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Eye movements in reading isolated words: evidence for strong biases towards the center of the screen

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Abstract

Three experiments were conducted that compared the eye movement pattern to a peripheral word or letter string as a function of the position of an initial fixation stimulus relative to the center of the screen and the straight-ahead position. Results revealed a strong bias of the eye behavior towards the center of the screen, but not towards the straight-ahead position. Saccades were greater in length, and landed closer to the center of words/strings when launched from a position left of center than when launched from either center or right part of the screen. In addition, the initial saccade launch site was deviated to the right, or to the left of the initial fixation stimulus depending on where relative to the center of the screen the fixation stimulus was displayed. Data were interpreted with the assumption that saccades are programmed in a visual reference framework, with saccade amplitude being computed in relative coordinates. Further research will determine whether the observed bias generalizes to text reading.

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1. Introduction

When reading a page of text in natural reading conditions, our eyes move along the lines while our head remains fairly stable (see Kowler et al., 1991; Seo & Lee, 2002). The center of the page of text is generally aligned with the straight-ahead position, and a variable angular deviation of the eyes from this position is required for the words to be fixated. As words get closer to the ends of the lines, a greater deviation of the eyes in the orbit and relative to the center of the external visual display becomes necessary, which may strongly constrain the eye movement pattern. The present paper investigates the possibility that readers employ an eye movement pattern that favors central word locations, using an isolated word reading paradigm.

Several previous findings indicate that saccadic eye movements to meaningless (or non-reading like) peripheral targets present strong biases towards central locations. First, when subjects move their eyes back and forth between two stimuli displayed sequentially, the resulting saccades present different levels of accuracy depending on whether they are directed towards central or lateral locations (Becker, 1972; Frost & Pöppel, 1976; Kapoula & Robinson, 1986). The centripetal saccades that return the eyes to the straight-ahead position are more accurate and more likely to overshoot their target than centrifugal saccades that move the eyes away from the straight-ahead position. In a similar manner, the saccades made in the dark, and that return the eyes to a previously exposed target are more accurate if the target is at the straight-ahead position than if it is peripheral (Heywood, 1973). On the other hand, when at least two visual targets are presented simultaneously in peripheral vision, the initial saccade is deviated towards the center-of-gravity of the visual configuration, a phenomenon that is referred to as the center-of-gravity or global effect

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(Coëffé & O'Regan, 1987; Coren & Hoenig, 1972; Deubel, Wolf, & Hauske, 1984; Findlay, 1982).

So far, biases towards the center of the line of text were never reported in reading. However, for both oculomotor and perceptual reasons, the eye movement pattern may vary depending on how far from the center of the line of text the eyes are launched. As shown in a large number of reading studies, the basic forward eye movement pattern that brings the eyes from one word to a next word is only slightly affected by ongoing perceptual and cognitive processes associated with word identification, and sentence comprehension (Brysbaert & Vitu, 1998; O'Regan, 1990). What primarily determines forward eye movements is the visual configuration formed by the words located to the right of the current eye location, including the length of the next word, and the word(s) following it. Short words (less than 5 letters) are more frequently skipped than long words, and the preferred initial landing position in long words lies between the beginning and the center of words (Dunn-Rankin, 1978; McConkie, Kerr, Reddix, & Zola, 1988; O'Regan, 1979; Rayner, 1979; Vitu, McConkie, Kerr, & O'Regan, 2001; Vitu, O'Regan, & Mittau, 1990). Word skipping rate and initial landing sites also strongly vary with the distance of the eyes from the beginning of a word: the smaller the distance, the more likely the word is skipped, or the eyes land toward the end of the word (McConkie et al., 1988; Vitu, O'Regan, Inhoff, & Topolski, 1995).

Thus, at each fixation in reading, the eyes are drawn by the visual material ahead of fixation. A classical assumption posits that most saccades in reading aim for the center of the next word or the word following it, and that the variability of initial landing sites around the center of words results from the influence of visuo-motor factors which deviate the eyes from their intended location (Just & Carpenter, 1980; McConkie et al., 1988; O'Regan, 1990, 1992; Reichle, Pollatsek, Fisher, & Rayner, 1998). The straight-ahead position and/or the center of the line of text may be one of these factors. First, as shown in several studies, there is a strong resemblance between eye movements during text reading, and the scanning of meaningless material (Vitu et al., 1995; Rayner & Fischer, 1996). The tendency for centripetal saccades to be more accurate than centrifugal saccades which was previously observed with single and meaningless visual targets may therefore generalize to reading. Second, given that a center-of-gravity effect was found with pairs of isolated words, it may well be the case that this effect extends to text reading with the eyes being deviated towards the center of the lines (Vitu, 1991). More particularly, if the perception of the exact location of the saccade target is biased towards the straight-ahead position or the center of the visual display, then this should result in a corresponding deviation of the initial landing sites in words.

To investigate the possibility that such perceptuo-oculomotor biases intervene in reading, the present se-

ries of experiments examined the pattern of eye movements made to an isolated word as a function of the initial position of the eyes relative to the center of the screen, and/or the straight-ahead position. Isolated words were studied rather than words in sentences or text to avoid the influence of ongoing linguistic processes. This also removed the possibility that an oculomotor rhythm resulting from making a series of eye fixations on the same line changed the eye movement characteristics (Vitu, 1993; Zingale & Kowler, 1987). In the experiments, the target words were always displayed at the same eccentricity to the right of fixation, and the resulting saccades were always directed to the right. However, given that the starting eye location was either left or right of center, or exactly at the center of the screen, the initial saccades moved either towards or away from the central location. Thus, if a bias towards the center of the screen, or the straight-ahead position, is at work in reading, initial saccades should present different characteristics depending on how far left or right of center these are launched. On the other hand, it may be that the same biases that were previously found with meaningless materials do not apply to reading words. To test for this, a control condition was added where words were replaced with meaningless x-letter strings that contained a centrally dissimilar target letter ('h' or 'k'). In that condition, subjects were asked to saccade to the target letter in order to perform a discrimination task.

2. Experiment 1

Experiment 1 was an attempt to reproduce normal reading conditions in which the center of the screen corresponds to the straight-ahead position, and the eyes are launched from various positions on the horizontal axis, with the words being positioned to the left or to the right of center. On every trial, a peripheral stimulus (word or letter string) of a variable length was presented to the right of fixation. The eccentricity of the first letter of the stimulus relative to the fixation point was kept constant (i.e. 1.5° to the right), but the starting eye position on the screen was varied between extreme-left, left, center, and right positions within each block of trials. If perceptuo-oculomotor biases towards the straight-ahead position or the center of the visual display were at work in reading, then these should be reflected in differences in the eye behavior between the different conditions.

2.1. Methods

2.1.1. Participants

Twenty-four psychology students from the University René Descartes, and the Catholic University of Paris (Ecole des Psychologues Praticiens) participated in the

experiment which was run at the Laboratory of Experimental Psychology, in Boulogne-Billancourt (France). Participants were between 20 and 30 years old, they were all native french speakers, and they had normal, or corrected-to-normal vision (in the latter case, only participants wearing glasses were accepted). All participants were unfamiliar with the purpose of the experiment.

2.1.2. Material

A set of 288 target words was selected from the french corpus Trésor de la Langue Française (1971). Target words were 5, 7, and 9 letters long, and the number of words for each word length was 96. Half the words were of a high frequency of occurrence in the language, and half were of a low frequency (more, and less than 20 occurrences per million respectively). For high-frequency 5-, 7-, and 9-letter words, the median frequency corresponded respectively to 86, 97, and 80 occurrences per million, and for low-frequency 5-, 7-, and 9-letter words, it corresponded respectively to 6.2, 7.9, and 6.7 occurrences per million. A set of 40 additional words which are referred to as fillers was selected, with about the same number of words for each length (5, 7, or 9 letters). All fillers corresponded to an animal name, and served to form the animal search task in the reading condition. The resulting set of 328 words was divided into four lists (corresponding to the four blocks of trials) which were equated in terms of word length, word frequency, and number of fillers.

A set of 288 letter strings was also prepared that comprised an equal number of 5-, 7-, and 9-letter strings. All letter strings contained a centrally-located target letter, which was in half the cases the letter 'h', and in the other half the letter 'k'. The remaining letters in the strings corresponded to the letter 'x' (e.g. 'xxxxxxx' or 'xxxhxxx' in the 7-letter string condition). The total set of letter strings was divided into four equivalent lists that corresponded to four different blocks of trials.

2.1.3. Design

For letter strings, a 4 by 3 within-subject design was defined, with initial fixation position (extreme-left, left, center, and right), and string length (5, 7, and 9 letters) as independent variables. For words, a 4 by 3 by 2 within-subject design was defined with initial fixation position (extreme-left, left, center, and right), word length (5, 7, and 9 letters), and word frequency (high vs. low) as independent variables. In addition, a latin-square design was used such that all words were seen in the different initial fixation conditions across participants, and that all participants were presented only once with all words.

The total set of stimuli was presented in eight blocks of trials. Half the participants ran the four blocks of words first, and then the four blocks of letter strings,

and the other half did the reverse. In each block, words or letter strings were presented in a random and different order for each participant. Initial fixation position was also randomized within each block of trials.

2.1.4. Procedure

The participant was seated in an adjustable chair. A bite bar minimized head movements. After setting up the eye tracker, a calibration phase began. Calibration was made using 15 points presented successively on the entire screen (5 points on both diagonal axes, and 5 points around the central horizontal axis of the screen (2 above and 3 below)). The first calibration point was presented in the left upper corner of the screen until the participant pressed a button, which made the point disappear, and appear at another location. Participants were asked to press the button only when they were fixating very precisely at the displayed dot location. If the calibration was not satisfactory (or the correlation between the actual and the estimated eye location was less than 0.99 for both horizontal and vertical coordinates), another calibration phase was initiated. Otherwise, a block of trials began.

Each trial began with the presentation of a '+' sign at one of four possible locations on the screen: extreme-left, left, center, and right, which corresponded respectively to visual angles of about -7.6° , -3.8° , 0° , and $+3.8^\circ$ from the center of the screen. Participants were asked to fixate at the center of the '+' sign. When the computer detected that the eyes were within a region of 1.5 character space of the '+' sign, it was replaced with a cross which was simultaneously presented with a word or a letter string to its right. The eccentricity of the word (or string) was kept constant throughout the experiment: the first letter of the word (or string) was always positioned at 5 character spaces (or 1.5°) from the center of the cross. Participants were asked to move their eyes to the peripheral stimulus only when the cross appeared, this in order to discourage anticipatory eye movements. In the word condition, their subsequent task was to read the word silently, and then to indicate by pressing one or another button, whether the presented word corresponded to an animal name. In the letter-string condition, participants were asked to move their eyes to the central target letter, and to indicate with one or another button press, whether the target letter was a 'h' or a 'k'. In both conditions, button press triggered simultaneously the disappearance of both the fixation cross, and the peripheral stimulus, and the display at the bottom of the screen of two codes (a number, and a letter), one corresponding to the past trial number, and the other indicating whether the participant's response was correct ('C') or false ('F'). After a delay of 2 s, the next trial began. On each trial, eye movement data were stored only for the period going from the beginning of

the trial (display of the initial fixation ‘+’ sign) up to the participant’s button press.

2.1.5. Apparatus

Eye movements were recorded using a 5th generation Dual Purkinje Image eye tracker (Fourward Optical Technologies, Inc.), sampling the right eye position every millisecond with a spatial accuracy of 1 min of arc (Cornsweet & Crane, 1973). The eye tracker was interfaced with two IBM-compatible microcomputers. The first computer recorded the eye movement parameters, and analyzed them on line, using the software developed at the Catholic University of Leuven by Van Rensbergen and de Troy (1993). The second computer controlled the visual presentation of the stimuli. Eye movement parameters were continuously sent to the second computer, so that the visual display could be changed contingent on the position of the eyes (see above). The first computer was interfaced with two response buttons. The decision to start the next trial was based on the signal of the button press, which indicated the decision made by the participant.

Stimuli were displayed in graphics mode on a 17" CRT monitor with 60-Hz refresh rate. Each letter subtended 0.3° of visual angle, at a distance of 1075 mm from the participants’ eyes. The monitor was placed on a wood plate which was itself installed on a fixed table. The plate could move towards or away from the participant’s face, as well as on the horizontal axis. To ensure that the center of the screen corresponded to the straight-ahead position, the plate was moved on the horizontal axis until a ruler that started out from the center of the bite board device would intersect the width of the screen in the center, and form a perpendicular angle with the face of the display. Several landmarks on both the table and the plate served to ensure that the monitor was positioned at this location for each participant. Vision was binocular. The room was dark except for a dim indirect light source.

2.1.6. Data analysis

The characteristics of the initial eye behavior (initial landing site in words and strings, length and latency of the initial saccade, and launch site of the initial saccade or exact position of the eyes relative to the initial fixation cross) were measured in the different conditions. For these analyses, data were selected using the following criteria: the display of the peripheral stimulus appeared while the eyes were fixating within a predefined region around the fixation ‘+’ sign (see above), there was no button press before the word or string was fixated, there was no blink or other signal irregularity before and after the initial saccade, and the latency of the initial saccade was more than 50 ms (to remove anticipatory eye movements which occurred in about 1% of the trials). Given that there were only a few errors in

response to the animal search task, and the letter discrimination task (0.5%, and 1% respectively), and that the dependent variables of primary interest were measured before the target word was read, both correct and false response trials were considered for analysis. In all analyses, means or proportions were calculated for each participant, and these were then averaged across participants, such that the weight of each individual’s contribution to the global mean was similar. Analyses of variance were run on the means for each participant in each condition, and when there were missing data points (which occurred in less than 1% of the cases), these were replaced with the mean of the corresponding condition.

2.2. Results

A first series of analyses revealed that the frequency of the words had no influence at all on the initial eye behavior. For this reason, and for clarity of presentation, no distinction was made between high- and low-frequency words in the analyses reported below.

Fig. 1a–f present the distributions of *initial landing sites* following saccades made from four different initial fixation zones, and for 5-, 7-, and 9-letter words and strings. These figures indicate first that most distributions have a single mode centered on one of the letters of the peripheral word or string. It is only in the extreme-left condition (and to a lesser extent in the left condition) that a tendency for a bimodal distribution can be observed, the eyes landing either within the peripheral word/string (in 80%, and 78% of the cases respectively), or on the large space in front of it (in 18%, and 19% of the cases). Second, and most importantly, when going from the extreme-left to the right condition, initial landing sites moved from a region near the center of the word or string, to the beginning of the word or string, with a shift of about one letter with each additional 4° deviation of the starting eye location. In the extreme-left condition, the eyes tended to overshoot the center of 5-, and 7-letter words/strings, and to land near the center of longer words/strings. As the initial fixation position on screen moved to the right, this tendency became less prominent, and the likelihood the eyes undershot the center of the stimuli increased. Finally, there was a tendency for initial landing sites to move further away from the beginning of the stimuli as stimulus length increased, replicating the classical word length effect previously reported in natural reading (McConkie et al., 1988; O’Regan, 1979; Rayner, 1979; Vitu et al., 1990).

An analysis of variance run on mean initial landing sites revealed that the effects of both initial fixation position and stimulus length were significant for words ($F(3, 69) = 17.48$, $p < 0.0005$, $F(2, 46) = 81.71$, $p < 0.0005$, respectively), and strings ($F(3, 69) = 15.34$, $p < 0.0005$, $F(2, 46) = 37.92$, $p < 0.0005$). The interaction between initial fixation position, and stimulus

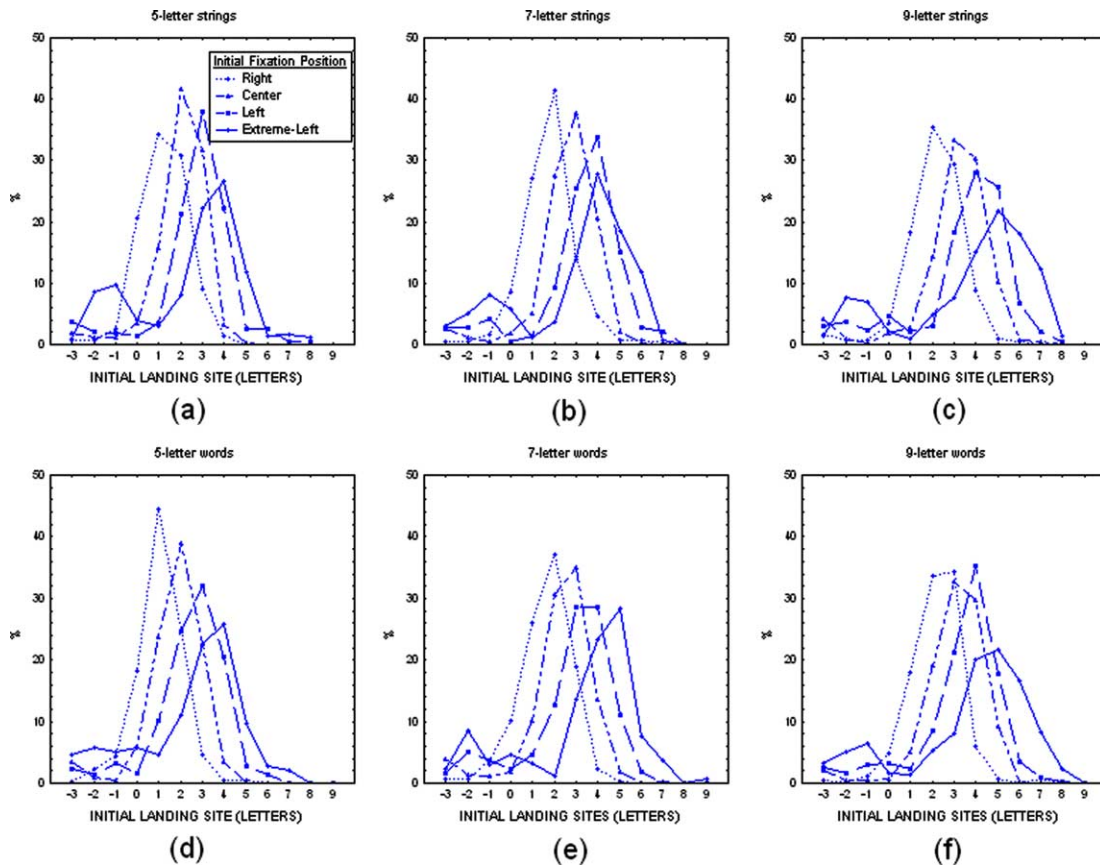


Fig. 1. Distribution of initial landing sites in 5-, 7-, and 9-letter strings (a–c), and words (d–f), for different initial positions in Experiment 1. Landing sites are expressed in number of letters from the beginning of the stimulus, with zero-, or negative values corresponding to initial landing sites on one of the five character spaces in front of the stimulus.

length was never significant ($F(6, 138) = 1.05$, $F(6, 138) = 0.63$, respectively for words, and strings).

In instances where the eyes initially landed on the peripheral stimulus, the absolute distance of the initial landing position to the center of the word/string (referred to as *mean absolute error*) was greater in both center and right conditions than in extreme-left and left conditions, the latter two conditions differing only slightly (see Fig. 2a and b). Furthermore, the mean absolute error became greater as the length of the stimulus increased. The effects of both initial fixation position, and stimulus length were significant for words ($F(3, 69) = 49.13$, $p < 0.0005$, $F(2, 46) = 59.77$, $p < 0.0005$, respectively) and strings ($F(3, 69) = 40.67$, $p < 0.0005$, $F(3, 69) = 95.14$, $p < 0.0005$, respectively). The interaction was also significant ($F(6, 138) = 5.98$, $p < 0.0005$, $F(6, 138) = 19.13$, $p < 0.0005$, for words and strings respectively).

In the present experiment, the eccentricity of the peripheral stimulus was kept constant across conditions, and word/string lengths. The effect of initial fixation position on initial landing sites should therefore result from shorter saccades being made in center and right conditions, unless the exact position of the eyes relative

to the initial fixation cross also varied between the different conditions. Table 1(Panels A and B) presents the characteristics of the initial saccades in the different conditions, including their length, launch site, and latency. These first confirm that the *mean length of the initial saccade* became smaller as the eyes were launched from a region closer to the right border of the screen ($F(3, 69) = 8.89$, $p < 0.0005$, and $F(3, 69) = 4.90$, $p < 0.005$, respectively for words, and strings), and as the length of the peripheral stimulus decreased ($F(2, 46) = 101.39$, $p < 0.0005$, and $F(2, 46) = 37.50$, $p < 0.0005$, respectively for words, and strings). However, there was in addition, a systematic deviation of the *initial saccade launch site* relative to the initial fixation stimulus: while the eyes were positioned on average to the right of the fixation cross in both extreme-left and left conditions, they were deviated to the left of the stimulus in the right condition. The effect of initial fixation position was significant for words ($F(3, 69) = 46.31$, $p < 0.0005$), and strings ($F(3, 69) = 64.31$, $p < 0.0005$), but the effect of the peripheral stimulus length was not significant ($F(2, 46) = 0.18$, $F(2, 46) = 0.18$). Thus, the location on the screen of the initial fixation stimulus affected not only the length of

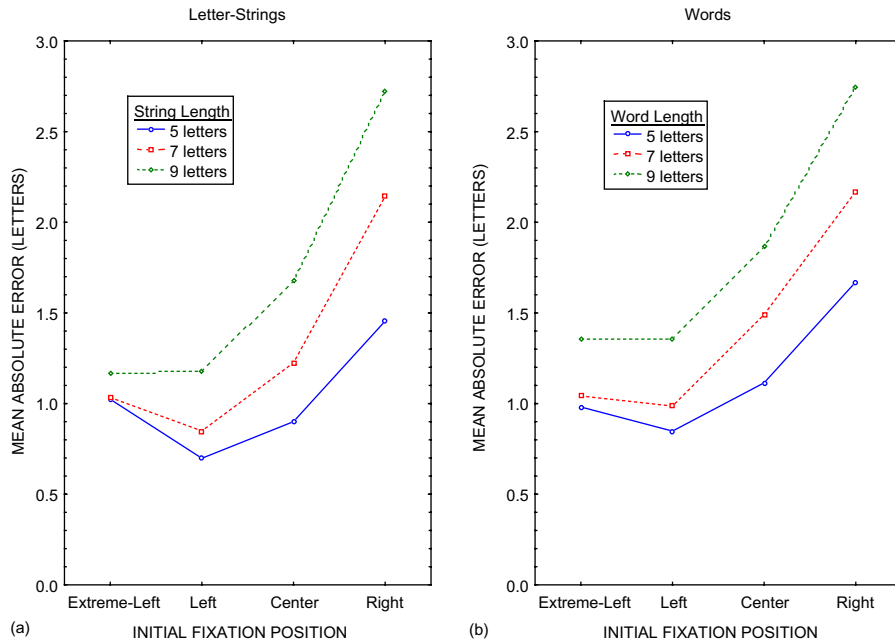


Fig. 2. Mean absolute error of the initial saccades (in letters) made towards 5-, 7-, and 9-letter strings (a), and words (b), as a function of the initial fixation position in Experiment 1. The mean absolute error corresponds to the absolute distance of the initial landing position to the center of the word or string, but only in instances where the eyes initially landed within the word/string.

Table 1

Characteristics of the initial saccades (mean length (in letters), mean launch site (in letters), and mean latency (in ms)) for 5-, 7-, and 9-letter words (Panel A), and strings (Panel B), and for different initial fixation positions (extreme-left, left, center, and right) in Experiment 1

	5-letter words/Strings				7-letter words/Strings				9-letter words/strings			
	E-L	L	C	R	E-L	L	C	R	E-L	L	C	R
<i>Panel A</i>												
Saccade length	6.83	6.62	6.16	5.75	7.62	6.98	6.70	6.31	8.10	7.51	7.41	6.91
Launch site	0.09	0.29	0.00	-0.28	0.14	0.26	0.00	-0.25	0.12	0.23	0.04	-0.27
Saccade latency	231	231	212	209	225	221	212	210	229	225	218	213
<i>Panel B</i>												
Saccade length	6.80	6.85	6.37	5.99	7.23	7.36	6.99	6.44	8.02	7.61	7.48	6.86
Launch site	0.25	0.28	0.08	-0.31	0.24	0.29	0.06	-0.25	0.27	0.32	0.05	-0.28
Saccade latency	231	238	228	227	246	237	232	227	239	236	228	225

the initial saccade, but it affected also the saccade's launch position.

The *mean latency of the initial saccade* (or delay that elapsed between the presentation of the peripheral stimulus, and the execution of the initial saccade), showed an overall decrease from the extreme-left to the right condition, although the difference between left and center conditions was larger on average than the difference between extreme-left and left conditions, or between center and right conditions. The effect of initial fixation position was significant with words ($F(3, 69) = 3.03$, $p < 0.05$), but only marginally significant with letter strings ($F(3, 69) = 2.27$, $p < 0.10$). In contrast, the length of the peripheral stimulus did not significantly influence saccade latency ($F(2, 46) = 1.11$, and $F(2, 46) = 0.94$, for words and strings respectively).

The interaction between initial fixation position and stimulus length was not significant ($F(6, 138) = 0.43$, and $F(6, 138) = 0.78$, respectively for words and strings).

A plot of the distributions of saccade latencies in the different conditions, but across words, and strings of different lengths (not presented here) confirmed that both extreme-left and left conditions produced longer latencies than center and right conditions, with the latter two conditions presenting no major difference. In addition, although all distributions were unimodal, those corresponding to the extreme-left condition presented in comparison with the three other conditions, a higher proportion of both short-, and long-latency saccades (between 50 and 150, and 250 and 375 ms, respectively). Interestingly, the short-latency saccades identified in the

extreme-left condition corresponded to instances where the eyes initially landed on the large space in front of the peripheral stimulus (see Fig. 1a–f). On average, the latency of the saccades landing on the large space in front of the peripheral stimulus was 100 ms shorter than the latency of saccades ending in the word or string (126 vs. 246, and 155 vs. 254 ms, respectively). Thus, in general, the latency of the initial saccade increased as the eyes were launched from a region closer to the extreme-left part of the screen, but there were some instances where an initial leftward deviation resulted in the execution of shorter-than-normal latency saccades.

2.3. Discussion

To determine whether biases towards central locations may intervene in a reading task, the present experiment compared the eye movement pattern made to an isolated word or string following different deviations of the initial fixation stimulus relative to the center of the screen and the straight-ahead position. Results revealed the presence of systematic variations of the eye behavior with the position of the initial fixation stimulus. First, the initial saccade launch site or exact starting eye position presented a slight but systematic deviation towards the center of the screen, being deviated to the right or to the left of the fixation stimulus depending on whether the stimulus was displayed in the left or right region of the screen. Second, when going from the extreme-left to the right condition, the landing position of the initial saccade was shifted from the center of the word (or a position right of center) to the beginning of the word or string. Third, and in a related manner, the length of the initial saccade became shorter as the eyes were launched from a region closer to the right border of the screen. Fourth, the latency of the initial saccade presented an overall decrease from extreme-left to center and right conditions.

The observation that the initial fixation position influenced both length, and latency of the initial saccade may suggest that a speed-accuracy trade-off was at the origin of the effects (see Coëffé & O'Regan, 1987; Viviani & Swensson, 1982). Indeed, as the initial fixation posi-

tion moved away from the left border of the screen, saccade latency became shorter, and the eyes were less likely to land near the center of words/strings. However, this hypothesis is rather unlikely. First, as can be noted from Fig. 2a and b and Table 1 (Panels A and B), the accuracy of the initial saccades made towards 7-letter words and strings was higher in the left compared to the extreme-left condition, and still saccade latency was shorter in the left condition. Second, as indicated in Table 2, an effect of initial fixation position on initial landing sites in words and strings was present in different subsets of data characterized with different saccade latency ranges. For saccade latencies between 200 and 250, and 250 and 300 ms, the mean absolute error was again significantly greater in center and right conditions compared to both left conditions.

An alternative hypothesis envisages the effect of initial fixation position on screen as resulting from a lack of precision in the eye movement recording. In the present experiment, the range of stimulus locations covered a total of about 14°, and systematic errors may have occurred in detecting where the eyes were exactly located when the stimuli were near the extremes of the range. While estimation of eye position would be biased to the right in left conditions, it would be biased to the left in the right condition. However, this hypothesis is also rather unlikely. A systematic analysis of the calibration data indeed revealed no clear deviation of the participants' eye position to the right or to the left of the calibration dots displayed respectively in the left and right part of the screen (see Fig. 3). Furthermore, a direct comparison between the individual calibration data, and the corresponding initial landing position curves indicated that the effect was present in most individuals even when the calibration was near to be perfect.

In conditions similar to our extreme-left condition, Findlay and Kapoula (1992) previously reported a systematic deviation of the eyes to the right of the initial fixation stimulus. To account for this trend, the authors made the assumption that the initial deviation of the eyes resulted from the occurrence of anticipatory eye movements in the direction of the saccade target which

Table 2

Mean absolute error (in letters) of the initial saccades made to peripheral words, and strings in Experiment 1 as a function of the initial fixation position (extreme-left, left, center, and right), and separately for initial saccade latencies between 200 and 250, and 250 and 300 ms

	E-L	L	C	R	<i>p</i> -value
<i>Words</i>					
[200,250[	1.04	0.83	1.38	2.23	0.0005
[250,300[	1.11	.91	1.22	2.18	0.0005
<i>Strings</i>					
[200,250[	1.19	.99	1.53	2.26	0.0005
[250,300[	1.08	1.05	1.38	1.96	0.0005

All word/string lengths were combined. The level of significance for the effect of initial fixation position on screen is indicated in a separate column.

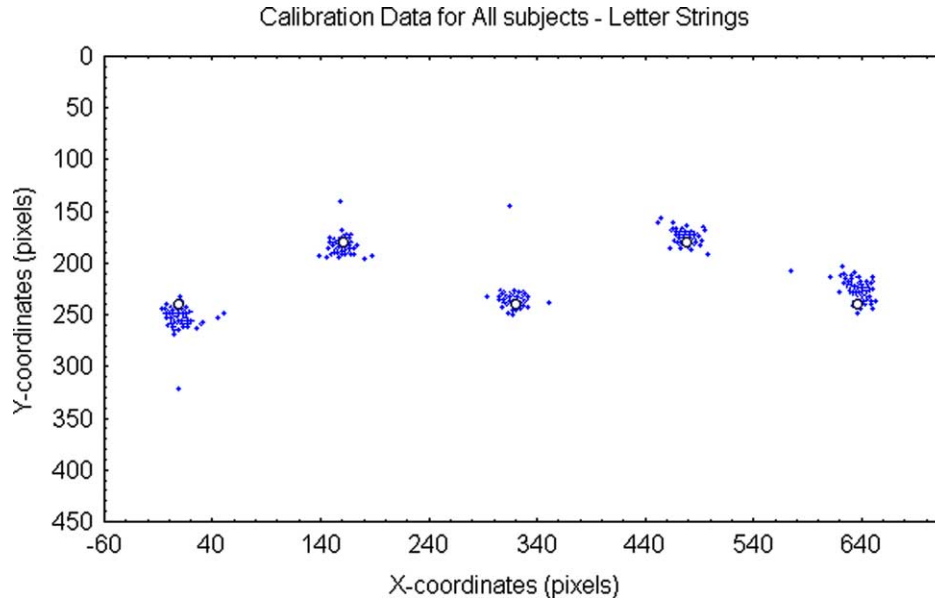


Fig. 3. Plot of the calibration data obtained over all subjects in the letter-string condition in Experiment 1, for the 5 calibration dots displayed around the central line of the screen. The large circles indicate the different locations of the calibration dots.

actually always appeared to the right of fixation. This interpretation does not hold however for the present data since the deviation of the eyes relative to the initial fixation cross was not always in the same direction as the peripheral stimulus and the following saccade: it was either to the right or to the left of the fixation stimulus, while the saccade target word or string always appeared to the right of fixation. On the other hand, we identified the presence of rightward short-latency eye movements in the extreme-left condition, but given that their proportion was strongly reduced in the left condition, these could not arise from the general tendency to move forward. Rather, the occurrence of short-latency saccades was determined by the distance of the eyes to the center of the screen.

The present data must therefore be interpreted in terms of a systematic bias of the eye behavior towards central locations. However, since in the present experiment, the center of the screen was aligned with the participant's straight-ahead position, it cannot be determined at this stage whether the bias was external or internal in nature, namely whether it was related to the initial deviation of the eyes relative to the center of the screen or to the straight-ahead position. In addition, given that all presentation conditions were randomized within each block of trials, the present results could also illustrate a range effect or a tendency to send the eyes towards the center of the range of possible stimulus locations on the screen (Kapoula, 1985; Kapoula & Robinson, 1986; Poulton, 1981). Experiments 2 and 3 were designed to determine the origin of the observed bias, namely whether this was related to the distance of the eyes (1) to the center of the screen, (2) to the straight-

ahead position, or (3) to the center of the range of possible stimulus locations.

3. Experiment 2

Experiment 2 examined whether the systematic influence of the initial fixation position on eye behavior reported in the first experiment could be attributed to a systematic deviation of the eyes towards the straight-ahead position. For this purpose, the position on the screen of the initial fixation stimulus was maintained constant (at the center of the screen), but the position of the initial fixation stimulus relative to the straight-ahead location was varied. This manipulation was made possible by shifting the screen for a complete block of trials to the left or to the right of the straight-ahead position by the same amount as in left, center, and right conditions of Experiment 1. If the effects reported in Experiment 1 were due to a systematic bias of the eye behavior towards the straight-ahead position, then these should be replicated in Experiment 2. If in contrast, the effect was due to a bias towards the center of the visual display or the center of the range of possible stimulus locations, then there should be no effect at all of the initial fixation position on the following eye behavior.

3.1. Methods

3.1.1. Participants

Eighteen individuals responding to the same recruitment criteria as in Experiment 1 participated in the experiment. All of them were unfamiliar with the purpose

of the experiment, and none of them had participated in the first experiment.

3.1.2. Material

A subset of 216 words was selected from the total set of 288 target words used in Experiment 1. Target words were 5, 7, and 9 letters long, and the number of words for each word length was 72. Half the words were of a high frequency of occurrence in the language, and half were of a low frequency (more, and less than 20 occurrences per million respectively). A set of 30 fillers was selected, with about the same number of words for each length (5, 7, or 9 letters). All fillers corresponded to an animal name, and served to form the animal search task. The resulting set of 246 words was divided into three lists (corresponding to the three blocks of trials) which were equated in terms of word length, word frequency, and number of fillers.

A set of 216 letter strings was also selected that comprised an equal number of 5-, 7-, and 9-letter strings. Letter strings had exactly the same characteristics as in Experiment 1, and were presented in three different blocks of trials.

3.1.3. Design

For letter strings, a 3 by 3 within-subject design was defined, with initial fixation position (left, center, and right), and string length (5, 7, and 9 letters) as independent variables. For words, a 3 by 3 by 2 within-subject design was defined, with initial fixation position (left, center, and right), word length (5, 7, and 9 letters), and word frequency (high vs. low) as independent variables. In that case, a latin-square design was used such that all words were seen in the different conditions across participants, and that all participants were presented only once with all words.

All stimuli were presented in a total of 6 blocks of trials. Half the participants run the 3 blocks of words first, and then the 3 blocks of letter strings, and the other half did the reverse. In each block, the stimuli were presented in a random and different order for each participant. The position of the screen and therefore the initial fixation position relative to the straight-ahead position was kept constant within a block of trials, but the order of the different conditions was counterbalanced across participants.

3.1.4. Procedure

The procedure was identical to that used in Experiment 1, except that the '+' sign presented at the beginning of each trial, and the following fixation cross, always appeared at the center of the screen. In addition, the computer screen was presented at variable locations relative to the straight-ahead position depending on the block of trials. It was either centered on the straight-ahead, or shifted to the left or to the right by an angle of

about 3.8°. The calibration phase that preceded each block of trials was always made with the screen positioned the same way as in the corresponding block of trials. However, care was taken that the initial phase of the experiment which consisted in preparing the participant's bite bar, as well as adjusting the eye tracker, was always made with the screen centered on the straight-ahead position.

3.1.5. Apparatus

This was identical to Experiment 1 with the following exception. Depending on the block of trials, the plate which held the monitor was positioned such that the center of the screen was either aligned with the straight-ahead position (using the same procedure as in Experiment 1), or deviated by an angle of about 3.8° left or right of the straight-ahead position. Landmarks on the table-plate device served to ensure that the monitor was positioned correctly for each participant and each block of trials.

3.1.6. Data analysis

The data were selected and analyzed the same way as in Experiment 1. Again, the word frequency factor had no reliable effect on the initial eye behavior, and it was not considered in the analyses reported below.

3.2. Results

Fig. 4a–f present the distribution of *initial landing sites* in 5-, 7-, and 9-letter words and strings, for the three different initial fixation conditions. In most instances, the eyes landed between the beginning and the center of the word or string, and they landed further from the beginning of the word/string as the length of the stimulus increased. Second, while there was a slight tendency for further landing sites in words in both center and right conditions compared to the left condition, there was a large overlap between the distributions obtained for letter strings, and the slight differences observed between the three conditions were not consistent across string lengths. The effect of initial fixation position on mean initial landing sites was not significant for letter strings ($F(2, 34) = 0.38$), while that it was significant for words ($F(2, 34) = 3.70$, $p < 0.05$), and the interaction was significant for letter strings ($F(4, 68) = 3.36$, $p < 0.05$), but not for words ($F(4, 68) = 0.66$). The effect of the peripheral stimulus length was significant in both words and strings ($F(2, 34) = 112.37$, $p < 0.0005$, $F(2, 34) = 102.13$, $p < 0.0005$, respectively).

To further investigate the effects of initial fixation position on the initial eye behavior, the mean *length of the initial saccade* was calculated in the different conditions. Results presented in Table 3 (Panels A and B) show that saccade length did not vary with initial fixation position for either words or strings ($F(2, 34) =$

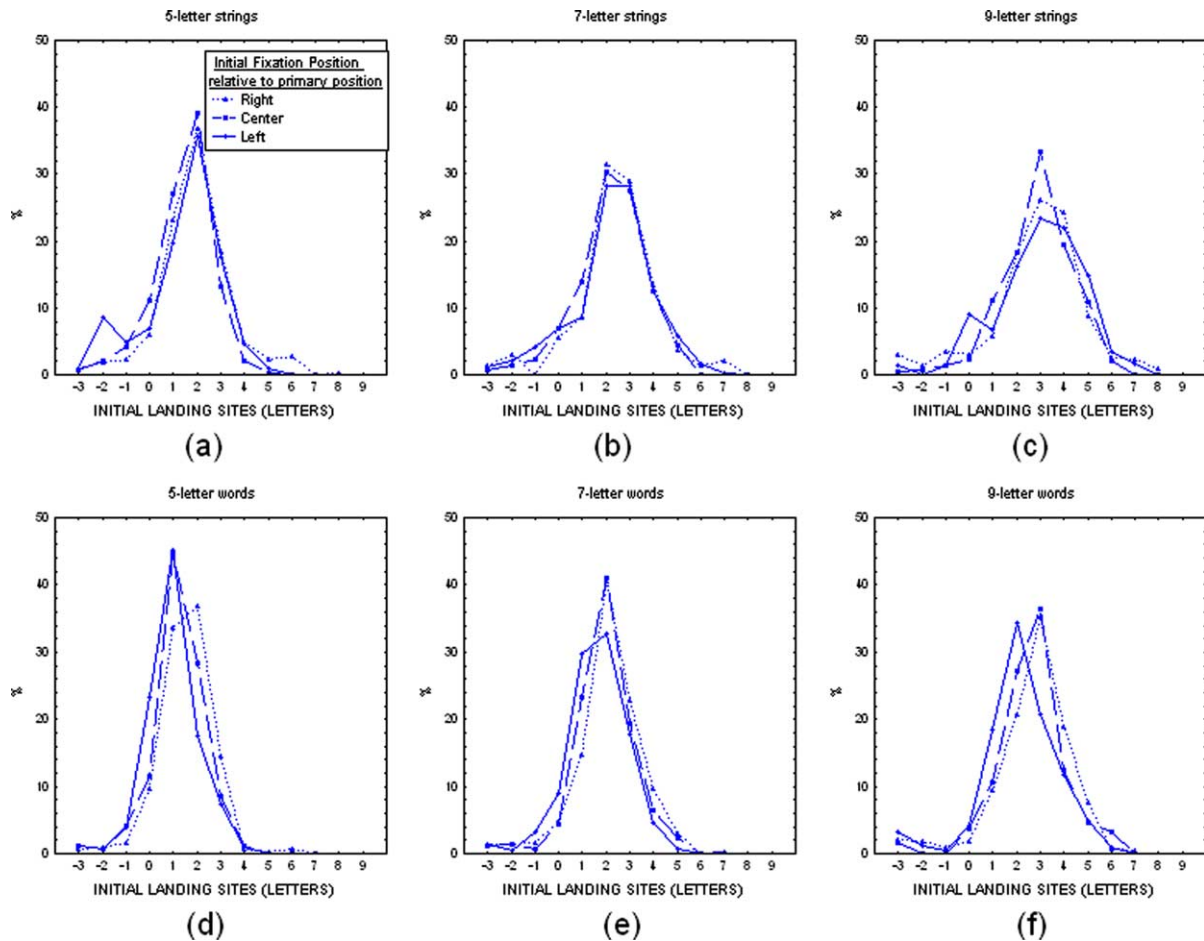


Fig. 4. Distribution of initial landing sites (in letters) in 5-, 7-, and 9-letter strings (a–c), and words (d–f), as a function of the initial fixation position relative to the straight-ahead position, in Experiment 2. Landing sites are expressed in number of letters from the beginning of the stimulus, with zero-, or negative values corresponding to initial landing sites on one of the five character spaces in front of the stimulus.

0.91, $F(2, 34) = 0.10$, respectively), but it varied with the length of the stimulus, saccades being longer when directed to longer words or strings ($F(2, 34) = 97.80$, $p < 0.0005$, $F(2, 34) = 243.31$, $p < 0.0005$, respectively). The interaction was not significant in words ($F(4, 68) = 0.59$), and strings ($F(4, 68) = 1.95$). Thus, for a word or string of a given length, saccades were of about the same length in all conditions. In contrast, the *mean launch site of the initial saccade* varied significantly between the three initial fixation conditions, being more largely deviated to the left of the initial fixation cross in both left and center conditions than in the right condition ($F(2, 34) = 14.20$, $p < 0.0005$, $F(2, 34) = 3.54$, $p < 0.05$, respectively for words, and strings) (see Table 3(Panels A and B)). This pattern although being present with both types of peripheral stimuli was clearer with words, accounting therefore for the significant influence of the initial fixation condition on initial landing sites in words.

The *mean latency of the initial saccade* slightly varied between the different conditions, but not in a consistent manner across word and string lengths (see Table

3(Panels A and B)). The effects of initial fixation position and stimulus length were not significant for either words ($F(2, 34) = 0.38$, $F(2, 34) = 2.20$, respectively), or strings ($F(2, 34) = 0.15$, $F(2, 34) = 0.24$, respectively). The interaction was not significant for words ($F(4, 68) = 0.77$), but it was marginally significant for letter strings ($F(4, 68) = 2.44$, $p < 0.10$).

3.3. Discussion

To determine whether the systematic bias of the eye behavior reported in Experiment 1 could be attributed to extra-retinal (or eye position signal) factors, the present experiment examined whether similar biases occur when the initial fixation position relative to the straight-ahead position is manipulated, but the initial fixation position on screen is kept constant. The results in general failed to replicate the findings reported in Experiment 1. First, both length, and latency of the initial saccade made to the peripheral stimulus were very similar between left, central, and right saccade launch sites. Second, there was a significant influence of the

Table 3

Characteristics of the initial saccades (mean length (in letters), mean launch site (in letters), and mean latency (in ms)) for 5-, 7-, and 9-letter words (Panel A), and strings (Panel B), and for different initial fixation positions relative to the straight-ahead position (left, center, and right) in Experiment 2

	5-letter words/Strings			7-letter words/Strings			9-letter words/strings		
	L	C	R	L	C	R	L	C	R
<i>Panel A</i>									
Saccade length	5.80	5.95	5.85	6.49	6.58	6.44	7.00	7.31	7.09
Launch site	−0.39	−0.25	0.02	−0.39	−0.26	0.02	−0.39	−0.23	0.03
Saccade latency	243	242	246	238	235	236	245	230	234
<i>Panel B</i>									
Saccade length	6.23	6.10	6.49	7.04	6.96	7.00	7.79	7.64	7.45
Launch site	−0.29	−0.20	−0.06	−0.31	−0.29	−0.08	−0.39	−0.30	−0.13
Saccade latency	246	252	247	246	240	250	255	246	242

initial fixation position on initial landing sites, but this occurred only with words, and the effect was in a direction opposite to the effect observed in the first experiment, with the eyes landing closer to the center of words in center and right conditions. In the same manner, there was a slight deviation of the initial saccade's launch site relative to the fixation cross in both left and center conditions, but this was again in a direction opposite to what was found in Experiment 1.

Failure to replicate the original bias of the eye behavior may suggest that the effect was unrelated to extra-retinal influences, unless the likelihood of any sort of bias was reduced in the present experimental situation. The position of the initial fixation stimulus was indeed predictable from one trial to the next in each block of trial, and this may have favored the use of a constant eye movement scanning pattern. However, this outcome was rather unlikely since initial landing sites in words and strings varied with the length of the stimulus in a similar manner as in the first experiment.

The reason why the present study also failed to replicate previous oculomotor findings showing that centripetal saccades are more accurate than centrifugal saccades remains unclear at present (Becker, 1972; Frost & Pöppel, 1976; Heywood, 1973; Kapoula & Robinson, 1986). First of all, the possibility that this was due to the presentation of reading or reading-like material is very unlikely as several of the effects that were originally reported with meaningless stimuli generalize to reading (see for instance, Vitu, 1991). Rather, the difference may simply result from the fact that in the present experiment, saccades went from left to right, while in previous studies, leftward and rightward saccades were interleaved, thereby favoring the appearance of biases towards the straight-ahead position. On the other hand, failure to report extra-retinal biases may have arose from the fact that in the present experiment, eye positioning could rely almost entirely on external or visual cues (the fixation stimulus always appeared at the center of the screen, with the frame of the screen being clearly

visible). This may have in turn reduced recourse to internal (eye position signal) cues (see Eggert & Kapoula, 1995, for similar findings in the disconjugate adaptation of saccades), or in a reverse manner favored a perfect compensation between retinal and extra-retinal information. The possibility that the central nervous system calibrates saccades on the basis of retinal information combined with extra-retinal information of eye position has indeed been proposed in several models of saccade control (see Leigh & Zee, 1999, for a review).

As concerns the slight but systematic leftward deviation of the initial saccade launch site that was observed in both left and center conditions, we doubt it is related to an oculomotor bias, as previous studies indicate a bias towards rather than away from the straight-ahead position. Instead, the observed deviation may be purely perceptual, and a consequence of the present manipulation of screen location together with the fact that the initial fixation stimulus was always located at the center of the screen. Past studies indeed revealed that if a luminous figure is shifted to the left or to the right of the primary position, the perceived straight-ahead is shifted towards the center of the figure, but this occurs when the shift of the figure is such that one of the edges of the figure is in the median plane, and the figure is presented in total darkness (see Howard, 1982, for a review). Our experimental situation although being quite different may have produced a smaller but similar misperception of the straight-ahead location, and in turn affect the localization of the initial fixation stimulus.

From the present set of data, it seems reasonable to conclude that the effect reported in the first experiment does not result from some sort of extra-retinal bias. Thus, there remains now only two possible explanations for this phenomenon. A first interpretation consists in assuming that the effect was due to a systematic bias of the eye behavior towards the center of the visual display. When aiming for an isolated peripheral stimulus (or the center of it), the eyes would be deviated towards the center of the screen, as the position of the saccade target

would be estimated in a global screen reference framework. The second interpretation accounts for the effect obtained in Experiment 1 in terms of a range effect, or a systematic bias of the eye behavior towards the center of the range of possible stimulus locations. Since the initial fixation position was randomized within each block of trials in the first experiment, and that the range of possible stimulus locations covered the whole screen in the horizontal direction, subjects may have developed some kind of prototypical eye movement pattern that tend to send (or keep) the eyes nearby central stimulus locations. Such a strategy could not be at work in Experiment 2 since in that case, the initial fixation position was maintained constant in each block of trials. Experiment 3 aimed at distinguishing both interpretations.

4. Experiment 3

The purpose of Experiment 3 was to distinguish between a range-effect type account, and an external/visual account for the systematic effect of initial fixation position reported in the first experiment. It tested whether the effect could be replicated by varying between blocks of trials, the initial fixation position relative to the center of the screen, but keeping constant the initial position of the eyes in the orbit (i.e. at the straight-ahead location). The present manipulation was made possible by shifting the screen in a direction that was opposite to the deviation of the initial fixation stimulus relative to the center of the screen (when the initial fixation stimulus was to the left of the center of the screen, the screen was shifted to the right, and when the initial fixation stimulus was to the right of the center of the screen, the screen was shifted to the left). Only if a bias towards the center of the visual display was identified in Experiment 1, should this effect replicate in Experiment 3.

4.1. Methods

4.1.1. Participants

Eighteen individuals responding to the same recruitment criteria as in Experiments 1, and 2, participated in the experiment. All of them were unfamiliar with the purpose of the experiment, and only one of them had participated in the first experiment.

4.1.2. Material

The material was exactly identical to that used in Experiment 2.

4.1.3. Design

The design was similar to the one of Experiment 2.

4.1.4. Procedure

The procedure was similar to that used in Experiment 2, except that the initial fixation ‘+’ sign was presented at variable locations on the screen across blocks of trials, and that it was always centered on the straight-ahead position within, and between blocks of trials. The initial fixation stimulus was displayed at the center of the screen in the center condition, and it was presented at about 3.8° to the right, and to the left of the center of the screen in both right and left conditions respectively. The computer screen was presented at variable locations relative to the straight-ahead position depending on the block of trials. It was centered on the straight-ahead position in the center condition, and it was shifted by an angle of about 3.8° to the left and to the right in respectively right and left conditions. The calibration phase that preceded each block of trials was always made with the screen positioned the same way as in the corresponding block of trials. However, care was taken that the initial phase of the experiment which consisted in preparing the subject’s bite bar, as well as adjusting the eye tracker, was always made with the screen centered on the straight-ahead position.

4.1.5. Apparatus

This was identical to Experiment 2.

4.1.6. Data analysis

The data were selected and analyzed the same way as in Experiments 1 and 2. Again, the word frequency factor which had no reliable effect was not included in the reported analyses.

4.2. Results

Fig. 5a–f present the distribution of *initial landing sites* in 5-, 7-, and 9-letter strings and words, and separately for the different initial fixation positions (left, center, and right). In the left condition, initial landing sites were near the center of words and strings, but those shifted towards the very-beginning of words and strings as the initial fixation position got closer to the right border of the screen. In addition, initial landing sites depended on the peripheral stimulus length, getting further from the beginning of words or strings with longer stimuli. The effect of initial fixation position on mean initial landing sites was significant for words and strings ($F(2, 34) = 6.62$, $p < 0.005$, and $F(2, 34) = 7.21$, $p < 0.005$, respectively). The effect of stimulus length was also significant in words ($F(2, 34) = 60.03$, $p < 0.0005$), and strings ($F(2, 34) = 39.97$, $p < 0.0005$). The interaction was never significant ($F(4, 68) = 1.84$, $F(4, 68) = 1.04$).

The *mean absolute error* (or absolute distance of the initial landing position to the center of the word/string) also varied significantly with both initial fixation posi-

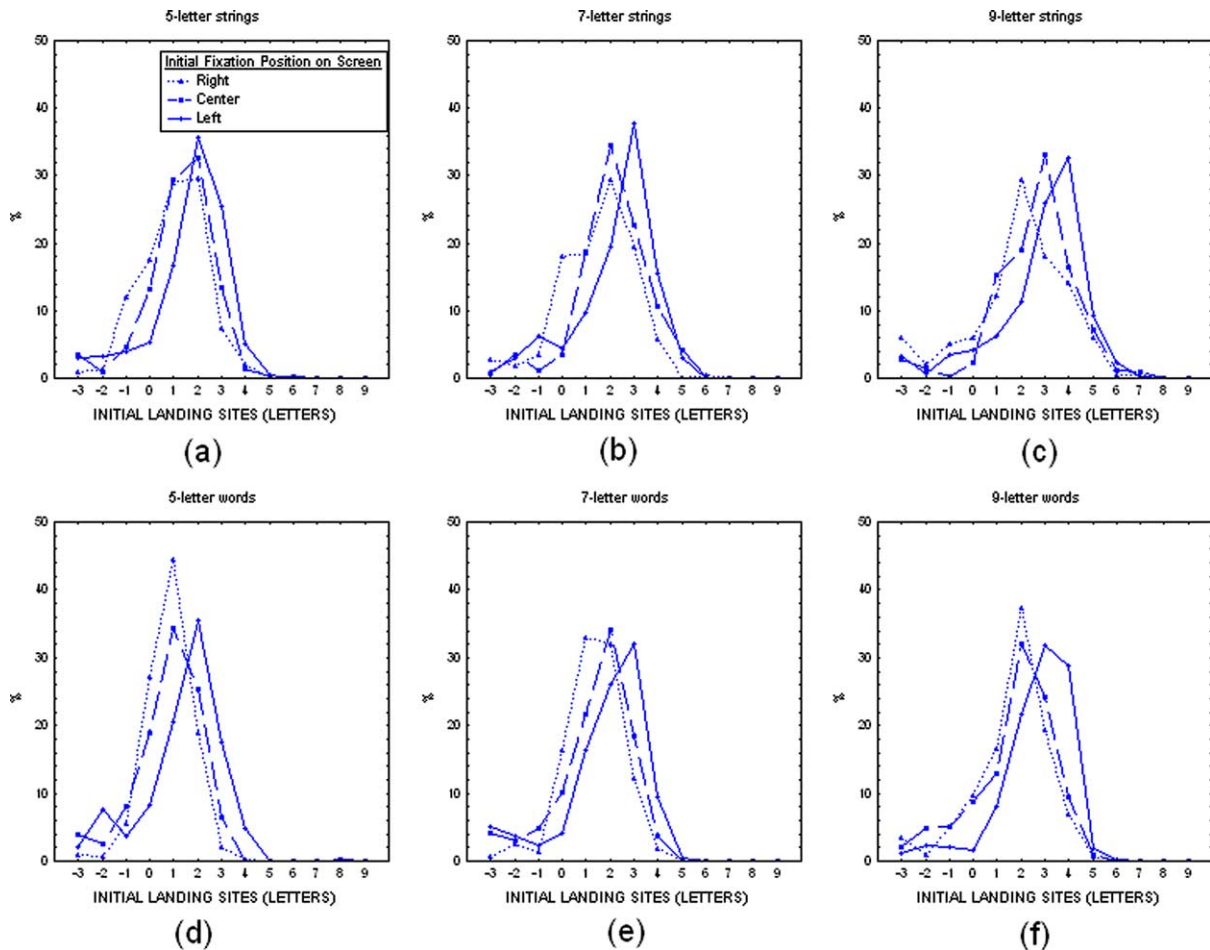


Fig. 5. Distribution of initial landing sites (in letters) in 5-, 7-, and 9-letter strings (a–c), and words (d–f), as a function of the initial fixation position relative to the center of the screen, in Experiment 3. Landing sites are expressed in number of letters from the beginning of the stimulus, with zero-, or negative values corresponding to initial landing sites on one of the five character spaces in front of the stimulus.

tion ($F(2, 34) = 19.58$, $p < 0.0005$, $F(2, 34) = 9.91$, $p < 0.0005$, respectively for words, and strings), and stimulus length ($F(2, 34) = 97.02$, $p < 0.0005$, $F(2, 34) = 60.93$, $p < 0.0005$, respectively for words, and strings). It became greater as the eyes were launched from a region closer to the right border of the screen, and the length of the peripheral stimulus increased (see Fig. 6a and b). A comparison between Figs. 6a and b, and 2a and b however reveals that the effect was a little less pronounced than in the first experiment, and that the eyes landed on average further from the center of words and strings than in Experiment 1.

Further analyses tested the influence of the initial fixation position on the *mean length of initial saccades*. Results presented in Table 4 (Panels A and B) show that when all initial saccades were considered for analysis, the effect of initial fixation position was not significant in either words or strings ($F(2, 34) = 1.87$, $F(2, 34) = 0.91$). However, a close examination at the distributions of initial saccade lengths (not presented here) revealed that for saccades shorter than 5 characters, the distri-

butions overlapped quite largely, and that in some instances the effect reversed. In contrast, for saccades of 5 characters or more, the distributions corresponding to center and right conditions were slightly shifted towards shorter saccades in comparison with the left condition distributions. The mean length of the initial saccades that were longer than 4 characters showed significant variations with initial fixation position at least for words ($F(2, 34) = 3.43$, $p < 0.05$), the effect being only marginally significant for letter strings ($F(2, 34) = 2.62$, $p < 0.10$). The effect of stimulus length was significant when either all saccades or only saccades longer than 4 characters were considered for analysis (for words: $F(2, 34) = 69.00$, $p < 0.0005$, $F(2, 34) = 67.83$, $p < 0.0005$; for strings: $F(2, 34) = 47.62$, $p < 0.0005$, $F(2, 34) = 51.48$, $p < 0.0005$).

As shown in Table 5 (Panels A and B), the *mean initial saccade launch sites* presented systematic deviations relative to the position of the initial fixation stimulus on screen. When the initial fixation cross was located in the left part of the screen, the eyes were slightly deviated to

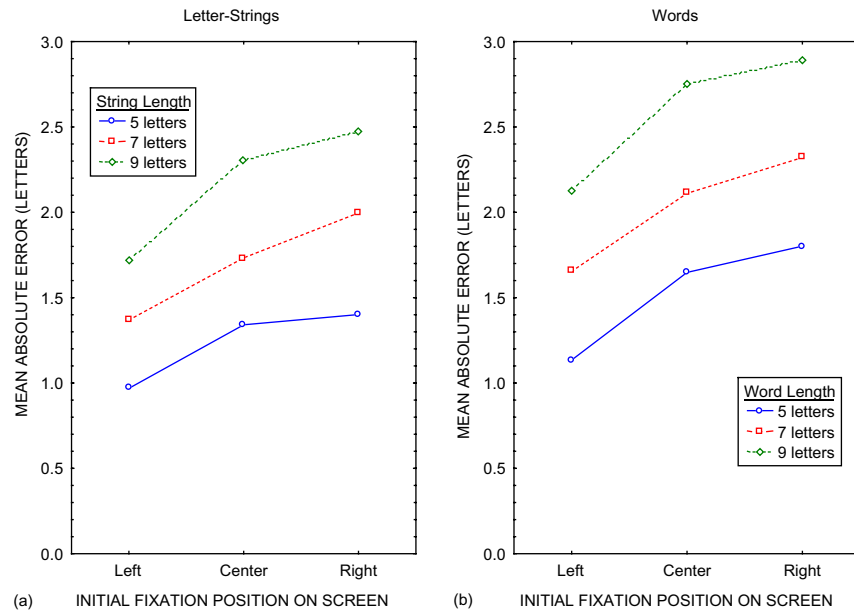


Fig. 6. Mean absolute error of the initial saccades (in letters) made towards 5-, 7-, and 9-letter strings (a), and words (b), as a function of the initial fixation position relative to the center of the screen in Experiment 3. The mean absolute error corresponds to the absolute distance of the initial landing position to the center of the word or string, but only in instances where the eyes initially landed within the word/string.

Table 4

Mean length of the initial saccades (in letters) for 5-, 7-, and 9-letter words, and strings, and for different initial fixation positions relative to the center of the screen (left, center, and right) in Experiment 3 (the analyses were based either on all data (Panel A), or only on saccades longer than 4 letters (Panel B))

	L	C	R
<i>Panel A</i>			
5-letter words	5.61	5.44	5.67
7-letter words	5.99	5.97	6.17
9-letter words	6.82	6.34	6.50
5-letter strings	6.12	5.94	5.88
7-letter strings	6.61	6.81	6.26
9-letter strings	7.19	7.22	6.75
<i>Panel B</i>			
5-letter words	6.04	5.78	5.81
7-letter words	6.52	6.37	6.31
9-letter words	7.07	6.69	6.68
5-letter strings	6.54	6.24	6.06
7-letter strings	6.94	7.02	6.60
9-letter strings	7.46	7.41	7.25

the right of the stimulus, and when the initial fixation cross was in the center or right part of the screen, the eyes were deviated to the left, the deviation being greater in the right than in the center condition. The effect of initial fixation position on mean launch sites was significant for words and strings ($F(2, 34) = 23.55$, $p < 0.0005$, $F(2, 34) = 17.27$, $p < 0.0005$), while the effect of stimulus length was never significant ($F(2, 34) = 0.11$, $F(2, 34) = 0.87$).

For the *mean latency of initial saccades*, these were in general slightly longer in the left condition compared to center, and right conditions (see Table 5 (Panels A and B)). However, the effect of initial fixation position was only marginally significant in words ($F(2, 34) = 2.63$, $p < 0.10$), and it was not significant in letter strings ($F(2, 34) = 1.52$). The effect of word length was never significant ($F(2, 34) = 0.51$, $F(2, 34) = 1.62$).

4.3. Discussion

The present experiment was an attempt to replicate the phenomenon observed in Experiment 1, but in conditions where only the initial fixation position relative to the center of the screen varied, and with the eyes being always initially directed at the straight-ahead position. Furthermore, to prevent subjects to adopt a range-effect type of strategy, initial fixation position was varied between, rather than within blocks of trials. Results clearly indicated an influence of the initial fixation position on the following eye behavior. First, there was a systematic deviation of the initial saccade launch site to the right of the fixation cross when it was displayed in the left region of the screen, and to the left of the initial fixation cross in the right and to a certain extent the center condition. Second, the initial landing position was closer to the center of words and strings in the left compared to center and right conditions.

Thus, the original bias of eye behavior that was reported in Experiment 1 could be replicated by varying only the initial fixation position relative to the center of the screen, which clearly suggests that this phenomenon

Table 5

Mean launch site (in letters), and mean latency (in ms) of the initial saccades for 5-, 7-, and 9-letter words (Panel A), and strings (Panel B), and for different initial fixation positions relative to the center of the screen (left, center, and right) in Experiment 3

	5-letter words/Strings			7-letter words/Strings			9-letter words/strings		
	L	C	R	L	C	R	L	C	R
<i>Panel A</i>									
Launch site	0.24	−0.17	−0.40	0.23	−0.15	−0.40	0.27	−0.15	−0.42
Saccade latency	230	220	220	224	217	223	246	219	213
<i>Panel B</i>									
Launch site	0.11	−0.17	−0.40	0.09	−0.24	−0.40	0.12	−0.23	−0.41
Saccade latency	250	242	237	254	257	237	256	255	237

was related in some way to a bias towards the center of the visual display. There were still a few differences with the original set of findings that need to be accounted for. First, the tendency for initial saccade length to decrease from left to right launch site regions was clearly present only for saccades longer than 4 characters, while it was present in all saccades in Experiment 1. Second, there was a trend for initial saccade latency to decrease from left to right conditions as in the first experiment, but this was not significant here. This discrepancy between both sets of data may originate from two different sources. First, it is possible that part of the effects reported in Experiment 1 were due to a range effect, or an oculomotor preference for stimuli located near the center of the range of possible stimulus locations. Indeed, such a strategy could only develop in the first experiment where the whole set of possible stimulus locations were mixed in a block of trials. At the same time, failure to exactly replicate the original effects may come from the fact that the position on the screen of the initial fixation stimulus was predictable from one trial to the next. This may have decreased the need to use on-line visual information for saccadic programming, and lead to a more variable eye movement pattern, or a weaker sensibility to global visual factors.

5. General discussion

To explore the possibility that the ocular behavior in reading is biased towards the center of the lines of text, a first experiment examined whether eye movements vary depending on where on the screen an initial fixation stimulus and a corresponding saccade target word or letter string are displayed. As in normal reading conditions, the screen was centered on participants' straight-ahead position, which means that the initial deviation of the eyes from the center of the screen corresponded to a similar deviation of the eyes in the orbit. In addition, the center of the screen corresponded approximately to the center of the range of possible stimulus locations in a block of trials. Results revealed the presence of a systematic bias of the eye behavior towards central loca-

tions with both words and letter strings as peripheral stimuli. First, initial saccades were greater in length, and they landed closer to the center of words and strings when they were launched from a region left of center than when they were launched from either center or right part of the screen. Second, the starting eye position or exact launch site of the initial saccades was deviated to the right of the initial fixation stimulus in leftward conditions, while it was deviated to the left in the right condition. Third, the latency of initial saccades decreased as the initial fixation position moved from the left to the center or right part of the screen.

To determine the origin of the observed phenomenon, two additional experiments were conducted where the position of the initial fixation stimulus was varied in reference to the straight-ahead position (Experiment 2), or in reference to the center of the screen (Experiment 3). Only the latter manipulation proved to be successful; this revealed again the presence of rightward deviations of the initial saccade launch sites and landing sites in the left condition compared to both center and right conditions. In contrast, varying the initial fixation position in reference to the straight-ahead position produced no consistent bias, suggesting therefore that the original bias did not result from extra-retinal (or eye position signal) influences. The observed phenomenon could neither be attributed to a range-effect type of strategy, or a preference to send the eyes near the center of the range of possible stimulus locations (see Kapoula, 1985; Poulton, 1981). Indeed, the effect was present when the initial fixation position varied within and between blocks of trials (as in Experiments 1, and 3, respectively). The reported effect must therefore be interpreted in terms of a systematic bias of the eye behavior towards the center of the visual display. The question now applies of the nature of the mechanisms that underlie this bias.

A first visuo-motor account envisages the effect in terms of a global effect, or tendency to move the eyes towards the center-of-gravity of the peripheral visual configuration (Coren & Hoenig, 1972; Findlay, 1982; Vitu, 1991). It assumes, in a manner similar to Findlay and Walker's (1999) model of saccade generation, that

all the visual information that is available on a given eye fixation contributes to some extent to the computation of the saccade amplitude. This would include not only the visual information carried out by the peripheral stimuli, but also the screen frame itself. The hypothesis of a large-scale center-of-gravity effect which suggests that the system does not succeed in isolating the saccade target object from the global visual context is however questionable. First, in the present experiments, the saccade target word or letter string could easily be distinguished from its surrounding since it was always presented in isolation, and in a predictable direction (i.e. it was always displayed to the right of the fixation point on the central horizontal line). Furthermore, as noted in one of our previous studies, only the stimuli contained in a limited area around the saccade target (referred to as attentional window) can deviate the eyes from their intended location (Vitu, 1991). On the other hand, if the observed phenomenon corresponded to some sort of center-of-gravity effect, then it should be reduced following prolonged saccade latencies (see Coëffé & O'Regan, 1987). Our data indicated on the contrary that the effect was of about the same amplitude following latencies between 200, and 250 ms, and between 250, and 300 ms (see Table 2). In addition, a deviation of the eye behavior towards the center of the screen occurred not only when aiming for the peripheral stimulus, but also when searching for the initial fixation stimulus, while in the latter case more time was spent positioning the eyes near the saccade target (the ultimate fixation in the region of the fixation cross was often preceded by a series of several small saccades).

An alternative, and more likely account for the systematic deviation of the eye behavior towards the center of the visual display relies on the assumption that for perceptual processes to be most efficient, eye movements must be contained within the part of the visual scene where stimuli are displayed (i.e. the screen). Under this assumption, the screen frame does not act as a distractor stimulus, but rather serves as a reference to localize or encode the position of the saccade target object. The target location, and the corresponding saccade amplitude would be computed in relative coordinates, or in reference to the screen frame, thereby ensuring that the eyes do not go beyond the limits of the visual display, but constraining at the same time, the eye movement pattern. A screen-based localization and/or eye guidance process may first influence where the eyes are going to be sent, and produce systematic deviations of the saccadic eye movements towards the center of the visual display. This may also result, when the eyes are relatively close to the border of the screen (as in the extreme-left, and to a certain extent the left conditions of Experiment 1), in the execution of short-latency saccades that quickly take the eyes away from that position. However, since these saccades land at random and mostly inappropriate lo-

cations (i.e. the large space in front the peripheral word/string—see Fig. 1a–f), they may need to be suppressed, which would in turn lengthen saccade latency compared to when the eyes are launched from less extreme screen locations (see Becker & Jurgens, 1979).

The present screen-frame reference view is in accordance with previous accounts for the perception of direction, which state that estimation of stimulus location in space relies mostly on retinal information, and relative rather than absolute positional judgments (see O'Regan, 1984; see also, Matin, 1972; Matin & Kibler, 1966). The possibility that the visual surround frame serves as a reference in direction judgements was also envisaged by Findlay (1974), but, according to his view, this would occur only after long delays (at least 350 ms), direction perception being estimated in the first place on the basis of eye position signals relative to the execution of microsaccades. Our data did not allow us to determine the exact timing of the observed bias, but the data presented in Table 2 reveal that visually- or screen-based modulations of initial landing sites in words and strings were already present at a delay of about 200 ms following the presentation of the peripheral stimulus. In addition, the data obtained in Experiment 2 indicated that extra-retinal information was not responsible for the observed bias, suggesting therefore that perceptuo-motor biases can be produced by visual information alone.

Further research will determine whether a systematic bias of the eye behavior towards the center of the visual display (or the center of the lines of texts) generalize to natural text reading, and how much it contributes to the variability of saccade lengths and fixation durations. Several arguments actually support the idea that the present findings may extend to natural reading. First, the conditions that provided the larger effects (Experiment 1) were close to the visual conditions which characterize text reading: the center of the screen corresponded to the reader's straight-ahead position, and both the length of the words and the position of the eyes relative to the center of the screen before each saccade were unpredictable. Second, as indicated in past research, several eye movement patterns observed in isolated word paradigms do generalize to text reading situations, even though these may get slightly weaker (see Vitu et al., 1990). Finally, and in accordance with the present findings, it was previously reported in a sentence reading experiment, that the initial words on a line are read more slowly than the later words (Ferreira & Henderson, 1993).

In conclusion, the position of the eyes in the visual display appears to be a critical factor in determining where the eyes are sent with respect to a peripheral word or letter string. The mechanisms that underlie the effect are unclear at present, but the effect strongly suggests that perceptual localization and/or saccade computation

processes are made in reference to the visual frame. The present findings may also provide additional evidence for a low-level visuo-motor basis of eye guidance in reading (see Vitu, 1991; Vitu et al., 1995), although this will need to be confirmed with further investigations.

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References

- Becker, W. (1972). The control of eye movements in the saccadic system. *Bibliotheca Ophthalmologica*, 82, 233–243.
- Becker, W., & Jurgens, R. (1979). An analysis of the saccadic system by means of double step stimuli. *Vision Research*, 19, 967–983.
- Brysbaert, M., & Vitu, F. (1998). Word skipping: implications for theories of eye movement control in reading. In G. Underwood (Ed.), *Eye guidance in reading, driving, and scene perception* (pp. 125–147). Oxford: Elsevier.
- Coëffé, C., & O’Regan, J. K. (1987). Reducing the influence of non-target stimuli on saccade accuracy: predictability and latency effects. *Vision Research*, 27, 227–240.
- Coren, S., & Hoening, P. (1972). Effects of non-target stimuli upon length of voluntary saccades. *Perceptual and Motor Skills*, 34, 499–508.
- Cornsweet, T. N., & Crane, H. D. (1973). Accurate two-dimensional eye tracker using first and fourth Purkinje images. *Journal of the Optical Society of America*, 63, 6–13.
- Deubel, H., Wolf, W., & Hauske, G. (1984). The evaluation of the oculomotor error signal. In A. G. Gale & F. W. Johnson (Eds.), *Theoretical and applied aspects of eye movement research* (pp. 55–62). Amsterdam: North Holland.
- Dunn-Rankin, P. (1978). The visual characteristics of words. *Scientific American*, 238, 122–130.
- Eggert, T., & Kapoula, Z. (1995). Position dependency of rapidly induced saccade disconjugacy. *Vision Research*, 35(23/24), 3493–3503.
- Ferreira, F., & Henderson, J. (1993). Reading processes during syntactic analysis and reanalysis. *Canadian Journal of Experimental Psychology*, 47(2), 247–275.
- Findlay, J. M. (1974). Direction perception and human fixation eye movements. *Vision Research*, 14, 703–711.
- Findlay, J. M. (1982). Global visual processing for saccadic eye movements. *Vision Research*, 22, 1033–1045.
- Findlay, J. M., & Kapoula, Z. (1992). Scrutinization, spatial attention, and the spatial programming of saccadic eye movements. *The Quarterly Journal of Experimental Psychology*, 45A(4), 633–647.
- Findlay, J., & Walker, R. (1999). A model of saccade generation based on parallel processing and competitive inhibition. *Behavioral and Brain Sciences*, 22(4), 661–720.
- Frost, D., & Pöppel, E. (1976). Different programming modes of human saccadic eye movements as a function of stimulus eccentricity: indications of a functional subdivision of the visual field. *Biological Cybernetics*, 23, 39–48.
- Heywood (1973). Assymetries related to cerebral dominance in returning the eyes to specified target positions in the dark. *Vision Research*, 13, 81–94.
- Howard, I. P. (1982). *Human visual orientation*. Chichester: John Wiley & Sons.
- Just, M. A., & Carpenter, P. A. (1980). A theory of reading: from eye fixations to comprehension. *Psychological Review*, 87, 329–354.
- Kapoula, Z. (1985). Evidence for a range effect in the saccadic system. *Vision Research*, 25(8), 1155–1157.
- Kapoula, Z., & Robinson, D. A. (1986). Saccadic undershoot is not inevitable: saccades can be accurate. *Vision Research*, 26(5), 735–743.
- Kowler, E., Pizlo, Z., Zhu, G.-L., Erkelens, C. J., Steinman, R. M., & Collewijn, H. (1991). Coordination of head and eyes during the performance of natural (and unnatural) visual tasks. In A. Berthoz, W. Graf, & P. P. Vidal (Eds.), *The Head-Neck Sensory Motor System*. N.Y.: Oxford University Press.
- Leigh, J. R., & Zee, D. S. (1999). *The neurology of eye movements*. New York, Oxford: Oxford University Press.
- Matin, L. (1972). Eye movements and perceived visual direction. In H. Autrum et al. (Eds.), *Handbook of sensory physiology. Vol. 7/4: Visual psychophysics*. Berlin: Springer-Verlag.
- Matin, L., & Kibler, G. (1966). Acuity of visual perception of direction in the dark for various positions of the eye in the orbit. *Perceptual and Motor Skills*, 22, 407–420.
- McConkie, G. W., Kerr, P. W., Reddix, M. D., & Zola, D. (1988). Eye movement control during reading: I. The location of initial eye fixations on words. *Vision Research*, 28(10), 1107–1118.
- O’Regan, J. K. (1979). Eye guidance in reading. Evidence for the linguistic control hypothesis. *Perception and Psychophysics*, 25, 501–509.
- O’Regan, J. K. (1984). Retinal versus extraretinal influences in flash localization during saccadic eye movements in the presence of a visible background. *Perception & Psychophysics*, 36(1), 1–14.
- O’Regan, J. K. (1990). Eye movements and reading. In E. Kowler (Ed.), *Eye movements and their role in visual and cognitive processes* (pp. 395–453). Elsevier.
- O’Regan, J. K. (1992). Optimal viewing position in words and the strategy-tactics theory of eye movements in reading. In K. Rayner (Ed.), *Eye movements and visual cognition: scene perception and reading* (pp. 333–354). New York: Springer-Verlag.
- Poulton, E. C. (1981). Human manual control. In V. B. Brooks (Ed.), *Handbook of physiology* (Vol. II, Part 2, pp. 1337–1389). Baltimore, MD: Am. Physiol. Soc., Williams & Wilkins.
- Rayner, K. (1979). Eye guidance in reading: fixation location within words. *Perception*, 8, 21–30.
- Rayner, K., & Fischer, M. H. (1996). Mindless reading revisited: eye movements during reading and scanning are different. *Perception & Psychophysics*, 58(5), 734–747.
- Reichle, E. D., Pollatsek, A., Fisher, D. L., & Rayner, K. (1998). Toward a model of eye movement control in reading. *Psychological Review*, 105(1), 125–157.
- Seo, H., & Lee, C. (2002). Head-free reading of horizontally and vertically arranged texts. *Vision Research*, 42, 1325–1337.
- Trésor de la Langue Française (1971). Nancy: CNRS.
- Van Rensbergen, J., & de Troy, A. (1993). *A reference guide for the Leuven dual-PC controlled Purkinje eyetracking system*. Technical

- Report, Laboratory of Experimental Psychology, Catholic University of Leuven.
- Vitu, F. (1991). The existence of a center of gravity effect during reading. *Vision Research*, *31*(7/8), 1289–1313.
- Vitu, F. (1993). The influence of the reading rhythm on the optimal landing position effect. In G. d'Ydewalle & J. Van Rensbergen (Eds.), *Perception and cognition: advances in eye movement research* (pp. 181–192). Amsterdam: North Holland.
- Vitu, F., McConkie, G. W., Kerr, P., & O'Regan, J. K. (2001). Fixation location effects on fixation durations during reading: an inverted optimal viewing position effect. *Vision Research*, *41*(25–26), 3511–3531.
- Vitu, F., O'Regan, J. K., Inhoff, A. W., & Topolski, R. (1995). Mindless reading: eye movement characteristics are similar in scanning strings and reading texts. *Perception & Psychophysics*, *57*, 352–364.
- Vitu, F., O'Regan, J. K., & Mittau, M. (1990). Optimal landing position in reading isolated words and continuous text. *Perception & Psychophysics*, *47*(6), 583–600.
- Viviani, P., & Swensson, R. G. (1982). Saccadic eye movements to peripherally discriminated visual targets. *Journal of Experimental Psychology: Human Perception and Performance*, *8*(1), 113–126.
- Zingale, C., & Kowler, E. (1987). Planning sequences of saccades. *Vision Research*, *27*(8), 1327–1341.