



# The planning of refixation saccades in reading

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## Abstract

The planning of the refixation saccade, i.e. the second saccade on 9- and 11-letter-strings, was assessed in two reading experiments that examined the influence of a length change at different times during the first fixation on a letter string. The results showed that the saccadic system was able to modify the first motor program if the new length information was available 150–190 ms before the execution of the refixation saccade. Moreover, the amplitude of the refixation saccade was found to be planned as a constant movement relative to the length of the item, regardless of the position of the initial fixation on the item. Finally, the refixation saccade seems to be preprogrammed before the primary saccade, depending on the length integrated at that time. Overall, these results suggest that the refixation saccade is programmed on the basis of the intrinsic properties of the item, such as its length. © 2000 Published by Elsevier Science Ltd.

*Keywords:* Saccade; Motor planning; Coordinate system; Reading

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## 1. Introduction

The action of reading a long word is commonly the outcome of two successive eye movements — directing the eye to a peripheral word, and reading it over with a second saccade, the refixation saccade. These successive movements concur to the same final goal: to enable visual and linguistic information to occur. However, they may differ widely in terms of their metrics. A great majority of studies devoted to eye movement control in reading have dealt with the determinants of the primary saccades to a word. The main finding is that primary saccades on a word are guided towards a functional target location — the word's center (McConkie, Kerr, Reddix, & Zola, 1988). Little attention, however, has been paid to the pattern of the refixation itself. So far, the probability of refixating has been shown to mainly depend on the word length, and the position of initial fixation (McConkie, Kerr, Reddix, Zola, & Jacobs,

1989; O'Regan, Lévy-Schoen, Pynte, & Brugailière, 1984).

Of central interest is whether refixation saccades, like primary saccades, are goal-directed movements that are guided towards a functional target location into the word. One possible mechanism would be that the saccadic system brings the eye to a position for taking in information that failed during the first fixation. One possible target position could be halfway between the current first fixation position and the item-ending boundary. Another possible target position could be the center of word as suggested by Reichle, Rayner, and Pollatsek, (1999). Consequently, the refixation saccade should be calculated as a function of initial landing position to aim a precise target position into the word. However, a previous experiment exploring the influence of different initial fixation locations on refixation saccades refuted such a hypothesis (Beauvillain, Dukic, & Vergilino, 1999). In this study, a double step experiment was performed in which letter strings of different lengths were shifted by one or two spaces in the same or opposite direction to that of the primary saccade to the item during its execution. Surprisingly, the refixation saccade amplitude was found to be invariant with respect to the first fixation position. This

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suggests that the refixation saccade does not aim for a precise target position into the word. Rather, the eye was shown to cover a specific distance within the stimulus that is mainly a function of the item's length. This preliminary experiment suggests that the word's length should be the primary determinant of the refixation saccade.

The finding that refixation saccades do not vary with changes in the retinal location of the item suggests that these saccades could be the second movement in a two-saccade sequence that is planned before the first fixation on the word. At the time the primary saccade is programmed, the refixation saccade could be preprogrammed on the basis of the stimulus properties, which are acquired at that time. Length information is a good candidate, insofar as it is established that this information guides the primary saccade to a word (Rayner, 1979). Moreover, this information is extracted and used quite rapidly by the saccadic system during fixations in reading. It may be that such an initial preprogram planned on the basis of the length information integrated before the primary saccade could be adjusted during the initial fixation as the length information is more accurate at that time.

In order to examine the extent, to which refixation saccades are mainly calculated on the basis of length information, the present experiments looked at the response of the saccadic system to a modification in the item's length at different times during the initial fixation on the item. Such a procedure can be used to test the ability of the saccadic system to update the refixation saccade with a new length information displayed at different times during the initial fixation. Two length changes were tested: a change from 9 to 11-letters and a change from 11 to 9 letters, corresponding to the lengthening and shortening of the initial length, respectively. In order to keep the different-length stimuli identical, nonsense letter strings that share the same nine initial letters were used (for instance, for the 9 to 11-letter change, *bougaille* became *bougailleur*). Item length was changed at the following times: 0 ms (i.e. during the primary saccade to the item), 50, 140 and 220 ms after the onset of the initial fixation. The saccade triggering time after the length change was expected to influence the amplitude of the refixation saccade. Refixation saccades triggered soon after the length change were expected to be calculated on the basis of the initial length. However, refixation saccades triggered a long time after a length change should be calculated on the basis of the final length. Finally, the present experiments looked again at whether or not the motor command of the refixation saccade is updated during the initial fixation irrespective of the location of the first fixation.

## 2. Experiment 1

### 2.1. Method

#### 2.1.1. Subjects

Six students were paid to participate in the experiment. All were native French speakers with normal uncorrected vision. They were unfamiliar with the purpose of the experiment.

#### 2.1.2. Procedure

Subjects were tested individually. They sat in an adjustable chair and their head was restrained with a submaxillar dental print and a forehead rest. A calibration of the eye-tracking system began each session in which subjects were required to sequentially fixate five positions arranged on a horizontal line of 12° angle. In order to check for the accuracy of eye movement recording with the last performed calibration procedure, each experimental trial was preceded and followed by a fixation bar at 6° left and right of the center of vision.

The sequence of events during one trial was as follows: (a) Subjects had to fixate a calibration bar displayed 6° left of the center of vision; (b) When the computer detected an accurate fixation on the bar, a fixation cross replaced the bar. Subjects were required to remain fixated on the cross until the cross disappeared. If the computer detected a saccade before the fixation cross' disappearance, the trial was discarded. Simultaneously to the disappearance of the cross, the target letter string was displayed at a visual angle of 1° 30 corresponding to three character-spaces to the right of the fixation cross, followed by a cross displayed at three character-spaces from the end of the target letter string. This was the signal to move the eyes to the stimulus; (c) Subjects had to move their eyes to read the target letter string. The target letter string could be shortened (11-to-9-letter) and lengthened (9-to-11-letter) at different times (0, 50, 140 and 220 ms) during the initial fixation reckoning from the end of the primary saccade; (d) After reading the item, subjects had to direct their eyes towards the second cross. When the eye crossed an invisible boundary located between the item ending and the cross, the target letter string disappeared and a comparison letter string was displayed at the same location as the cross; (e) Subjects were asked to judge whether the second comparison string was orthographically similar to the target letter string. Subjects answered by pressing one of two buttons; (f) A fixation bar was displayed at 6° to the right of the center of vision and the next trial began.

The experimental block of trials was preceded by 50 training trials that had the same characteristics as the test trials.

### 2.1.3. Design

The design was a 4\*2 factorial design, in which the four delays (0, 50, 140, and 220 ms after the onset of fixation) and the two types of length change were within-subjects factors. Two control conditions with no length change were added that consisted of 9-letter and 11-letter strings. Each subject was exposed to the ten conditions, but no subject saw the same target item more than once. Nevertheless, each item was presented under the ten conditions across subjects. All conditions were mixed within the experimental session and items were presented in random order.

### 2.1.4. Materials

A total of 350 pairs of 9- and 11-letter nonsense strings were constructed, respecting the orthographic and syntactic rules of French. Letter strings are used to avoid any lexical effects on the planning of the refixation saccade and to control the information derived from initial letters, since each pair of a 9- and 11-letter string shared the same nine initial letters (ex: *bougaille/bougailleur*). These letter strings were constructed from 35 frequent trigrams in French and ten items were constructed from each trigram. To increase the number of trials by subjects, each item was repeated twice (giving three items of each type) by changing the letter between the first and the second syllable of the target letter string. For one subject, the thrice-replicated items were seen during different blocks. Each subject was presented 1050 trials divided in three blocks of 350 trials each. Each item was associated with a comparison item. In half the cases, the comparison item was identical to the test item and in the other half different by its four initial or final letters from the test item.

### 2.1.5. Apparatus

Stimuli were presented on a Hewlett Packard 1310A CRT (P15 phosphor) that was interfaced by a fast graphic system providing a frame frequency of 1000 Hz for stimulus presentation. One character subtended 30 min of visual angle. Eye movements were monitored using a Bouis Oculometer System. The eye tracker has an absolute resolution of 6 minarc and the output was linear over 12° of visual angle. The signal from the oculometer was sampled every 2 ms. Complete details of the eye-movement recording apparatus, calibration procedure, and numerical data processing can be found in Beauvillain and Beauvillain (1995). Primary saccade starting and ending points were calculated using a velocity criterion of 25°/s.

## 2.2. Results

The following data were removed from the analyses: (1) trials in which accurate measurements of the eye position could not be made; (2) trials in which blinks

occurred; (3) trials in which the reader made a regression. Altogether, 5% of the trials were excluded from the analysis reported below. Trials in which the reader made only one fixation on the letter string — 10% of the total trials — were also removed from the analyses.

### 2.2.1. First fixation position and duration

Before examining data on the refixation saccade amplitude, we wished to be sure that the length of the letter string was correctly integrated in parafoveal vision. As expected, first fixation position was found to be significantly further to the right when the parafoveal item was an 11-letter string (mean 3.5) rather than a 9-letter string (mean 3.3) [ $F(1,5) = 17.46$ ,  $P < 0.009$ ] and there was no interaction of this factor with the delay condition [ $F(4,20) = 1.47$ , NS]. The length change had no significant effect on the first fixation durations [ $F_s < 1$ ]. This can be seen in Fig. 1a,c, which presents the distributions of the first fixation duration and their corresponding means. The shape of distributions is very similar for no length change condition and length changes occurring during the primary saccade, and up until 140 ms after the onset of the first fixation. It can be seen that, at the 220-ms delay, the great majority of saccades are executed after the length change, suggesting that the length change triggered refixation saccades that were on the point of being initiated. Nevertheless, the first fixation durations obtained in the different delay conditions did not significantly differ from the control 9- (mean 209 ms) and 11-letter control conditions (mean 220 ms) [ $F(1,5) = 1.43$ , NS].

### 2.2.2. Refixation saccade amplitude

As expected, the refixation saccade amplitude was larger in the 11- (mean 3.8) than in the 9-letter string (mean 3.3) condition, with the 0.5 character space difference between the two means being significant [ $F(1,5) = 996.29$ ,  $P < 0.0005$ ]. The length change effect interacts with the delay conditions [ $F(3,15) = 28.88$ ,  $P < 0.0005$ ]. Consider first the change involving a letter string shortening. An examination of the refixation saccade amplitude distributions (Fig. 1b) shows that the 11-to-9-letter and the 9-letter control condition overlap when the length change occurred during the primary saccade (11-to-9, 0 ms delay). Nevertheless, when the target shortening occurred 50, 140 and 220 ms after the first fixation onset, the 11-to-9 letter and 11-letter control conditions overlap. This was confirmed by the analysis of variance done on mean refixation saccade amplitudes. Mean refixation saccade amplitudes obtained in the 11-to-9 letter condition significantly differed from that obtained in the 11-letter control condition when the length change occurred during the primary saccade [ $F(1,5) = 98.62$ ,  $P < 0.0005$ ]. When the target shortening occurred 50, 140 and 220 ms after the first fixation onset, mean refixation saccade amplitudes

significantly differed from the 9-letter control condition [respectively,  $F(1,5) = 34.15$ ,  $P < 0.005$ ;  $F(1,5) = 171.76$ ,  $P < 0.0005$ ;  $F(1,5) = 94.55$ ,  $P < 0.0005$ ]. This indicates that the saccadic system fully considers the final length (i.e. nine letters) to compute the refixation saccade only when the length change occurred during the primary saccade.

The pattern of data was slightly different when the change involved a letter string lengthening. The final length was considered by the saccadic system when the modification occurred during the primary saccade to the target and 50 ms after the onset of the first fixation (Fig. 1d). In this case, the mean refixation amplitude was different from that obtained for the nine letter strings [ $F(1,5) = 56.59$ ,  $P < 0.004$ ;  $F(1,5) = 40.39$ ,  $P < 0.005$  for the 0- and 50-ms delays, respectively]. When the length change occurred later in the first fixation (140- and 220-ms delay), the refixation saccade was not

modified by it. In these conditions, refixation saccade amplitudes were significantly different than in the 11-letter string control condition [ $F(1,5) = 6.10$ ,  $P < 0.055$ ;  $F(1,5) = 32.44$ ,  $P < 0.005$ , respectively]. Overall, these data indicate that the length change is integrated when it occurs early during the initial fixation on the target. Any change occurring 140 ms or later after the onset of the first fixation is not taken into account in the computation of the refixation saccade. However, for length changes occurring 50 ms after the onset of the first fixation, the letter string lengthening results in a correction of the refixation saccade whereas the letter string shortening does not. This initial analysis suggests that a modification of the refixation saccade amplitude is more difficult when it requires a reduction rather than an increase.

Nevertheless, these global analyses do not take into account the delay ( $D$ ) between the length change and

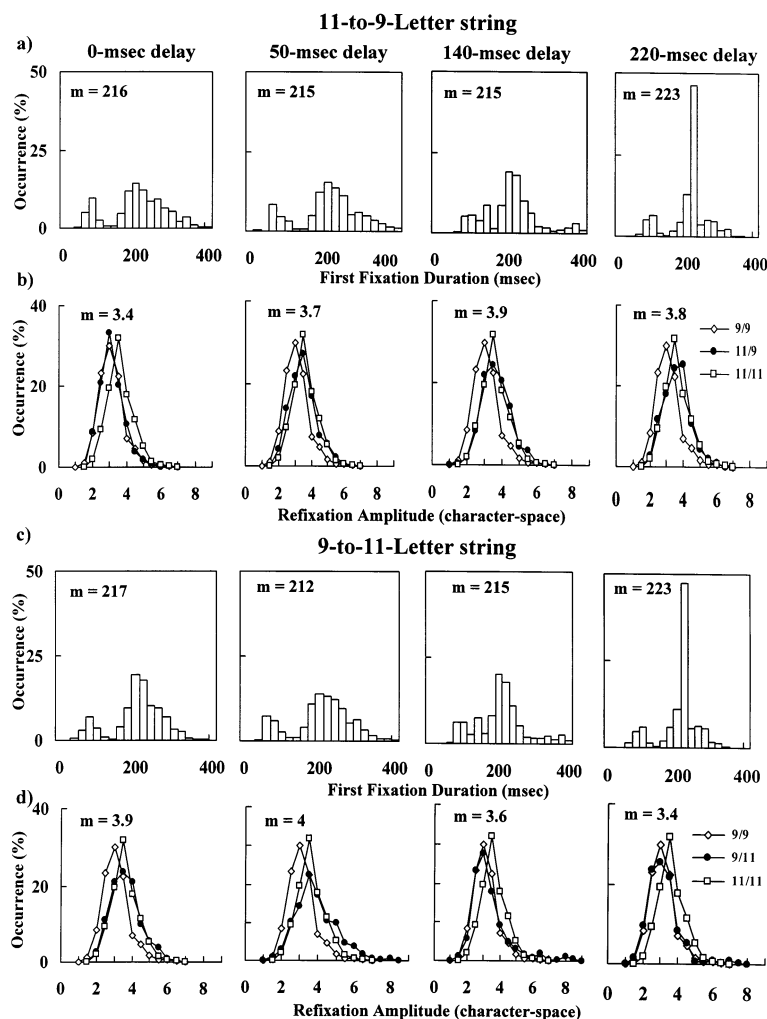


Fig. 1. Experiment 1. Figures represent data obtained on the 11-to-9- and 9-to-11-letter strings when the length change occurs 0, 50, 140 and 220 ms after the onset of the first fixation duration. (a, c) Distributions and means of first fixation durations for each length change condition. (b, d) Distributions and means of refixation saccade amplitude for each length change condition, compared with the refixation amplitude obtained for 9- and 11-letter control strings.

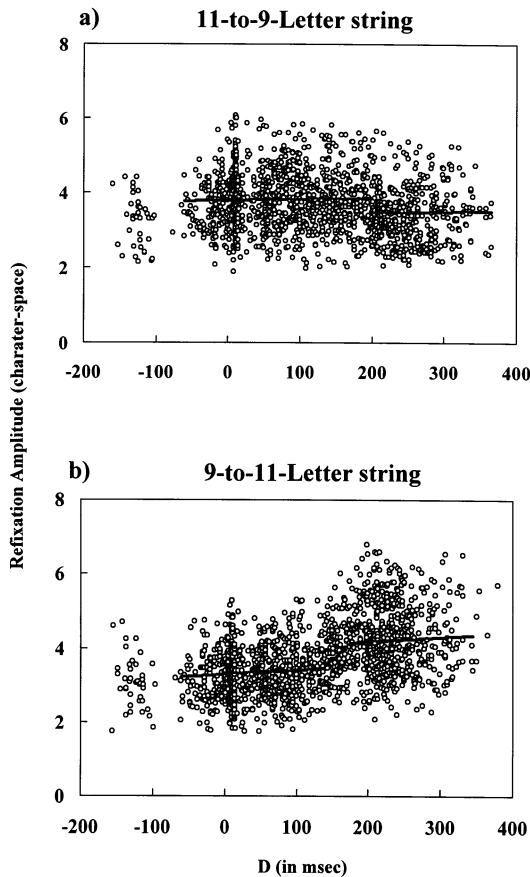


Fig. 2. Experiment 1. Amplitude of the refixation saccade as a function of the delay ( $D$ ) between the length change and the triggering of the refixation saccade in the (a) 11-to-9- and (b) 9-to-11-letter strings. Negative values correspond to refixation saccades triggered before the length change while positive values correspond to refixation saccades triggered after the length change.

the triggering of the refixation saccade that is expected to influence the modification of the saccade amplitude calculation. The more time that is given to the saccadic system to integrate the new length information, the better should be the correction of the refixation saccade amplitude. Fig. 2 plots the refixation saccade amplitude as a function of ( $D$ ).

Linear regressions were performed by least square fit procedure to describe the relation between the two parameters ( $D$ ) and saccade amplitude. In Fig. 2b, one can clearly see two different linear relations of saccade amplitude versus  $D$ . In order to clarify the limits of these two relations, we have performed a statistical analysis using the following procedure. The linear least square fits were calculated by varying the limits  $D_{\min}$  and  $D_{\max}$ .  $D_{\min}$  was first fixed to the negative minimum value of the delay ( $D$ ) and the variation of the slope of the linear function versus  $D_{\max}$  was computed. For letter string lengthening, the variation of the slope versus  $D_{\max}$  exhibits a breaking point  $d_1$  considered as the limit of the first linear fits (140 ms). The same

procedure was applied to the second linear fit obtained by fixating  $D_{\max}$  to the maximum value of ( $D$ ) and varying  $D_{\min}$ . The breaking-point  $d_2$  of this second linear fit considered as the limit of the second linear fit was found to be 180 ms. These two different breaking points revealed the limits of two different classes of saccade amplitudes corresponding to the amplitude obtained in the 9- and the 11-letter control conditions, respectively. Intermediate saccadic responses were obtained 140–180 ms after the length change. An arbitrary slope was plotted between  $d_1$  and  $d_2$ . The same procedure was applied to letter string shortening. As seen in Fig. 2a, the breaking point of the two linear fits is not as obvious as for letter string lengthening. The breaking point of the two linear fits was found to be 190 ms. Overall, this analysis suggests that an initial motor program is not so efficiently and rapidly corrected when it requires shortening rather than lengthening of the saccade's size. This is consistent with the previous analysis done separately for each delay condition.

For short ( $D$ ), the computation of the refixation saccade amplitude was based on the initial length displayed during the initial fixation. As this initial length was also given before the primary saccade, the first motor program could have been planned before the onset of the first fixation, based on the length of the to-be-fixated letter string. Such a hypothetical preprogramming of the refixation saccade amplitude can be tested when the length change occurred during the primary saccade to the target as the initial length was only displayed before the first fixation on the target. Nevertheless, such pre-programmed saccadic responses should be obtained only for short first fixation durations when saccades are triggered too early to integrate the final length given during the fixation. This hypothesis had been tested on half of the subjects that presented a bimodal first fixation duration distribution with fixation duration less and more than 140 ms (Fig. 3a).

Interestingly, Fig. 3b indicates that, for first fixation durations less than 140 ms, refixation saccade distributions in the length change conditions overlap the initial length control condition distribution, whereas, for first fixation durations more than 140 ms, refixation saccade distributions overlap the final length control condition. This was confirmed by the analysis of variance which showed that for first fixation durations less than 140 ms, mean refixation saccade amplitudes were equal to those in the initial length control conditions [ $F(1,2) = 19.06$ ,  $P < .05$  and  $F(1,2) = 11.91$ ,  $P < 0.07$ , for 11-to-9-letter and 9-to-11-letter strings, respectively]. Only refixation saccades triggered more than 140 ms after the length change had amplitudes significantly different from the initial length

control conditions [ $F(1,2) = 32.62$ ,  $P < 0.05$  and  $F(1,2) = 17.84$ ,  $P < 0.049$ , for 11-to-9-letter and 9-to-11-letter strings, respectively] and similar to those in the final length control conditions [ $F_s < 1$ ]. This suggests that both primary and refixation saccades are preprogrammed at the same time, and are a function of the length of the letter string encoded in parafoveal vision. However, the initial refixation saccades preprogram can be corrected as a function of the new information given at the beginning of the first fixation in so far as the saccade is triggered later than 140 ms after the first fixation onset.

### 2.2.3. Relationship between first and second fixation position

Previous experiments that induced an artificial error in the initial landing position have shown that refixation saccades are invariant regardless the landing position on the item (Beauvillain et al., 1999). It is of interest to examine in the present experiment whether the updating of the refixation saccade based on the new

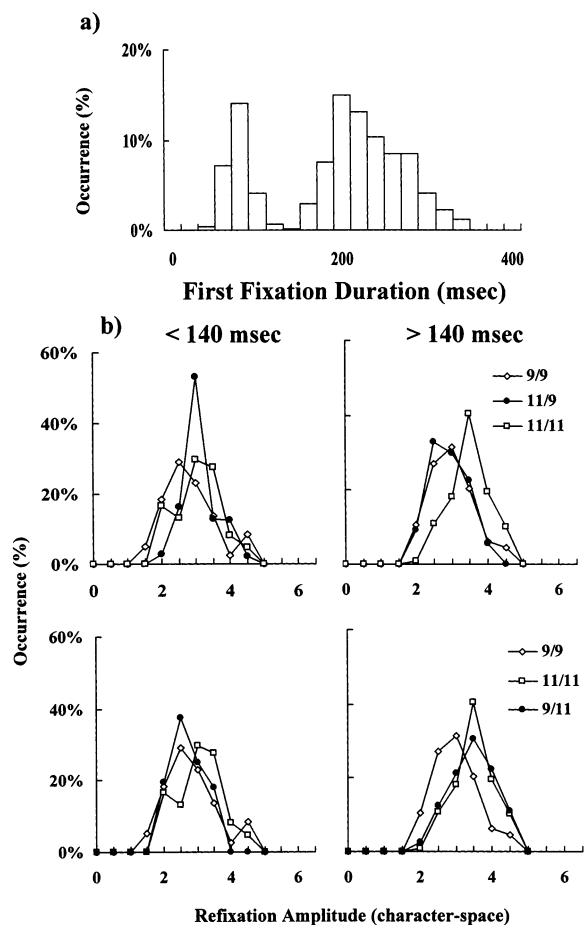


Fig. 3. Experiment 1. Figures represent the data for the 11-to-9- and the 9-to-11-letter strings in the 0-ms delay for three subjects. (a) Distribution of first fixation durations; (b) Distributions of refixation saccade amplitudes for first fixation durations less and more than 140 ms, compared with the two no-length-change conditions.

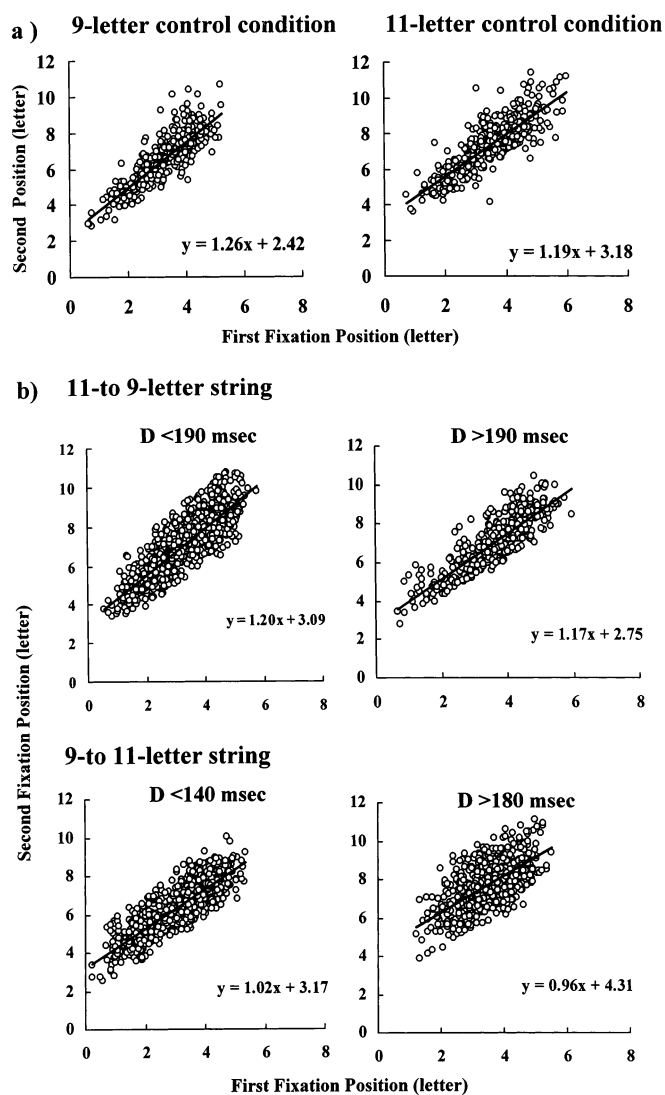


Fig. 4. Experiment 1. Second fixation positions plotted as a function of first fixation positions for refixation saccades (a) in the no-length-change conditions; (b) triggered before and after the correction for the 11-to-9- and the 9-to-11-letter strings.

length information is made regardless of the initial landing position. One might predict that, if the eyes are simply sent a particular distance relative to an item's length, regardless of initial locations, then a strong relationship should be observed between the first and second fixation positions (e.g. slope = 1). Alternatively, if the eyes always go to a precise target location (e.g. the center of word), then no relationship should be observed between first and second fixation positions (e.g. slope = 0). Finally, if the eyes always go to the center of gravity of the spatial configuration (i.e. between the first fixation position and the boundary marking the end of the item), then a slope of 0.5 should be observed between the first and second fixation positions.

Fig. 4 plots the relation between the first and the second fixation locations for a) the two controls conditions, and b) the refixation saccades triggered before (left column) and after (right column) the correction for the 11-to-9-letter and the 9-to-11-letter strings. Refixation saccades were partitioned as a function of the breaking points previously estimated: 190 ms after the length change for the 11-to-9-letter strings, and both before 140 ms and after 180 ms for the 9-to-11-letter strings (defined as the saccade modification time). For the 9-to-11-letter strings, data from the transition region (140–180 ms after the length change) were excluded from the analysis. An examination of the data obtained in the control condition indicates slopes of 1.3 and 1.2 for 9- and 11-letter conditions, respectively. Likewise, strong positive relationships were found between first and second fixation positions for saccadic responses triggered before and after the saccade modification time in the 11-to-9- and 9-to-11-letter strings. This suggests that the eyes are simply sent a particular distance, which is a function of initial string length, irrespective of the initial fixation locations. Moreover, even when the refixation saccade is recomputed using the new string length, the saccade is not aimed at a precise target location in the string. Rather, this saccade is re-calculated using the item length, irrespective of the current retinal location of the item.

### 2.3. Discussion

This experiment demonstrates the ability of the saccadic system to calculate refixation saccade amplitude on the basis of item-length information. First, it was shown that the first program, calculated from initial length information, is updated to account for new length information if the length change occurs early enough during the initial fixation. The modification of the initial program is based mainly on length information, irrespective of the location of the first fixation. Second, refixation saccades triggered soon after the onset of the first fixation are calculated from the initial length information that was integrated before the primary saccade. Therefore, the programming of refixation saccade amplitude seems to be initiated before the primary saccade on the basis of length of the parafoveal stimulus. Third, the time required to shorten an initial refixation saccade was found to be longer (190 ms) than the time taken to lengthen it (140 ms).

Two possible explanations can be given to account for this difference in the time required to increase or decrease a saccade. The first, a motor explanation, is related to the greater ability of the saccadic system to increase an initially programmed movement. Indeed, previous results have shown that corrective saccades requiring only an increase in metrics were triggered faster than corrective saccades requiring either a de-

crease in metrics or a direction change (Henson, 1978; Deubel, Wolf, & Hauske, 1982; Hou & Fender, 1979). This is consistent with the undershooting preference of the oculomotor system. For 11-to-9-letter strings, an initial refixation saccade that is planned on the basis of an 11-letter item will overshoot a final saccade calculated on the basis of a final 9-letter item. Consequently, the length change requires a decrease in the initially programmed saccade. For the 9-to-11-letter strings, an initial refixation saccade planned on the basis of the 9-letter item will undershoot a saccade calculated for a final 11-letter item. In this case, the correction of the planned movement only requires the lengthening of the movement. The second possible explanation is related to the difference in the visual feedback between the 11-to-9- and 9-to-11-letter strings. In the case of string lengthening, the two characters that appeared abruptly as the end of the letter string (i.e. as sudden onsets) produced the perception of a 'streak' of lightning. This perception of a streak was not produced by the sudden disappearance of two letters. Actually, after completing Experiment 1, subjects reported having sometimes the impression of a movement at the end of the letter string in the case of string lengthening but not in the case of string shortening. This was confirmed by the presence of some large amplitude responses in the 9-to-11-letter strings (Fig. 2b). Such responses could be due to the fact that the eyes were attracted to the end of the string when the stimulus was lengthened.

## 3. Experiment 2

In Experiment 2, a 30-ms gap preceded the onset to the length change. Based on a pilot experiment, the 30-ms duration gap was chosen to be the smallest value impeding the perception of a streak that accompanies the sudden appearance of new letters in the 9-to-11-letter string. As such, the initial and final length appeared as two very fast successive stimuli for the 9-to-11 as for the 11-to-9 stimuli. This manipulation reduced as far as possible the difference in the visual feedback between the two-length change conditions.

### 3.1. Method

#### 3.1.1. Subjects

Six students were paid to participate in this experiment. All were native French speakers with normal uncorrected vision. They were unfamiliar with the purpose of the experiment.

#### 3.1.2. Procedure

The procedure was the same that described in Experiment 1, except that a blank period was inserted 30 ms before the length change when it occurred during the

first fixation. However, no blank period was inserted when the length change occurred during the primary saccade to the target letter string, as the presence of a blank period during the saccade determines an illusory perception of a displacement of the target (Dassonville, Schlag, & Schlag-Rey, 1995; Schlag & Schlag-Rey, 1995).

### 3.1.3. Materials, design and apparatus

The material, design and apparatus were identical to the first experiment.

## 3.2. Results

The data were analyzed in the same way as Experiment 1. Using the same criteria, 4% of the data were excluded from analysis. Moreover, 18% of the trials were one-fixation cases that were removed from the following analysis.

### 3.2.1. Landing position and first fixation duration

Globally, mean first fixation position was shifted rightward more for a parafoveal 11- than (mean 3.5) a 9-letter string (mean 3.3) [ $F(1,5) = 6.99, P < 0.04$ ]. This length effect interacted with the delay condition [ $F(4,20) = 3.66, P < 0.02$ ]. Indeed, for the 11-to-9-letter conditions, the mean landing position was found to be further to the left than for the control 11-letter strings (mean 3.6) at the 0- (mean 3.3) and 50-ms (mean 3.4) delays [ $F(1,5) = 9.72, P < 0.02$ ;  $F(1,5) = 7.74, P < 0.03$ , respectively]. An explanation of this phenomenon cannot be given at present. Overall, first fixation durations were slightly longer in the length-change than in the no-change control conditions [9 ms;  $F(1,5) = 14.69, P < 0.01$ ]. Whereas no significant effect of the length change was found at the 0-ms ( $F < 1$ ), 50 ms (3.5 ms; [ $F(1,5) = 4.67, P < 0.10$ ]), and 220-ms ( $F < 1$ ) delays, the length change significantly increased first fixation durations at the 140-ms delay (28 ms; [ $F(1,5) = 22.22, P < 0.005$ ]). As seen in Fig. 5a,c, first fixation duration

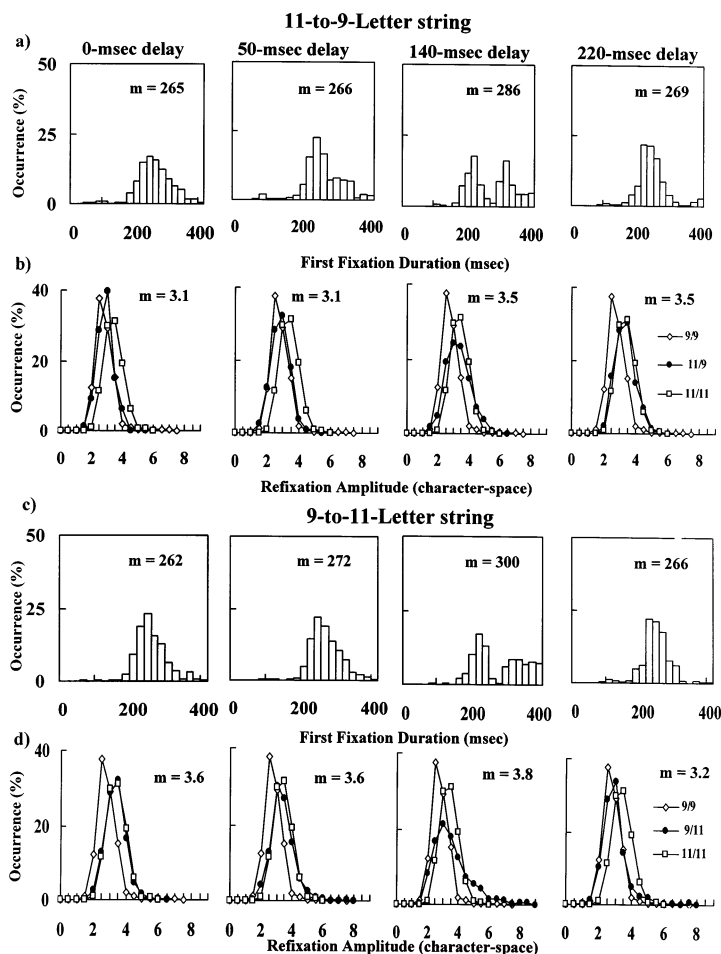


Fig. 5. Experiment 2. Figures represent data obtained on the 11-to-9- and 9-to-11-letter strings when the length change occurs 0, 50, 140 and 220 ms after the end of the primary saccade. (a, c) Distributions and means of first fixation durations for each length change condition. (b, d) Distributions and means of refixation saccade amplitude for each length change condition, compared with the refixation amplitude obtained for 9- and an 11-letter control strings.



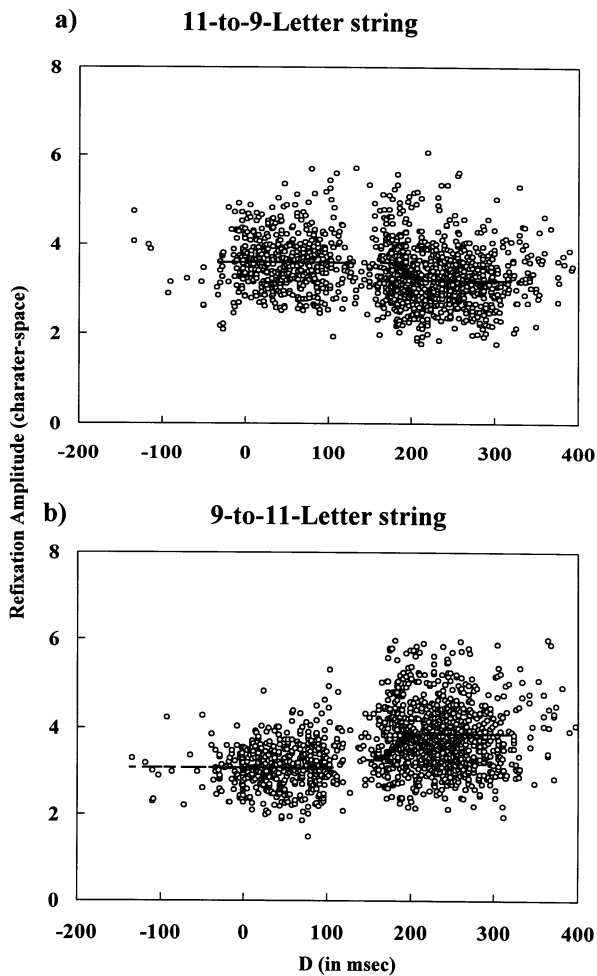


Fig. 6. Experiment 2. Amplitude of the refixation saccade as a function of the delay between the length change and the triggering of the refixation saccade in the (a) 11-to-9- and (b) 9-to-11-letter strings. Negative values correspond to refixation saccades triggered before the length change and positive values correspond to refixation saccades triggered after the length changes.

distributions obtained at this delay are clearly bimodal, with two peaks at 240 and 340 ms.

### 3.2.2. Refixation saccade amplitude

As expected, the refixation saccade amplitude was larger in the 11-letter control condition than in the 9-letter control condition, with the difference of 0.5 between the two means being significant [ $F(1,5) = 126.53$ ,  $P < 0.0005$ ]. The interaction of length change with delay conditions was significant [ $F(3,15) = 11.85$ ,  $P < 0.0003$ ]. For the letter string shortening at the 0- and 50-ms delays, the refixation saccade amplitude was significantly different from the initial 11-letter length [ $F(1,5) = 56.58$ ,  $P < 0.001$  and  $F(1,5) = 42.25$ ,  $P < 0.001$ , respectively] and similar to the final 9-letter length [ $F(1,5) < 1$ ] as seen in the overlap between the 11-to-9-letter and the 9-letter saccade amplitude distributions (Fig. 5b). For later delays, the saccade ampli-

tude differed from the final length [ $F(1,5) = 20.46$ ,  $P < 0.01$  and  $F(1,5) = 90.12$ ,  $P < 0.0005$ , at the 140- and 220-ms delays, respectively]. Indeed, saccade amplitude distributions overlap between the 11-to-9-letter and the 11-letter control condition. For the letter string lengthening at the 0-, 50- and 140-ms delay, the saccade amplitude was different from the initial length [ $F(1,5) = 42.33$ ,  $P < 0.001$ ,  $F(1,5) = 38.75$ ,  $P < 0.002$ , and  $F(1,5) = 25.20$ ,  $P < 0.004$ , respectively] and similar to the final length [ $F_s < 1$ ] as seen in the overlap between the 9-to-11-letter and the 11-letter control condition distributions (Fig. 5d). When the target letter string was lengthened 220 ms after the onset of the first fixation, it was too late for the oculomotor system to modify the motor program computed on the basis of the initial length, and the saccade amplitude was not modified on the basis the final length [ $F(1,5) = 179.96$ ,  $P < 0.0005$ ]. The distribution of amplitudes in this condition overlaps with that of 9-letter control condition.

Compared to Experiment 1, length changes occurring later in the first fixation were considered by the oculomotor system. In Experiment 1, the refixation saccade amplitude for the 11-to-9-letter strings was modified when the length change occurred during the primary saccade, whereas, for the 9-to-11-letter string, it was modified up to 50 ms after the onset of the first fixation. This difference between the two experiments is probably due to first fixation durations that were 50 ms longer in Experiment 2 in which more time was given for the oculomotor system to correct the refixation saccade in the present experiment. Interestingly, the difference in the time for the correction of the refixation amplitude by the saccadic system remained between the two types of length change (i.e. string lengthening versus shortening), in spite of the insertion of the blank period. Again, the refixation saccade amplitude was more difficult to modify when it required shortening than lengthening.

Fig. 6 plots the refixation saccade amplitude relative to the delay ( $D$ ), and the linear regressions performed by the least square fit procedure. For the two types of length change, the linear fits calculated by varying the limits  $D_{\min}$  and  $D_{\max}$  exhibit two breaking points at 120 and 200 ms after the length change. A transition region is observed between 150 and 200 ms after the length change, in which intermediate refixation amplitudes are obtained. Nevertheless, only few saccadic responses were triggered between 120 and 160 ms after the length change for both 11-to-9-letter and 9-to-11-letter strings. As shown previously, this lack of saccadic responses is due to the 140-ms delay where the saccadic reaction times split into two populations. Fig. 7 plots the relation between the refixation saccade amplitude and the delay ( $D$ ) for each population of saccadic reaction times. For the 11-to-9-letter strings, the refixation saccades do not consider the final length whatever the time

of their triggering. For the 9-to-11-letter strings, the refixation saccades shorter than 150 ms after the length change are computed on the basis of the initial length whereas the refixation saccades triggered more than 150 ms after the length change consider the final length. Replicating Experiment 1, a difference in the time of integration of the final length is again observed between the two types of length changes. The lengthening of the letter string fully compensated for the correction whereas the shortening of the letter string was not corrected. This supports the motor rather than perceptual explanation of this difference because the saccadic system preferred to lengthen rather than to shorten an initially programmed saccade, even if the perception of the length change is made as equivalent as possible for the two types of length changes.

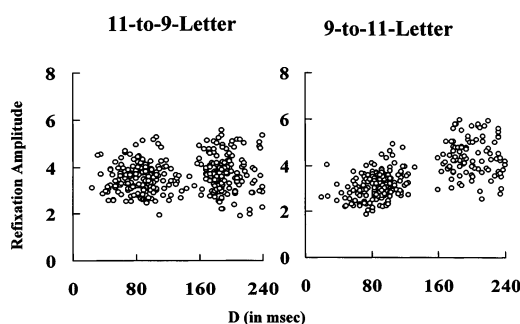


Fig. 7. Experiment 2. Figures represent the amplitudes of the refixation saccade as a function of their latencies after the length change obtained for the 11-to-9- (left) and the 9-to-11- (right) letter strings in the 140-ms delay.

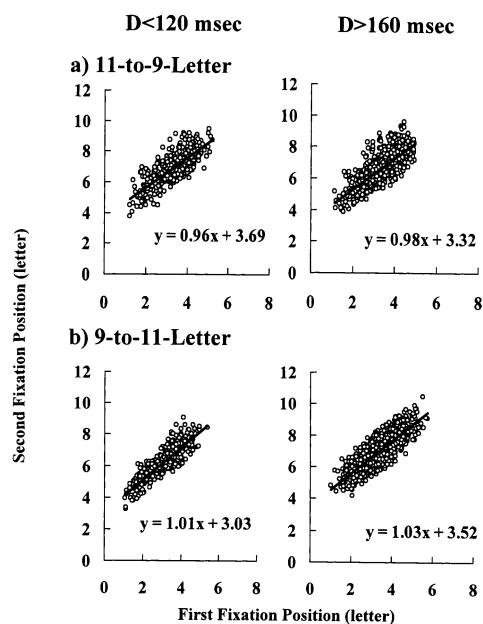


Fig. 8. Experiment 2. Second fixation positions plotted as a function of first fixation positions for refixation saccades triggered less than 120 ms and more than 160 ms after the length change for (a) 11-to-9- and (b) 9-to-11-letter strings.

### 3.2.3. Relationship between first and second fixation position

Replicating Experiment 1, the slopes for saccadic responses obtained before (left column) and after (right column) the transition region in the 11-to-9-letter strings (Fig. 8a) and in the 9-to-11-letter strings (Fig. 8b) are identical and approximately equal to 1. This strong positive relationship between the first and the second fixation positions indicates that the eyes are moved a particular distance during refixation saccades. Before the transition region, the refixation saccade amplitude is found to be computed on initial length information, with initial fixation location having no influence. After the transition region, the updating of the refixation saccade on the final length is done irrespective of the first fixation position.

### 3.3. Discussion

Replicating Experiment 1, this experiment showed that length is the main information involved in calculating the refixation saccade, irrespective of the first fixation position. For short time intervals between the length change and the onset of the refixation saccade, saccadic responses reflect initial string length. A certain minimum time has to elapse before any effect of the final length was manifest. The minimal reprocessing interval of the refixation saccade amplitude appears to be 150–190 ms. This interval includes the time needed to integrate the final length and to adjust the initial program. In this experiment a gap has been added before the length change in order to equalize the perception of the two types of length change. This manipulation has reduced the occurrence of saccadic responses attracted by the transient activity at the end of the stimulus in the case of string lengthening. However, the saccadic system was seen to lengthen an initially preprogrammed saccade more easily than to shorten it, as in Experiment 1. Interestingly, this preference persists even if the perception of the lengthening of the letter string is made as equivalent as possible as its shortening. However, we cannot rule out the possibility that the appearance of two new letters is more effective in capturing attention and the eyes than their disappearance, as reported from the literature (Irwin, Colcombe, Kramer, & Hahn, 2000).

## 4. General discussion

The present study provides new information on the planning of the refixation saccade, showing that the primary determinant of the refixation saccade is the stimulus length. The refixation saccade was shown to be programmed as a fixed motor vector calculated from letter-string length irrespective of the initial position of

the eye into the item. The refixation saccade, pre-planned on the length information integrated before the primary saccade, was found to be updated in accordance with the new length information given at different times during the initial fixation on the stimulus. A minimum amount of time must elapse before the final length has any effect. This interval was estimated to be between 150 and 190 ms. It includes the time needed to integrate the new length information and to adjust the initial motor program. Finally, our data suggest that the saccadic system can lengthen a pre-planned saccade more easily than to shorten it.

#### 4.1. *Properties of the experimental paradigm*

Our experiments bear close resemblance with several studies using a paradigm in which changes are made in the visual display, contingent on the preparation or the execution of the movement (Becker & Jürgens, 1979; Hallet & Lightstone, 1976a,b; McConkie & Rayner, 1975). Such a paradigm has provided important evidence for the understanding of the eye movement control. By manipulating the delay of the length change in our experiment, it is possible to test the ability of the saccadic system to integrate length information and to estimate the useful time to correct an initial motor program. Of course, such a paradigm may have enhanced the influence of the length information on the saccade computation. Indeed, the gaze contingent paradigm produces a new transient stimulation that can influence the saccade generation (Findlay & Walker, 1999). Some longer refixation saccades drawn towards the end of the letter strings arise in Experiment 1. The introduction of the gap period in Experiment 2 has removed the effect of the visual transient on the saccade amplitude. However, some aspects of the data suggest that the gap may be responsible of the dip observed in saccade triggering when the length change occurred 140 ms after the first fixation onset, as guessed from the Reingold and Stampe's study (2000) showing a similar dip in saccade latencies with the introduction of a 33-ms mask. Nevertheless, this paradigm reveals that the updating of the refixation saccade is done as a constant movement relative to the new length.

#### 4.2. *Preprogramming of the refixation saccade*

Our data suggest a preprogramming of refixation saccades before the primary saccade on the basis of the length information acquired at that time. At the time the first saccade is planned, the second intended movement is coded as a movement to acquire all of the information within the word. Evidence from reading studies argue for the notion of a preprogramming mode of operation. Indeed, the perceptual span, i.e. the span of the visual field useful for saccade programming

extends about 14–15 character spaces to the right of the fixation (McConkie & Rayner, 1976). This suggests that the saccadic system can acquire length information from two or three words to the right in order to plan more than one saccade at a time. In line with such a preprogrammed mode of operation, the E-Z Reader model (Reichle, Pollatsek, Fisher, & Rayner, 1998) assumes the systematic planning of the refixation saccade at the onset of the first fixation on a word. This idea of a pre-established organized plan has previously been proposed for target scanning tasks (Zingale & Kowler, 1987), and in other situations requiring the execution of a motor plan such as typing or handwriting (Viviani & Terzuolo, 1980, 1982). More recently, Ditterich, Eggert, and Straube (1998) showed that sequences of three saccades could be preprogrammed and executed with fixed amplitudes irrespective of actual eye position. It can be argued that these sequences of saccades constitute units of motor action memorized before execution, with visual information used for correcting the plan during execution (Viviani, 1990).

#### 4.3. *Metrics of the refixation saccade*

The present study provides some new insight into the motor planning of the refixation saccade. The motor command for the refixation saccade can be described as a movement of constant amplitude relative to the length of the item, regardless of where the eye initially fixates. The perfect relationship found between the first and the second fixation position argues for the notion that refixation saccade is coded as a fixed vector dependent on the stimulus length regardless of where the eye initially fixates. The lack of an effect of the initial landing position is a surprising result. It shows that the refixation saccade is not directed towards a precise target location into the item, as the primary saccade that has been shown to be guided towards the word's center (McConkie et al., 1988; Rayner, 1979).

Our data suggest that different frames of reference are used for the metrical control of saccades in reading depending on the saccade to be performed. When readers refixate the same word, the saccade amplitude appears to be coded in an oculocentric coordinate system, as a displacement relative to the current fixation point. Such a saccade calculation differs from saccades directed to a new target word for which the goal of the action — the word's center — is represented, as suggested from the literature. Such inter-word saccades use a spatial coordinate system. Whereas the reference point for the inter-word saccade is determined by the selected target position, the endpoint of refixation saccades appears in the present study to be determined with reference to first fixation position. Indeed, the refixation saccade is computed as the sum of the first fixation position and a fixed-motor vector proportional

to the item's length. In preparation for a refixation saccade, the signal for the saccadic system is a command to move the eyes for a certain distance in the orbit.

Further evidence for the existence of different types of coordinate systems controlled by different cortical areas comes from neurophysiological studies (Pierrot-Deseilligny, Rivaud, Gaymard, Müri, & Vermersch, 1995). Particularly, single unit data in macaque show the existence of neurons coding saccades in an oculocentric coordinate system with constant amplitude and direction independent of initial orbital positions (Gnadt & Andersen, 1988; Goldberg & Bruce, 1990; Mushiake, Fujii, & Tanji, 1999; Russo & Bruce, 1996). The present study suggests that the representation of the action in reading is coordinated with the perceptual and cognitive recognition processes. Although intra- and interword saccades differ in their metrics, these two word-oriented actions — aiming a new selected target word and reading it over — may be embedded into a broader representation of the word where the two specific motor plans are encoded altogether to concur to the same goal: to recognize the word.

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