken into consideration) relative to the initial fixation position are given: almost no refixations were found between the first fixation position and the beginning of the string.

If the obtained results are due to oculomotor constraints, the course of the refixation curves should be inverted, when instead of saccading to the right, as in this experiment, subjects had to saccade to the left in order to reach the comparison string. In Experiment 2, the comparison string to which the eye had to saccade was therefore placed left of the test string. It was hypothesized that the probability of refixation would thus be maximal with the initial fixation position at the end of the string, and that it would decrease the more the initial fixation was shifted toward the beginning.

EXPERIMENT 2

Method

Subjects. Eight subjects 20–30 years old participated in the experiment. All had normal vision. None had participated in the previous experiment.

Materials, Design, and Apparatus. The materials, design, and apparatus used in Experiment 2 were the same as those in Experiment 1.

Procedure. The experimental procedure was as that in Experiment 1, but instead of the comparison string's being presented to the right of the test string, here it appeared to the left of the test string.

Results

Probability of errors. The probability of errors averaged .038 over the whole experiment. These data were excluded from further analysis.

Probability of refixation. As in Experiment 1, the refixation curves obtained in Experiment 2 were not flat. Figure 7 gives the proportion of refixations in the test string as a function of the distance from the initial fixation position to the comparison string for the four string lengths. An ANOVA performed for each string length showed that here too the effects of initial fixation position were strongly significant for all string lengths: 5 letters [$F(4,28) = 22.82$, $p < .01$], 7 letters [$F(3,21) = 11.42$, $p < .01$], 9 letters [$F(4,28) = 16.56$, $p < .01$], and 11 letters [$F(5,37) = 12.57$, $p < .01$]. As predicted, the probability of refixation was highest for the initial fixation position's being at the end of the string; it decreased toward the middle of the string, but from there on, contrary to the results of Experiment 1, the proportion of

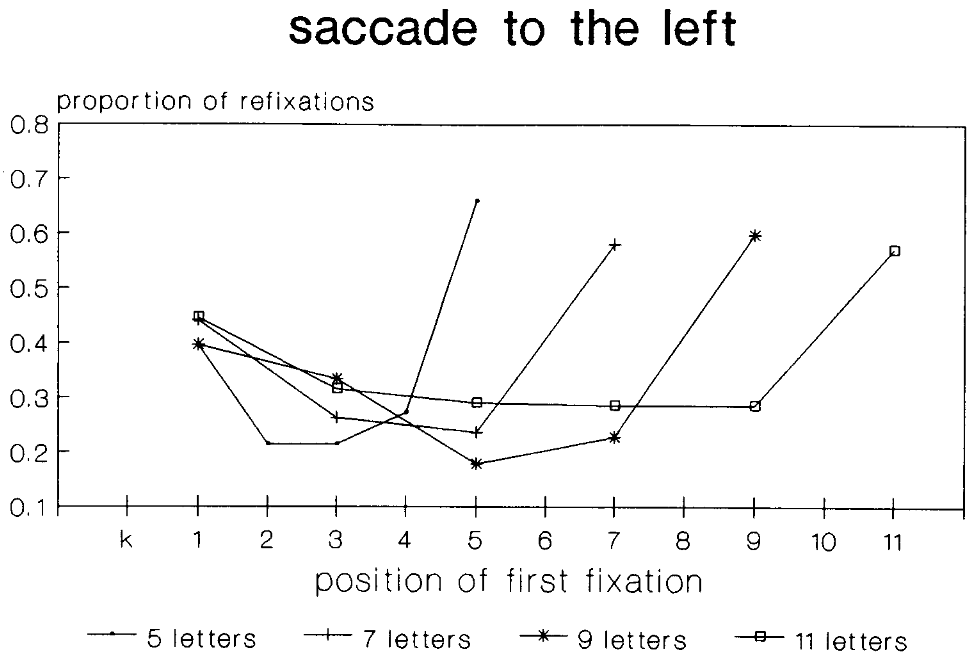


Figure 7. Proportion of refixations in the test string as a function of the first fixation position for the four string lengths. The letter "k" indicates the end of the comparison string. The numbers indicate the distance (in letters) from the first fixation position to the comparison string. Thus, 1 means that the first fixation position is on the first letter in the test string.

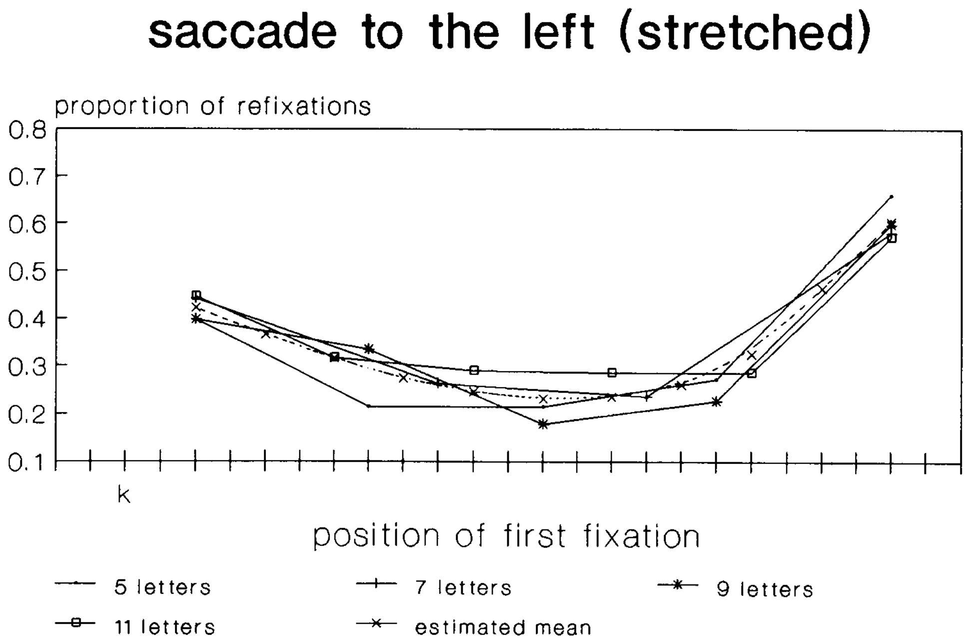


Figure 8. Proportion of refixations in the test string as a function of the first fixation position, presented independently of the absolute length of the four strings. The beginning and the end of each curve fall on the same point. The dashed line is an estimation of the mean of the four curves.

Table 3
Proportion of Refixations as a Function of Its Position Relative to the Initial Fixation Position

Number of Letters	On Parts of the String Over Which the Eye Has to Pass to Reach the Comparison String	On Parts of the String Opposite the Direction in Which the Eye Has to Go
5 letters	.73	.27
7 letters	.60	.40
9 letters	.62	.38
11 letters	.57	.43

refixations increased again. The analysis of the number of refixations made in the four test strings showed a similar distribution obtained in Experiment 1: in 88.3% of the cases in which refixations were made, the eye refixated the string only once, and in the remaining 11.7%, twice or more. Again, the stretched version of the curves (Figure 8) shows that the shape of the refixation curves was independent of the absolute length of the letter strings. Thus, except for the reincrease of the refixation probability toward the beginning of the string, the results obtained in this experiment are consistent with the results obtained in Experiment 1: refixation probability is higher the larger the proportion over which the eye has to pass. The distribution of the first and second fixation duration (not shown here) was comparable to the one obtained in Experiment 1.

The fact that refixation probability increases again when the first fixation position is shifted toward the beginning is probably due to reading habits; in reading, most saccades are made to the right. Thus, although subjects had to saccade to the left in order to perform the task, in some cases they spontaneously saccaded to the right. This assumption is supported by the analysis of the positions of refixations relative to the initial fixation position (see Table 3). While in Experiment 1, the second fixations almost always occurred on parts of the string over which the eye had to pass in order to reach the comparison string, in Experiment 2, more refixations were made on parts of the string opposite the direction in which the eye had to go. The exact distribution of the positions of the second fixation in the string is given for the two conditions in Figure 9 for the seven-letter string. The panels on the left give the condition with saccades to the right (Experiment 1) and the panels on the right give the condition with saccades to the left (Experiment 2).

A comparison of the mean refixation curves of Experiment 1 with those of Experiment 2 as a function of the distance from the initial fixation position to the comparison string (the mean refixation curve of Experiment 2 is inverted) is given in Figure 10. The striking result is that, except for the reincrease of the curve in Experiment 2, the two refixation curves are virtually the same. This supports the hypothesis that the refixation probabilities obtained in these experiments were determined by factors related to the oculomotor system.

Since different subjects participated in the two experiments, the reincrease of refixation probability toward the beginning of the string in Experiment 2 could not be interpreted clearly. It might have been that the difference was due to different intersubject strategies rather than general reading habits. Thus, an additional experiment was run, in which each subject participated in both conditions (comparison strings to the left and to the right, respectively).

EXPERIMENT 3

Method

Subjects. Ten subjects 20-30 years old participated in Experiment 3. All had normal vision. None had participated in Experiment 1 or 2.

Materials and Apparatus. The material and apparatus in this experiment were identical to those in the previous experiments.

Design and Procedure. Like Experiments 1 and 2, Experiment 3 contained two blocks of 320 trials. In one block, the comparison string appeared to the right of the test string (as in Experiment 1); in the other block, it appeared to the left (as in Experiment 2). Each subject participated in both experimental conditions. Half of the subjects started with the comparison string to the right of the test string; the other half started with the comparison string to the left. Other than this, the design and the procedure of Experiment 3 were identical to those of the previous experiments.

Results

Percentage wrong responses. The percentage of errors was .038 for the condition with the comparison string to the right of the test string and .029 in the condition with the comparison string to the left of the test string. These data were excluded from further analysis.

Probability of refixation. Note that for each of the two conditions in Experiment 3, each subject received only half as many trials as did the subjects in Experiment 1 or 2. In the first two experiments, each subject received 640 trials with saccades either to the right or to the left, whereas in Experiment 3, each subject received 320 trials with the comparison string to the right and 320 with the comparison string to the left. Thus, the subjects in the first two experiments were better trained for the task that they performed.

Figure 11A gives the proportion of refixations in the test string as a function of the distance from the initial fixation position to the comparison string for the condition with saccades to the right, Figure 11B for the condition with saccades to the left. An ANOVA showed again that the probability of refixations depended significantly on imposed fixation location for all four string lengths: 5 letters [$F(4,36) = 9.8, p < .01$], 7 letters [$F(3,27) = 16.5, p < .01$], 9 letters [$F(4,36) = 17.5, p < .01$], and 11 letters [$F(5,45) = 10.96, p < .01$]. No significant effect was found for the left versus right conditions. This shows that global performance in the two conditions was not different. A significant interaction of fixation location and left/right condition was found for the strings with 5 letters [$F(4,36) = 4.97, p < .01$], 7 letters [$F(3,27) = 7.76, p < .01$], and 9 letters [$F(4,36) = 2.7, p < .05$], but not for the string with 11 letters [$F(5,45) = 1.227$, n.s.], showing that the course of the obtained refixation curves was significantly different in the two conditions.

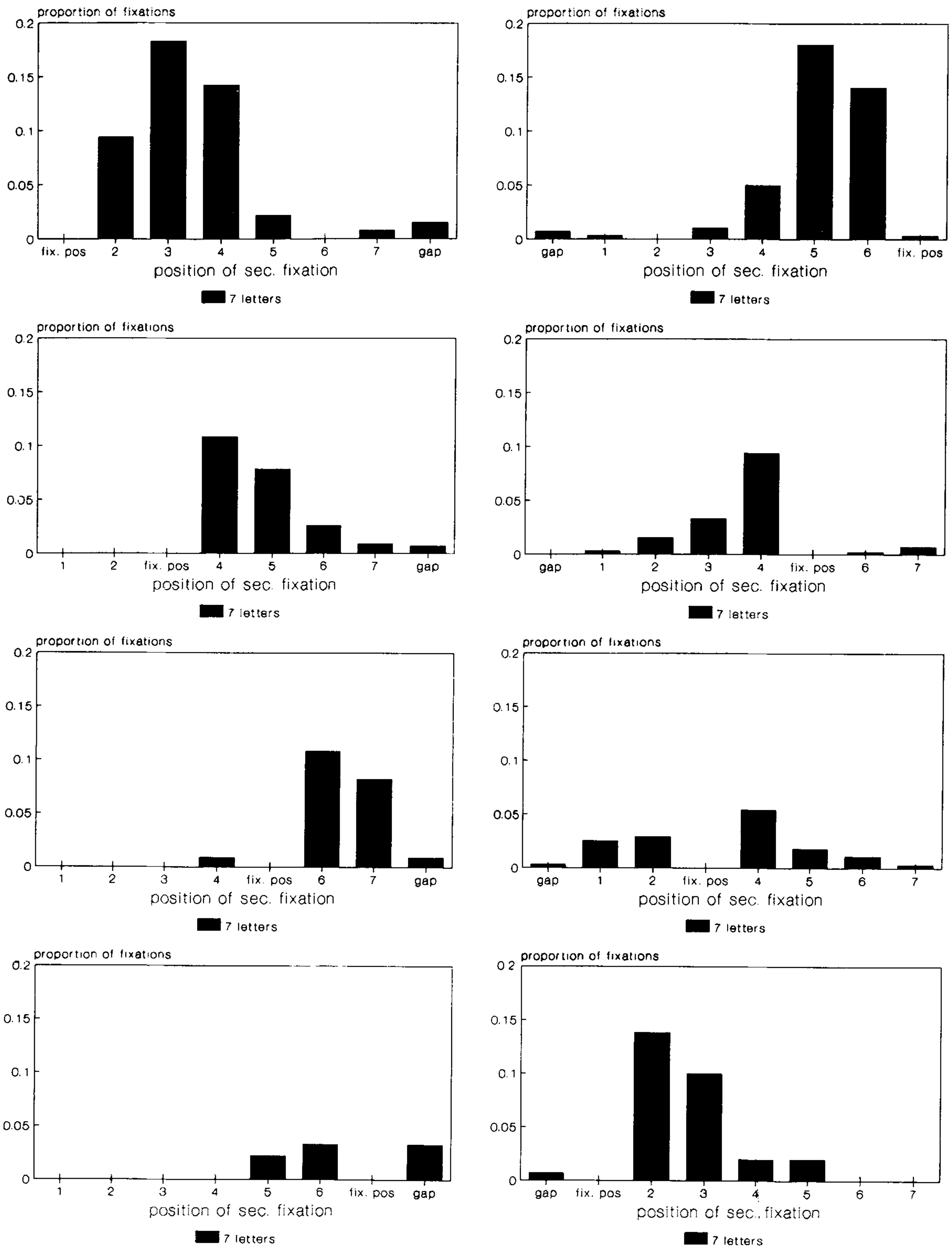


Figure 9. Distribution of the position of second fixation in the test string for the seven-letter string as a function of the first fixation position. The initial fixation position as well as the position of the gap between the test string and the comparison string is indicated in the figure. Panels to the left give the condition with saccades to the right (Experiment 1); panels to the right give the condition with saccades to the left (Experiment 2).

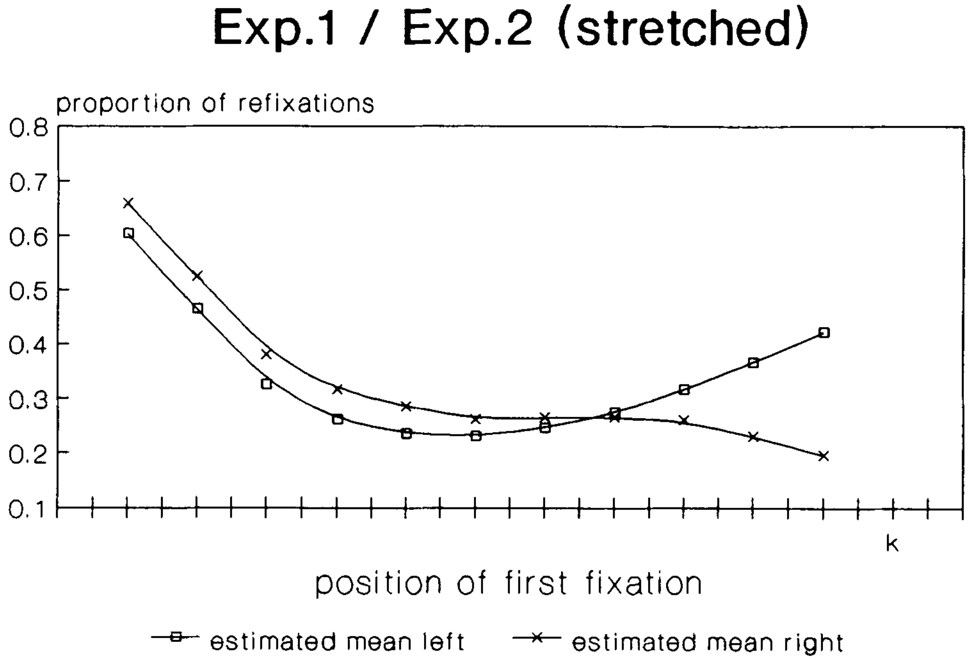


Figure 10. Mean refixation curves (estimated) of Experiment 1 (saccades to the right) and Experiment 2 (saccades to the left) as a function of the distance from the initial fixation position to the comparison string (indicated by the letter "k"). The refixation curve of Experiment 2 is inverted.

The curves are essentially the same as the curves obtained in Experiments 1 and 2. With the comparison string to the right, the probability of refixation is highest when the first fixation position is at the beginning of the string, and it decreases toward the end; with the comparison string to the left, the probability of refixation is high at the end of the string, it decreases toward the middle of the string, and it increases again toward the beginning. Again the shape of the curves is independent of string length (see Figure 12).

Given the replication of the results of Experiments 1 and 2 in Experiment 3, using the same subjects in the two conditions, the reincrease of the refixation curves toward the beginning in Experiment 2 cannot be interpreted in terms of intersubject differences.

A comparison of the performance of the subjects in Experiments 1, 2, and 3 allows us to examine the differences between the more trained subjects of the first two experiments and the less trained subjects in Experiment 3. Figure 13A gives the mean refixation curve of Experiment 1 and the mean refixation curve of Experiment 3 (the condition with saccades to the right). In Figure 13B, the mean refixation curve of Experiment 2 is compared with the mean refixation curve of Experiment 3 (the condition with saccades to the left). The less trained subjects of Experiment 3 generally made more refixations than did the more trained subjects of Experiments 1 and 2, but globally the refixation curves for the two conditions are the same. A qualitative change of the shape of the curves becomes evident only when the proportion over which the eye has to pass in order to reach the comparison string becomes smaller (at the end for the condition with saccades to the right; at the beginning for the conditions with saccades to the left). Here, trained subjects made fewer and fewer refixations. If training reduces task-inappropriate strategies, these results might support the hypothesis that the reincrease of refixation probability obtained in Experiments 2 and 3 (condition with saccades to the left) reflects habits related to reading, which go contrary to the demands of the task. Although these cannot be totally suppressed, they nevertheless become weaker the more the subject gets used to the task.

GENERAL DISCUSSION

The three experiments reported here clearly demonstrate that even when the information obtained at various positions in a letter string is identical, the probability of refixating the string varies as a function of the position of the first fixation. Thus, at least in this task, refixations do not necessarily reflect insufficient visual information extraction during the preceding fixations. The position of the eye in a letter string per se affects refixation probability, although the exact underlying mechanism of these "unnecessary" refixations is not yet known. The independence of refixation probability with regard to the length of the letter strings shows that these refixations are related to the proportion of the string over which the eye has to pass in order to reach the next string. The larger this proportion, the more likely it is that the eye will refixate the string.

Is it possible that the influence of oculomotor factors observed in this study also occurs during isolated word recognition or even during normal reading?

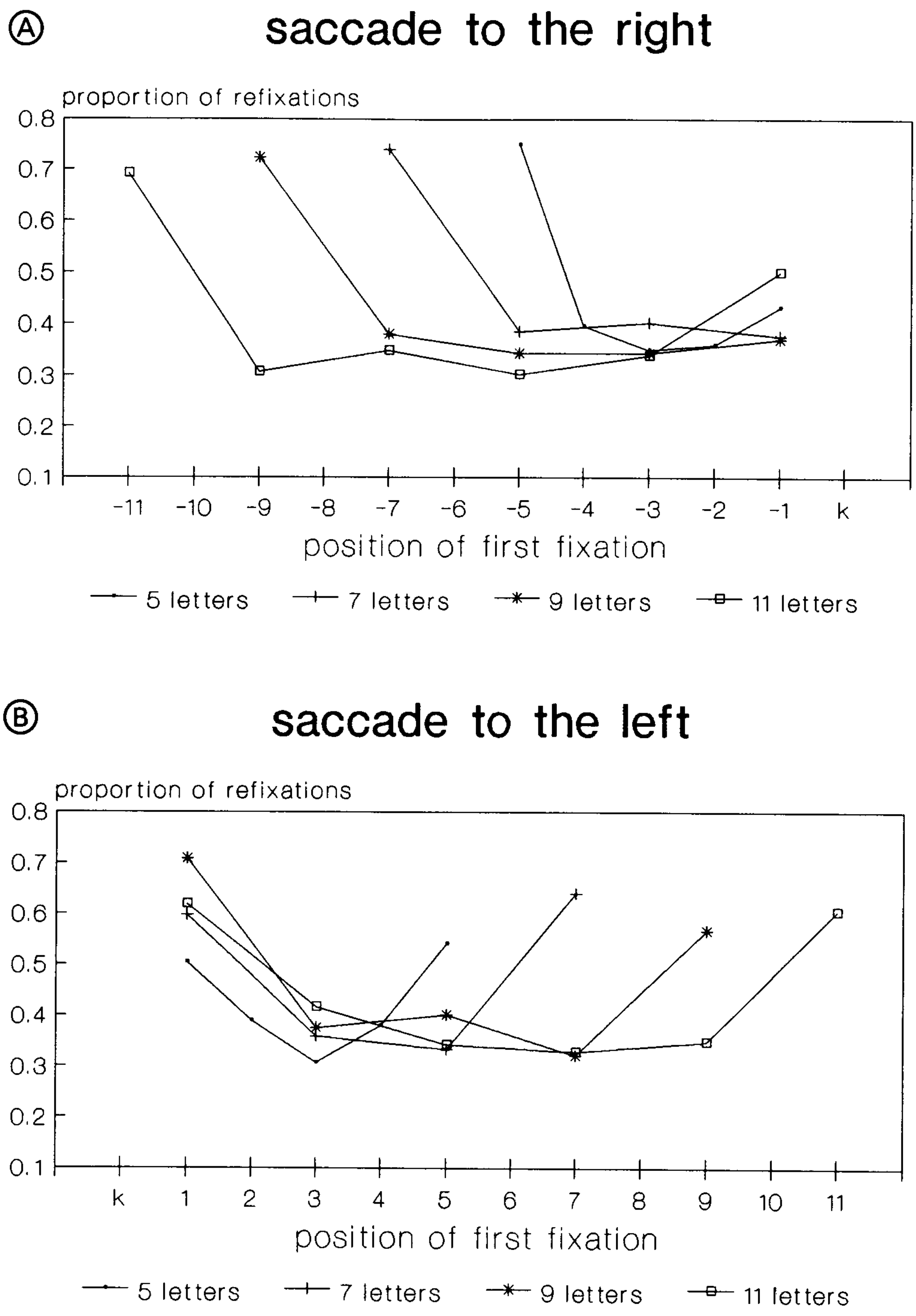
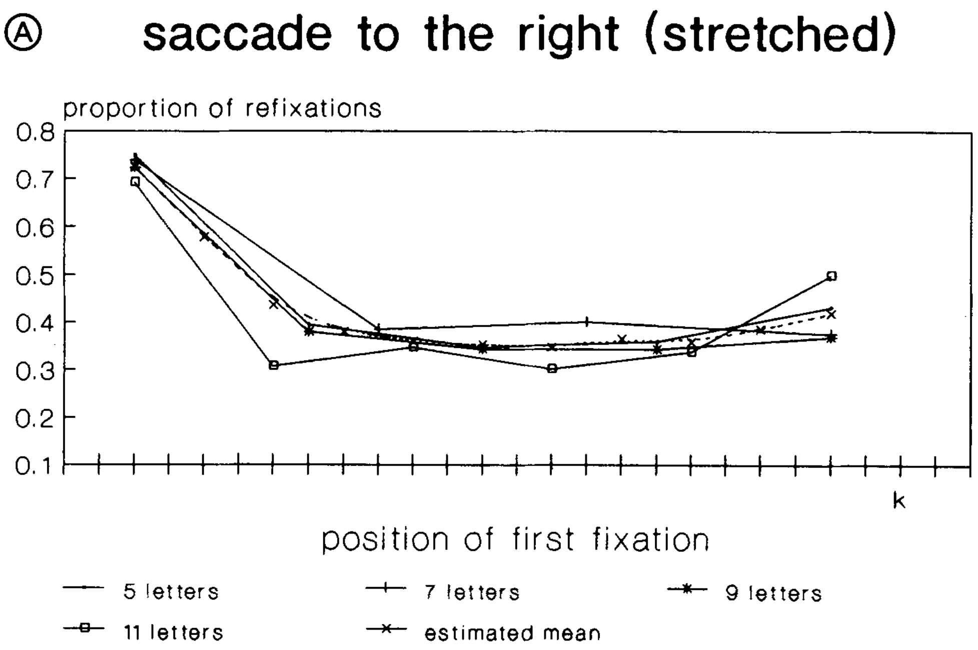


Figure 11. Proportion of refixations in the test string as a function of the first fixation position for the four string lengths. (A) Condition with saccades to the right. (B) Condition with saccades to the left.



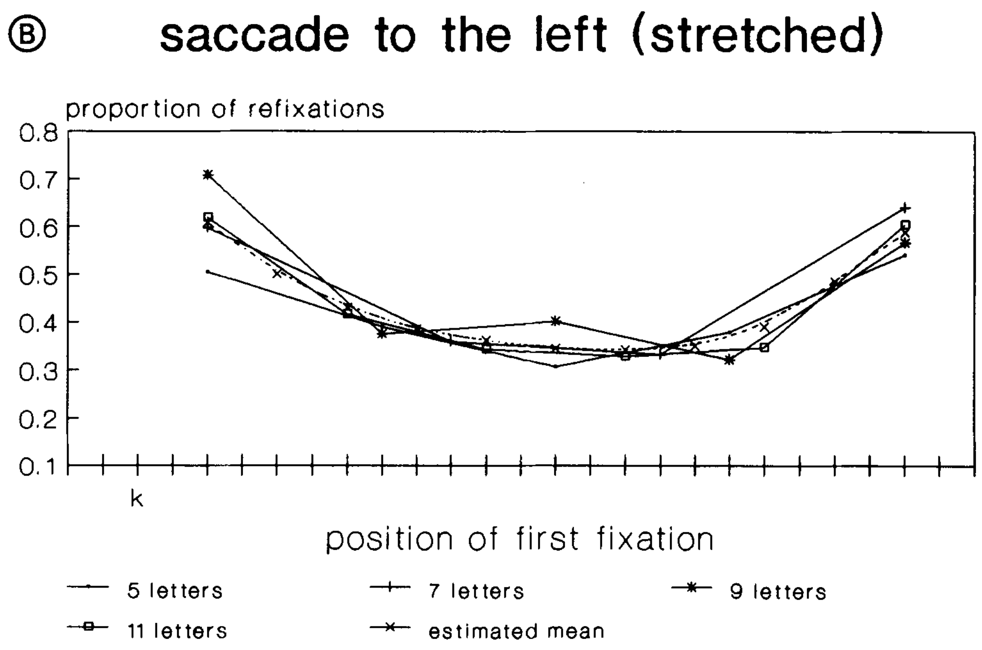


Figure 12. Proportion of refixations in the test string as a function of the first fixation position, presented independently of the absolute length of the four strings. (A) Condition with saccades to the right. (B) Condition with saccades to the left. The beginning and the end of each curve fall on the same point. The dashed lines are the estimated means for the curves.

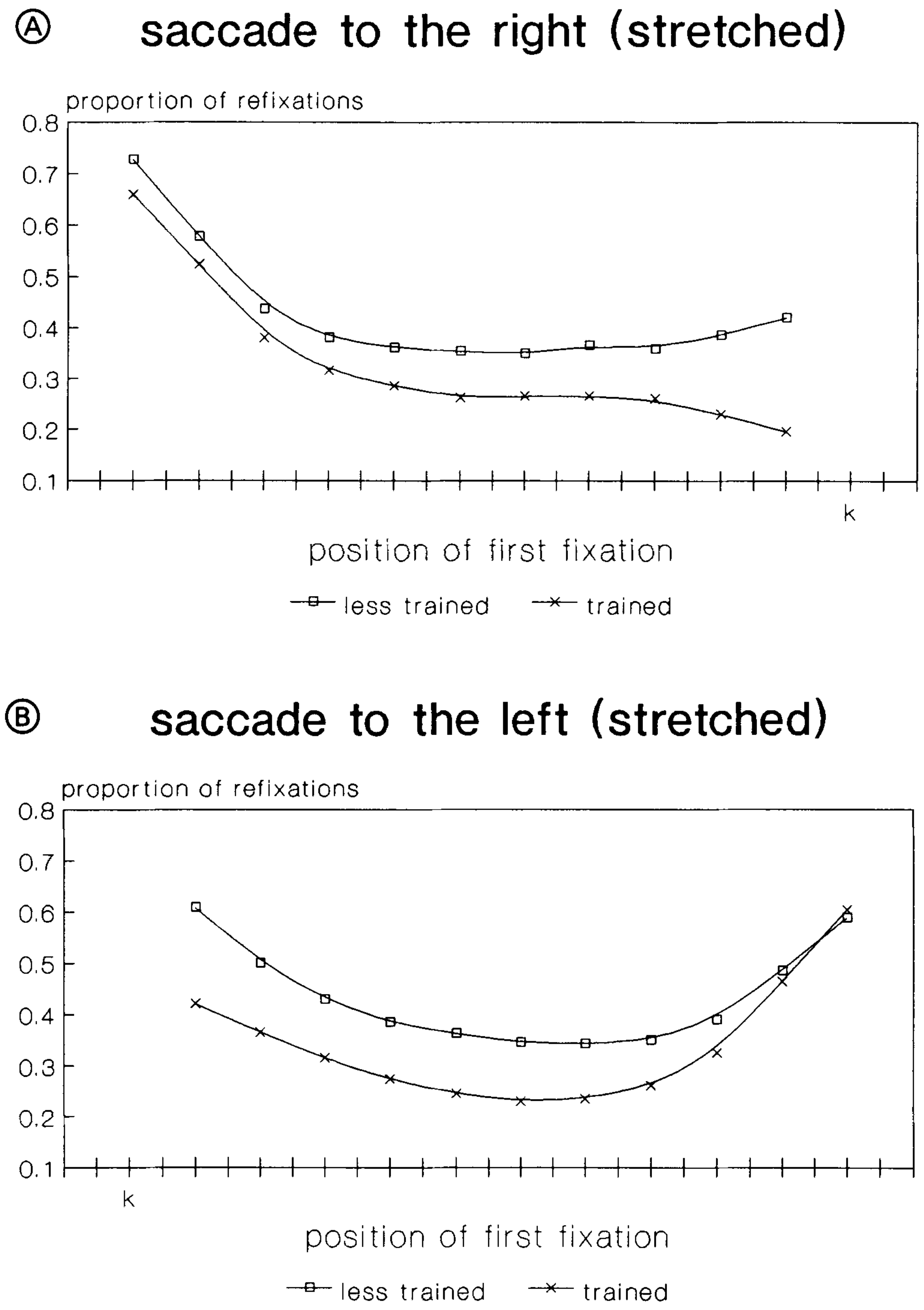


Figure 13. Comparison of the mean refixation curves (estimated) obtained in Experiments 1, 2 (trained subjects), and 3 (less trained subjects). (A) Mean refixation curve of Experiments 1 and 3 (saccades to the right). (B) Mean refixation curve of Experiments 2 and 3 (saccades to the left).

One can argue that the task in the present study was somewhat artificial, and that the identification of one letter embedded in a letter string before the saccade to a comparison string is different from what happens during isolated word recognition (see, e.g., O'Regan et al., 1984; Vitu et al., 1990) and even more different from normal reading (see, e.g., McConkie et al., 1989). However, in order to reach the next word in a text, the eye has to pass over a letter string as well and it might be that oculomotor factors influence this saccade in much the same way as they did in the present experiments. This assumption would be strengthened if, by separating refixations that we suppose reflect primarily oculomotor properties from refixations obtained during word recognition, the remaining word refixation curve would make sense in relation to the results in other word recognition studies. Thus, suppose that the obtained influence of the oculomotor system does exist at least during isolated word recognition. A comparison of the pattern of refixations obtained in this study and the pattern of refixations obtained during isolated word recognition would give us an estimation of the amount of refixations that, according to the model of McConkie et al. (1989), are caused by information extraction processes. Therefore, our data were compared with the refixation curves obtained by Vitu et al. (1990; see Figure 1A). Such a comparison is convenient, because the experimental paradigm, the apparatus, and the typography of the two studies were identical.

Because in Vitu et al.'s (1990) study subjects always made saccades to the right in order to reach the comparison word(s), only the data of Experiment 1 will be compared with their data. First, the refixation curves obtained by Vitu et al. were stretched, like the refixation curves in this study. The results show strikingly that even though the intercept of the curves increases for about 5% per additional letter with increasing word length, the shapes of the curves are quite similar (see Figure 14). In addition, for the first part of the words, the refixation curves for the different word lengths lie close together; they only disperse the more the first fixation position is shifted toward the end of the words. Thus, for the words' first halves, the curves seem to be less dependent on word length than they do for the words' second halves. This might be a hint that here refixations reflect mainly oculomotor constraints. In Figure 15, the estimation of the mean refixation curve of Experiment 1 is presented together with the mean refixation curve calculated for the data by Vitu et al. Compared to the data obtained in the present study, the first difference is that there were globally more refixations made during word recognition. The second important difference is that, contrary to the refixation curves obtained in Experiment 1, the refixation probabilities in Vitu's study reincreased with the initial fixation position shifted toward the end of the word. If the refixation curves obtained in Experiment 1, which we suppose reflect primarily oculomotor properties, are subtracted from the results obtained by Vitu et al., leaving only the proportion of refixations that are caused by factors other than oculomotor ones, the first half of the refixation curves obtained during reading becomes flat. Only

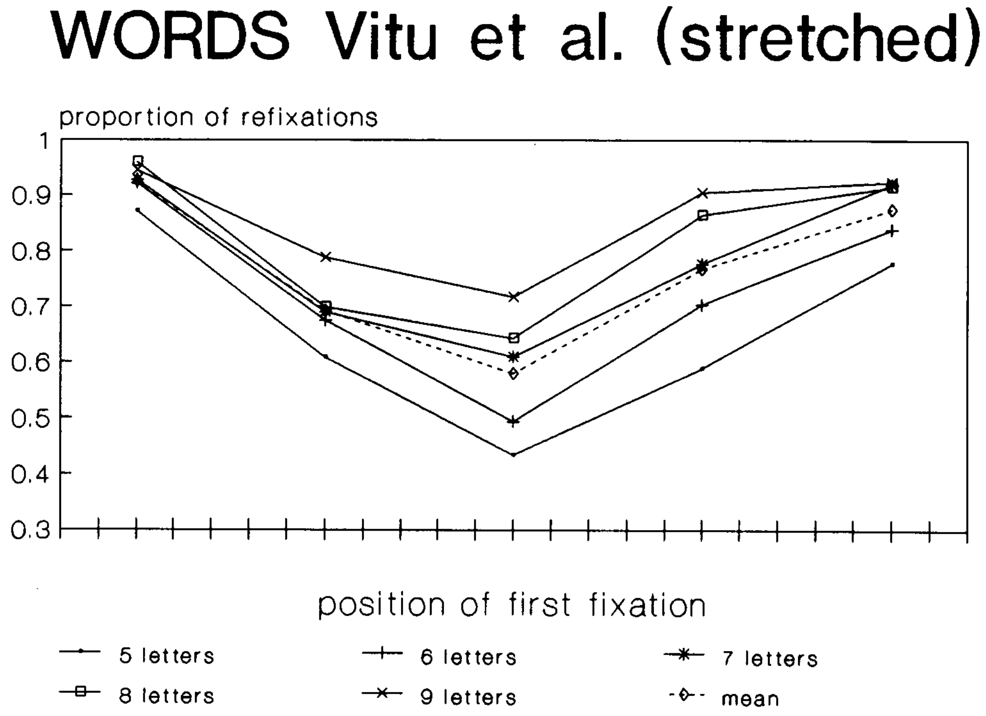


Figure 14. Proportion of refixations in words obtained by Vitu et al. (1990), presented independently of the absolute length of the word (five-, six-, seven-, eight-, and nine-letter words). The beginning and the end of each curve fall on the same point. The dashed curve is the mean of the five curves.

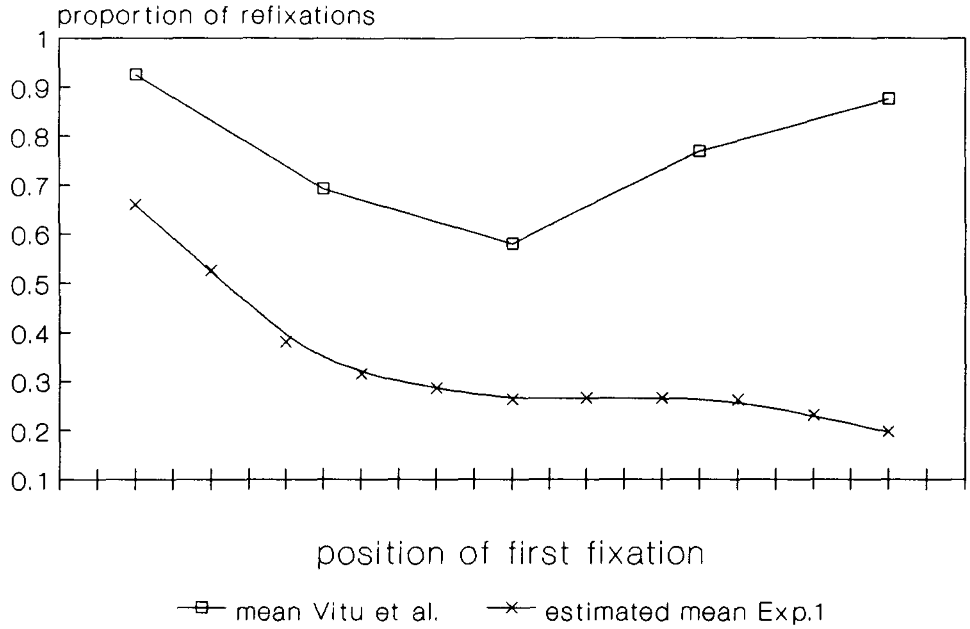


Figure 15. Comparison of the mean refixation curve obtained during word recognition (Vitu et al., 1990) with the mean refixation curve obtained in Experiment 1.

when the initial fixation position is in a word's second half, is an increase of refixation probability, as predicted by the summed letter information model, obtained.

The conclusion of this comparison would thus be that, without the influence of the oculomotor system, the refixation curves should become asymmetric, being at least flatter in the first half of the word, and increase strongly toward the end of it. According to McConkie et al.'s (1989) model, this would be equivalent to the notion that more information about the word can be extracted when the eye starts to fixate in the word's first half rather than its second half, which in fact seems to be the case. In a study done by Brysbaert and D'Ydewalle (1988), word-naming latencies were measured as a function of the position of initial fixation. The presentation duration of the words was limited to prevent the eye from making more than one fixation in the word. The results showed that naming latencies were generally shorter when the eye fixated the first half of the word rather than the second half, the optimal landing position was shifted to the left of center. Similar results were obtained by Nazir, O'Regan, & Jacobs (1991), who measured the probability of correct lexical decision for briefly presented words (allowing only one fixation) as a function of initial fixation location. The probability of recognizing the word was highest when the eye was fixating to the left of the word's center, and it decreased more toward the end than toward the beginning of the word. Thus, although isolated words seem to be easier to recognize when fixated in the words' first halves, this asymmetry is not evident in the distribution of refixation probabilities for isolated words (see top of Figure 1A). This should have been the case, however, if all refixations were due to identification failure during the preceding fixation. These results thus support the idea that, at least for isolated word-recognition, refixation probabilities are indeed influenced by the same kind of oculomotor factors as those in the present study: the symmetry of the refixation curves obtained by Vitu et al. (1990; see Figure 1A) might be due to refixations triggered by the relative position of the eye in the word and not by the necessity to extract additional information.

The data of McConkie et al. (1989; see Figure 1B) show that the optimal landing position during normal reading is at the center of the word as well, although the noisier data of Vitu et al. (1990) at the bottom of Figure 1A reveal a slight leftward shift. Thus, it cannot be excluded that, even during normal reading, the relative position of the eye in the word can influence the probability of refixations. However, the underlying mechanism(s) causing the different patterns of refixations during isolated word recognition as compared with word recognition during reading is (are) not yet known. It might be that even though the overall shapes of the refixation curves in the two conditions is similar, the curves are caused by different factors. A generalization of the present results to normal reading would thus be premature.

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Announcement

Second International Symposium
on Memory and Awareness in Anesthesia
Atlanta, Georgia
April 23-25, 1992

CALL FOR ABSTRACTS

The Department of Anesthesiology and the Department of Psychology of Emory University are pleased to announce that the Second International Symposium on Memory and Awareness in Anesthesia will be held at the Hotel Nikko, Atlanta, April 23-25, 1992.

Abstracts are invited on the following topics: Awareness in general anesthesia, including definition, occurrence/incidence, and causes; memory for intraoperative events; effects of suggestion; information processing in the unconscious mind; memory and awareness in relation to anesthetics used; techniques for monitoring the nervous system.

Abstracts, preferably one page single spaced, should be sent to one of the members of the organizing committee: Eugene Winograd, Department of Psychology, Emory University, Atlanta, GA 30322; Peter Sebel, Department of Anesthesiology, Crawford Long Hospital, Glenn Building, 25 Prescott Street, N.E., Atlanta, GA 30308; or Benno Bonke, Department of Medical Psychology, Faculty of Medicine, Erasmus University, Rotterdam, The Netherlands. The deadline for receipt of the abstracts is November 1, 1991.

For registration information, write to Susan J. Duensing, Continuing Medical Education Program Director, Emory University School of Medicine, 1440 Clifton Road, N.E., 109 WHSCAB, Atlanta, GA 30322.