Reference frames in reading: evidence from visually and memory-guided saccades

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Abstract

In order to examine the frames of reference used for the planning of inter- and intra-word saccades, subjects were required to execute a two-saccade sequence toward one or two words. The first saccade was visually guided while the second saccade was visually or memory-guided. Results demonstrate that readers hold an internal representation of the target word in at least two different reference frames that are specific to the action to be performed: to aim for a new target word or to read it over with a second fixation. When a word is selected as a target for the next saccade, the spatial location of the second word is stored in memory. Then, the second saccade is updated with respect to the current eye position in the first word in order to aim a functional target location in the second word that is the word's center. When the second saccade is directed within the fixated word, the saccadic system uses the intrinsic features of the word to code a fixed-motor vector relative to the word's length. Our present results demonstrate that readers hold an internal representation of the saccade target in different reference frames specific to the action performed on the word. © 2001 Elsevier Science Ltd. All rights reserved.

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1. Introduction

To make an eye movement toward a remembered object, the location of the object has to be stored in memory. Accurate eye movements to remembered locations are possible (Becker & Fuchs, 1969; Gnadt, Bracewell, & Andersen, 1991; Karn, Moller, & Hayhoe, 1997). Memory representations of spatial information can be maintained in egocentric (relative to the observer's eye, head or body) or exocentric (relative to relations between objects or parts of an object) reference frames. Most of what we know, however, concerning the use of memory in guiding eye movements comes from highly structured, unnatural tasks in sparse environments. We know very little about the nature of the representations used to guide saccadic movements in the context of natural tasks. How sequential saccades are programmed and maintained in memory and the

exact role of visual signals remains unclear. The experiment described in this paper examined the nature of the memory representations in the production of two-saccade sequences in a reading-like situation.

In a complex visual environment, the location of the saccadic target may be rediscovered from its spatial relation relative to other objects or different parts of the object. The ability to make use of spatial information defined in an object-centered reference frame has been seen in the guidance of eye movements in reading. Early visual processes parse the text stimulus into word-objects (McConkie & Zola, 1987) and a specific location of the word-centered representation, the word's center, is selected as the saccade target (Mc-Conkie, Kerr, Reddix, & Zola, 1988). Exocentric representations are recognized as playing a crucial role in object identification and recognition. Recent works by Hayhoe, Lachter, and Moller (1992), Karn et al. (1997), and Dassonville, Schlag, and Schlag-Rey (1995) demonstrate the role of exocentric cues in oculomotor spatial accuracy. In the study of Hayhoe et al., the subject's

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task was to saccade toward two short-duration visual stimuli when one of the stimuli was lit up again. When the location of the re-lit stimulus was slightly shifted, the subject's localization of the remembered stimulus was similarly shifted, albeit to a lesser extent than the actual shift of the stimulus. The authors conclude that when egocentric and exocentric cues are discordant, oculomotor localization relies on a combination of the two. The physiological basis of exocentric encoding was recently provided by Olson and colleagues, who have given direct evidence for the existence of neurons in the supplementary eye field coding specific locations of parts relative to an object (Olson & Gettner, 1995; Olson, Gettner, Ventura, Carta, & Kass, 2000).

Memory representations of spatial information could be maintained in egocentric reference frames, as their origins are within the observer's body. There has been much debate on the nature of egocentric reference frames. A simple target casts an image on the retina in a location that is directly related to the saccade required to fixate the target. A retina-centered representation seems to be all that is necessary to direct an eye movement to a single target. However, in a delayed-double-task experiment, in which an observer memorizes two consecutively flashed targets and plans two saccades to the targets, the movement to achieve the second target is different from the earlier retinal location of the target. In order to program the second saccade accurately, the retinotopic representation maintained in memory has to be updated after the first eye movement. This is achieved by what appears to be a vector subtraction of the last saccade made, from target's retinal image position (Goldberg & Bruce, 1990; Goldberg & Segraves, 1989). Such an updated retina-centered representation has been found in the monkey parietal cortex where certain neurons perform an anticipated updating of target locations before an impending movement (Duhamel, Colby, & Goldberg, 1992). However, the fact that saccades accurately reach the second flashed target has been taken as evidence that the absolute target location is coded in head-centered coordinates, that is, with respect to the head at the time the target is presented. Using information in a head-centered representation requires access to an accurate, real-time estimate of the eye position in the orbit (Hallet & Lightstone, 1976; Hansen & Skavensky, 1977; Viviani & Velay, 1987; Mays & Sparks, 1980; Sparks & Mays, 1983). Recently, Andersen and his colleagues provided an alternative explanation of the updating mechanism. They refer to a representation in motor coordinates specifying the direction and amplitude of the movement rather than the locations of visual stimuli (Snyder, Batista, & Andersen, 1997; Andersen, Snyder, Bradley, & Xing 1997). In a recent neural network modeling memory activity in macaque lateral intraparietal cortex (Xing & Andersen, 2000), the motor command of the second saccade in a memory double-saccade task is achieved by different neuronal populations rather than by a dynamical updating of the same neuronal population. One group of neurons encodes the location of the second target in head-centered coordinates during the execution of the first saccade. Then, the other group of neurons computes the motor coordinates of the second saccade before its execution by combining the second target position with the new eye position.

In our experiment, we investigate the reference frame used in saccade targeting while a reader performs a two-saccade sequence. We sought to gain some insight into the special case in which eye movements are made to remembered locations of a second saccade target. The first saccade was visually guided while the second saccade was visually or memory-guided. Therefore, we must assume that the brain is able to hold some form of spatial representation of oculomotor targets, which is not dependent on the presence of targets. Little is understood about the form of these representations. These representations could exist in terms of retino-, head- or oculocentric coordinates, which do not require the physical presence of the stimulus. Or they could exist in object-centered coordinates independent of retinal or motor parameters. Furthermore, these representations may not to be mutually exclusive. We reasoned that if the memory trace encodes the location of a specific second target in a retina-centered frame, there should be an updating of the remembered location of the second target to account for the first saccade. Alternatively, if the memory trace is encoded in motor coordinates as a fixed-vector for a certain distance, the first fixation position error should be propagated on the second fixation position. Previous experiments done in our lab suggest that the representations used in saccade programming in reading differ for intra-word saccades, which are made when a word is read with a second fixation, and inter-word saccades directed to another target word selected in the periphery (Beauvillain, Dukic, & Vergilino, 2000; Vergilino & Beauvillain, 2000). In our experiment, the respective length of the stimuli makes it possible to compare the accuracy of targeting saccades as the second saccade was directed at a second position on the currently fixated word or at another word. Moreover, we varied the length of the stimuli. Thus, the one-word condition consisted of a nine- or an 11-letter word while the two-word condition consisted of an initial five-letter word followed by a four- or by a six-letter word.

2. Experiment

2.1. Method

2.1.1. Subjects

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

2.1.2. Procedure

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

The sequence of events during one experimental trial was as follows: (a) Subjects had to fixate a calibration bar displayed 6° to the left of the center of vision; (b) When the computer detected an accurate fixation on the bar, the bar disappeared and a cross was displayed at one of 10 different positions between 6° and 1° to the left of the center of vision. Subjects had to fixate the cross until it disappeared. If the computer detected a saccade before the fixation cross disappeared, the trial was discarded. When the cross disappeared, stimuli were displayed at a visual angle of 1°30 to the right of the fixation cross. In the one-word condition, two different lengths of stimuli were used: nine- or 11-letter words. In the two-word condition, the first word was a five-letter word and the second word, separated by one blank space from the end of the first word, was either a four- or a six-letter word. The disappearance of the cross was the signal to move the eyes towards the target words; (c) *In the visually guided trials*, the subjects read the words and then pressed a button. *In the memory-guided trials*, the words were erased when the primary saccade crossed a boundary located at two character spaces from the cross. Then, subjects had to execute a second saccade toward the remembered location of the second word or toward a second position in the memorized long word. Words reappeared 400 ms after the eye crossed an invisible boundary located at 7.5 character spaces from the cross, thereby providing the subject with feedback about his performance. The subjects had to press a button. If the subject did not execute a second saccade, the words reappeared after 2 s; (d) The words were erased and a fixation bar was displayed 6° to the right of the center of vision. The next trial began.

For each session, the presentation order of the visually and memory-guided trials was random. Moreover, 50% of the trials were fillers aimed at preventing subjects from learning a regular sequence of saccades. Different lengths of fillers were used: three-, five- and seven-letter words in the two-word condition and eight- or 13-letter words in the one word condition. In these filler trials, the location of the fixation cross, the eccentricity of the words from the fixation cross, and the number of blank spaces between the two words varied.

Subjects were instructed to read the words in the visually guided trials and to make eye movements as if they read the words that have disappeared in the memory-guided condition. Subjects were trained before the experimental block in 80 trials that had the same characteristics as the test trials. During this training period, feedback was given to the subjects about the occurrence of memory-guided saccades in the removed stimuli, as they were frequently unaware of making a second memory-guided saccade. Three subjects were discarded who felt the memory trials were too difficult.

2.1.3. Design

The design was a 2*2*2 factorial design, in which the Type of saccade (visually or memory-guided), the Type of stimuli (one- or two-word cases), and the Length of the sequence (nine letters for the five-then-four-letter words and the nine-letter words and, 11 letters for the five-then-six-letter words and the 11-letter words) were within-subject factors. Each subject was exposed to the eight conditions, but no subjects saw the same word more than once. All conditions were mixed within the experimental session and items were presented in random order.

2.1.4. Materials

Stimuli consisted of 240 five-letter French words and 120 four-, six-, nine- and 11-letter French words. In the one-word condition stimuli consisted of nouns and in the two-word condition of a five-letter noun followed by a four- or a six-letter adjective that was semantically related to the first noun. Low-frequency words were selected in order to obtain a great majority of two-fixation cases in the one-word condition. Frequencies were estimated using the printed frequency counts in the Trésor de la langue Française (1971), calculated on a 38 million-word corpus. The five-letter words of the two-word condition were matched in frequency to the nine- and 11-letter words. The mean frequency was 52 with a frequency range between 1 and 200. The mean frequency of the four-, and six-letter words of the two-word condition were 1647. For the two-word conditions, two experimental lists were formed so that each five-letter word associated with a four- and a six-letter adjective that were matched in frequency was not presented in the same experimental list. Each par-

ticipant was randomly assigned to one experimental list. Fillers consisted of 240 seven-letter French words and 120 five-, three-, eight- and 13-letter French words. Each subject performed 960 trials into four separate experimental sessions of 240 trials each. One hundred and twenty experimental trials and 120 filler trials were presented in each experimental session.

2.1.5. Apparatus

Stimuli were presented on a Hewlett Packard 1310A CRT (P15 phosphor) interfaced with a fast graphic system providing a frame frequency of 1000 Hz for stimulus display. The P15 phosphor of the scope does not produce any measurable persistence even when the observers were fully dark-adapted, as previously shown (Groner, Groner, Müller, Bischof, & Di Lollo, 1993; Di Lollo, Seiffert, Burchett, Rabeeh, & Ruman, 1997). Moreover, stimuli were displayed at a low level of luminance in order to reduce the phosphor persistence and allow the reading of words in the visually guided trials. The apparent luminance of the letter line was 0.28 cd/m². A LS-110 Minolta photometer was used to control the luminance of the letter line before each experimental session. As the brightness of letters also depend on the number of pixels, an algorithm is used to control the letter line luminance as a function of the number of pixels of the different letters. Thus, the brightness of the different letters was equalized. One character subtended 30 min of visual angle. In the two word experimental trials, the words were separated by one blank space.

Eye movements were monitored using a Bouis Oculometer System. The eye tracker had an absolute resolution of 6 min of arc 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 & Beauvillain, 1995). In the memory-guided trials, stimuli disappeared in less than 5 ms after the primary saccade crossed the boundary located at two character-spaces from the fixation cross, that is about 10 ms before the saccade ending.

3. Results

Trials in which accurate measurements of the eye position could not be made (5%) and trials in which blinks occurred (3%) were discarded. Note that the number of trials in which eye position measurement was not precise enough was greater than usually observed in our previous experiments. This seems to be due to the darkness condition, which made it more difficult to do the calibration procedure due to eye fatigue experienced by the subjects. In all, 8% of the trials were excluded from the analysis, reported below.

3.1. Probability of landing on the words

The main focus of our data analysis concerns the second saccade of the sequence, which could be visually

Table 1
Probability (%) of making or not a second fixation on the different word spaces in the two- and one-word conditions for visually and memory-guided saccades

		N	No. 2nd saccade	Probability of making a second fixation		
				On the first word	On the second word	Beyond the second word
Two-word condition						
Visually guided saccades	Five-/four-letter words	568	4	10	86	0
	Five-/six-letter words	592	4	7	89	0
Memory guided saccades	Five-/four-letter words	507	4	24	65	7
	Five-/six-letter words	543	3	19	71	7
One-word condition				On the word		Beyond the word
Visually guided saccades	Nine-letter words	518	8	91		1
	11-letter words	564	4	95		1
Memory guided saccades	Nine-letter words	531	9	84		7
	11-letter words	543	8	86		6

N represents the total number of observations in the different conditions.

or memory-guided. Most subjects had the impression that they were not able to execute the memory-guided saccade. However, as seen in Table 1 that gives the ocular behavior of the subjects for the two- and one-word cases, subjects execute a second memory-guided saccade in about 95% of the cases. For the two-word cases, the second saccades either refixated the first word, or landed on the second word, or skipped the second word. Among the visually guided saccades, 88% landed on the second word; only 68% did so for the memory-guided saccades $[F(1, 11) = 18.09; P < 0.001]$. This difference can be largely explained by the increase of 13% in the probability of refixating the first word for the memory-guided saccades as compared to the visually guided ones $[F(1, 11) = 11.49; P < 0.005]$. Subjects failed to reach the second word, their saccades landing at the end of the first word. Such effect was more marked when the five-letter word was followed by a four- than by a six-letter word $[F(1, 11) = 7.32; P < 0.01]$. Moreover, subjects tended to skip the second word on the memory-guided saccades (7%) whereas this behavior was not observed on the visually guided ones $[F(1, 11) = 3.23; P < 0.09]$. Together, these results are related to the decay of the memory trace of the second word. For the one-word cases, eye behavior on the memory-guided saccades was not very different from that observed on the visually guided saccades. However, the probability of refixating the word decreased by about 8% on the memory-guided saccades $[F(1, 11) = 5.79; P < 0.03]$. This was mainly due to the fact that saccades landed more frequently beyond the word ending in memory- than in visually guided conditions. However, this effect was not reliable $[F(1, 11) = 2.09;$ Ns]. Moreover, no length effect was found on the probability of refixating the word $[F < 1,$ Ns].

This initial analysis shows that the absence of visual information does not impede the triggering of saccades. Visual information, however, seems to have been more crucial for guiding the movement in two-word than in one-word cases. In the two-word cases, compensation for the lack of visual information is provided by extraretinal information about the eye's position in the orbit after the first saccade and by the remembered location of the two words. Several sources of errors due to the decay of the memory trace and an inaccurate eye position signal may contribute to the eye movement behavior.

3.2. Systematic and variable errors on the second saccade

It is commonly accepted that memory-guided saccades are usually less accurate than visually guided saccades (Krappmann, 1998; Zingale & Kowler, 1987), due to both systematic and variable errors. Systematic errors consist in a spatial distortion with saccades usu-

ally hypermetric whereas variable errors consist in a greater dispersion of the data around this mean (White, Sparks, & Stanford, 1994; Gnadt et al., 1991). However, specific hypotheses could be advanced about the systematic and variable errors, relative to the reference frame used in the targeting eye movements. First, concerning the systematic errors, an updating mechanism is expected to reduce the hypermetry of the memory-guided saccade, since a precise location is aimed for as the target for the saccade. If, however, the second saccade is coded as a fixed-vector without any precise target location, the hypermetry might be more important. Then, the only signal for the saccade is a displacement of the eye for a certain distance in the orbit. Second, the errors resulting from an updating mechanism are expected to show up in the variability of targeting eye movements. The variation resulting from the updating mechanism is added to the other sources of variability that include error in localizing the image on the retina, memory decay during the first fixation, and motor error in the eye movement itself (see Karn et al., 1997, for a good discussion on this point).

Mean second saccade amplitudes tell us whether there is any bias in the metrics of memory-guided saccades as compared to visually guided saccades, whereas standard deviations inform us about the variability in the targeting eye movements (see Table 2).

This analysis was done on the overall data, excluding the very large saccades landing beyond one character space after the end of the remembered stimuli. These saccades that occurred in the same proportion for the two-word than the one-word cases (see Table 1) were triggered when the observer did not know where he directed his eyes. Globally, the mean amplitude was not found to be larger for memory- than for visually guided saccades $[F(1, 11) = 0.67,$ Ns]. However, this effect depended on the type of stimuli $[F(1, 11) = 5.76; P < 0.03]$. Whereas no difference was found between the amplitude of visually and memory-guided saccade for the two-word cases $[F < 1,$ Ns], an hypermetry clearly appeared for the one-word cases $[F(1, 11) = 5.74; P < 0.03]$.

It is of interest to examine from the landing position data if the memory trace codes the length of stimuli displayed before the primary saccade. As seen in Table 2, the word length effect caused landing positions that were farther to the right in six-letter words than in four-letter words $[F(1, 11) = 42.89; P < 0.0005]$ and a second fixation position with a greater rightward shift in 11-letter words than in nine-letter words $[F(1, 11) = 124.46; P < 0.00005]$. Interestingly, this effect did not depend on the type of visually or memory-guided saccades being executed $(F < 1)$. The word length effect observed on the visually guided saccades was significant for one and two-word cases $[F(1, 11) = 99.64; P < 0.00005$ and $F(1, 11) = 53.81; P < 0.00005,$ respec-

Table 2
Mean fixation positions, amplitudes of the second visually and memory-guided saccades

	Five-/four-letter words		Five-/six-letter words		nine-letter words		11-letter words	
	Visually guided saccades	Memory-guided saccades	Visually guided saccades	Memory-guided saccades	Visually guided saccades	Memory-guided saccades	Visually guided saccades	Memory-guided saccades
Fixation position of the second saccade	2.14 (0.96)	1.92 (1.73)	3.00 (1.09)	2.98 (2.01)	6.28 (0.98)	6.64 (1.42)	7.09 (1.11)	7.84 (1.76)
Amplitude of the second saccade	5.46 (0.81) [0.15]	5.17 (1.63) [0.32]	6.23 (0.82) [0.13]	6.14 (1.88) [0.32]	3.44 (0.68) [0.21]	3.84 (1.29) [0.35]	4.25 (0.83) [0.20]	4.91 (1.56) [0.34]

Average of standard deviations calculated for each subject in brackets and average of absolute standard deviations calculated for each subject in square brackets for the one- and two-word conditions. The data are given in character-spaces.

tively]. The word length effect was also observed for the memory-guided saccades despite the greater dispersion of the data [$F(1, 11) = 20.43$; $P < 0.0009$ and $F(1, 11) = 74.60$; $P < 0.00005$ for the one- and two-word cases]. This shows that stimulus length is stored in memory and used to compute the eye movement towards remembered targets.

To estimate the variable error of the inter- and intraword saccades, the absolute standard deviation of the second saccade amplitude was calculated separately on each subject. As expected, the variable error was smaller for visible than remembered targets [$F(1, 11) = 60.66$; $P < 0.00005$]. The precision was slightly better for the two-word than for the one-word cases [$F(1, 11) = 7.84$; $P < 0.01$]. These factors did not interact at a significant threshold [$F(1, 11) = 2.59$; $P < 0.13$]. Recall that a mechanism for updating the location of the remembered stimulus predicts higher variable errors than a mechanism that codes the memory trace as a fixed-vector. In fact, no difference was found between the absolute variable error for memorized intra and inter-word saccades ($F < 1$).

To summary, the hypermetry of the memorized intra-word saccades gives evidence for a coding of a fixed-vector, whereas the absence of hypermetry in the memorized inter-word saccades suggests the presence of an updating mechanism for the two-word cases. However, such an updating mechanism does not show up the variable error.

3.3. Relationship between first and second fixation position

Results presented above seem to indicate two different reference frames in the programming of inter- and intra-word saccades. The updating mechanism posits that the memory target is updated after the first saccade. If such an updating mechanism were in use, we would expect the oculomotor system to correct the first fixation position error in order to aim for the second target position. It is possible to find such a mechanism in reading, given that the word's center has been shown to be the functional target position for the primary saccade directed to a word (McConkie et al., 1988). However, if motor commands are stored without any updating after the first saccade, the first fixation position error should be propagated onto the second fixation position. This second mechanism may be used in reading, since previous experiments have shown that the saccade directed to a second location in the word, i.e. the intra-word saccade, is coded as a fixed vector, irrespective of the first fixation position (Vergilino & Beauvillain, 2000). Moreover, it was shown that this saccade was calculated on the basis of word length. An updating mechanism hypothesis predicts a slope of 0 between the first and second fixation positions. A prop-

agation error mechanism predicts a slope of 1 between the first and the second fixation position. In order to test precisely these hypotheses, the following analysis was done by selecting trials in which the second saccades landed on the second word for the two-word cases and on a second location on the same word for the one-word cases.

Interestingly, as seen in Fig. 1, two types of pattern emerge in the relationship between the first and the second fixation position measured from the center of the words depending on the type of stimuli. However, the measure of the errors on the first and the second fixation position from different reference locations for the one- and two-word cases does not affect the slope of the relation.

For one-word cases, slopes on visually and memory-guided saccades that are near 0.9 argue in favor of a propagation error mechanism (Fig. 1c, d). The same relation between the first and the second position error can be seen in visually and memory-guided trials without any influence of the first fixation position. This indicates that the oculomotor system doesn't correct the first position error. The eyes are sent a certain distance, regardless of initial fixation locations. As shown by the b parameter of the regression function, this distance is computed on the length word. For two-word cases, the slopes were 0.4 on memory-guided saccades and 0.6 on visually guided saccades (Fig. 1a, b). This shows that, for memory-guided saccades, extraretinal feedback is used to estimate the consequences of the first eye movement and aim the remembered second word's center. The observed slopes indicate that, for visually and memory-guided saccades alike, the second saccade does not perfectly correct the first fixation position error. Mainly, the correction seems to be better on memory-guided trials as the slope nears to 0. A sliding window technique was used to precise the relationship between the first and second fixation position errors for the two-word cases. The data were collapsed across the two length conditions since very similar relationships were found between the first and second fixation position in the five-then-four-letter and -six-letter words. The data were sorted by the size of the first position error as measured from the word's center. The window was defined by the 100 largest position errors. For this window, the means of the first and second position errors were calculated. Then, the window was stepped by an increment of one first-position-error and at each new position, the mean first and second position errors were calculated for the 100 cases contained within the window (Fig. 2).

Very interestingly, the second memorized saccade was near the second word's center even for the largest first fixation errors. Visually guided saccades were found to be influenced more by the launch site of the saccade. Clearly, the reader's eyes tend to go to the
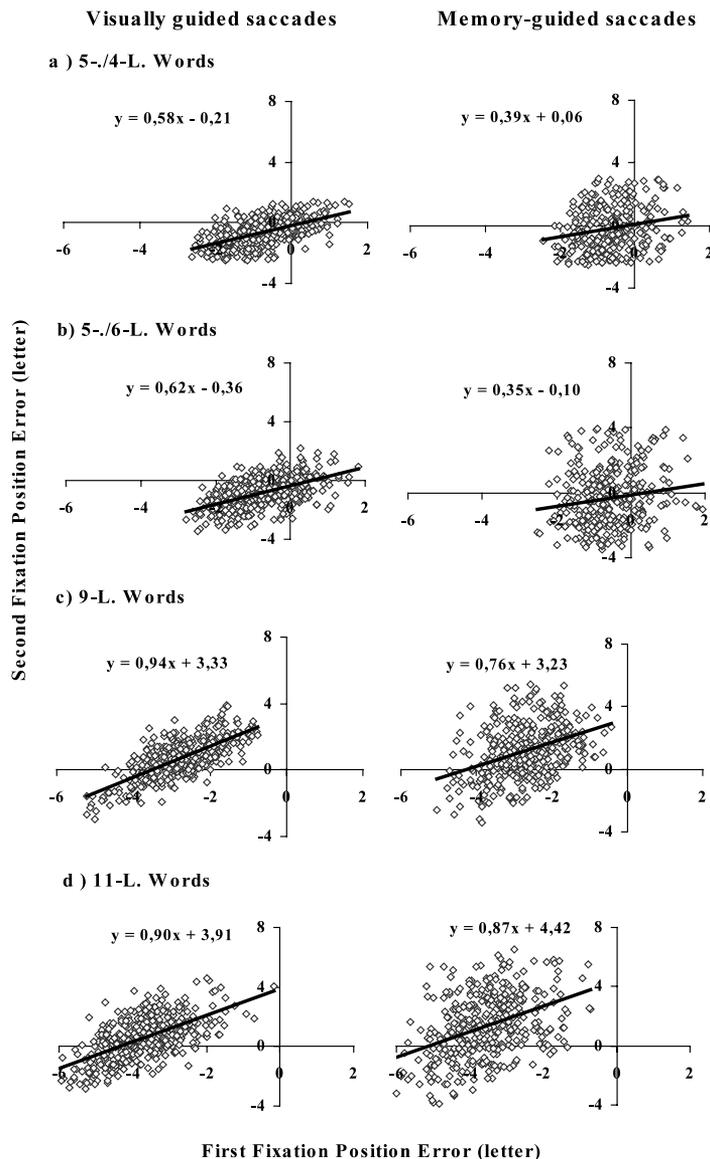
Fig. 1. Second fixation position errors plotted as a function of first fixation position errors measured from the words center for visually guided (left) and memory-guided saccades (right). Data were presented for: (a) five-then-four-letter words; (b) five-then-six-letter words; (c) nine-letter words; and (d) 11-letter words. Estimated standard deviations of the slopes are 0.70, 0.87, 0.82, 1.11 for visually guided saccades and 1.37, 1.77, 1.58, 1.96 for memory-guided saccades displayed in a, b, c, d, respectively.

'center of gravity' of the spatial configuration that started at the first fixation position and ended on the last letter of the second word. For memory-guided saccades, the oculomotor system mainly uses extraretinal information to update the second saccade. This suggests that the memory representation encoded the location of the second's word center in a head centered representation as a precise position in the orbit.

4. Discussion

In this experiment, subjects were required to make a two-saccade sequence, with the second visually or mem-

ory-guided saccade being directed at a new target word or at a second location in the currently fixated word (i.e. intra-word saccades). In order to discriminate between a mechanism that updates the location of the second target with respect to the eye position after the first saccade and a mechanism that encodes the second saccade in motor coordinates, we examined the relation between the first and the second saccades and compared this relation with and without visual information after the first saccade. The coordinate systems used in the second saccade were found to be specific to the action being performed. On the one hand, saccades directed at a second location in the currently fixated word were coded in motor coordinates as a fixed-vec-

tor, irrespective of the first fixation position error. This was shown by a propagation of the first position error onto the second fixation position. On the other hand, saccades that aimed for a second target word were found to be updated relative to the new eye position after the first saccade. A representation in an object-centered frame also exists for saccades directed to a remembered second target word. We measured the accuracy of the memory representation by looking for the effect of the remembered stimuli length and the systematic and variable errors of the memorized saccades. The hypermetry usually obtained in memorized saccades was found only for intra-word saccades. Despite this hypermetry, the memory trace was shown to maintain the remembered stimulus length. Otherwise, the data show that the absence of visual information after the first saccade resulted in increased variable errors of the second saccade. This increased variable error was similar for inter- than for intra-word saccades. Overall, the present results indicate that the reference frame used in reading is specific of the action being performed.

4.1. An error propagation mechanism in an oculocentric reference frame

An error propagation mechanism predicts that saccades are coded as a fixed motor vector irrespective of the first fixation position. Clearly, such a mechanism is found in the present data for visually as well as memory-guided intra-word saccades. The slope close to 1 for the relationship between the first and second fixation positions indicates that a movement of particular amplitude is executed without any influence of the initial
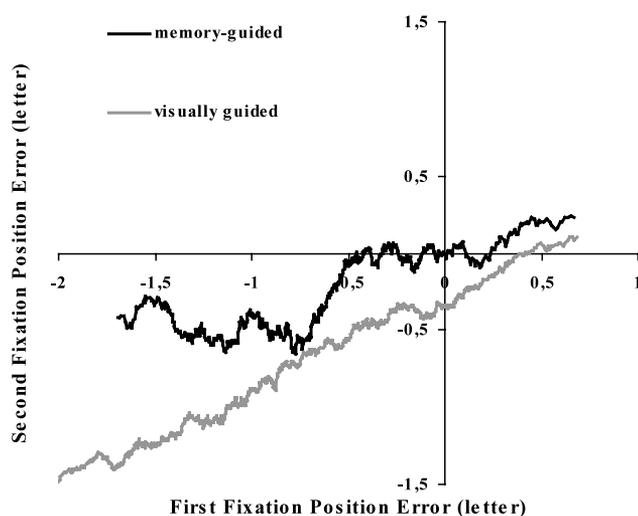

Fig. 2. Relationship between first and second fixation position errors measured from the words center for the two-word cases. The relationship is obtained by the sliding window technique. Each mean first and second fixation position errors is based on the 100 cases (see text).

landing position into the word. We interpret this result as evidence that the saccadic system has access to a motor representation of the word that encodes the movement required to fixate it again with a second fixation. The memory trace is maintained in a motor format that is not updated after the first saccade. These saccades are coded in an oculocentric reference frame as an eye movement of a particular size and direction regardless of the eyes' starting point in the orbit. In line with previous results, the amplitude of the motor vector was seen to be calculated on the basis of the word length (Vergilino & Beauvillain, 2000). Interestingly, the current data replicated this result pattern when no visual information was given before the triggering of the second saccade. In other respects, the memory-guided intra-word saccades were seen to be hypermetric. Becker and Klein (1973) have offered the following suggestion to account the hypermetry of memorized saccades: the larger the saccades, the better the subjects' ability to perceive the change of the eye position in the orbit. This in agreement with the result that the hypermetry was only observed for intra-word saccades, that are coded as a displacement of the eye in the orbit.

The use of an oculocentric reference frame without any updating after the first saccade argue in favor of a pre-programming of the intra-word saccade along with the first saccade. However, an alternative interpretation is that the motor vector of the second saccade may have been planned only after the first saccade, on the memory trace of the word's length. Indeed, neurophysiological studies on memorized double-saccade tasks found that the motor activity related to the second saccade is achieved only after the first saccade (Gnadt & Andersen, 1988). However, earlier results from this laboratory (Vergilino & Beauvillain, 2000) suggested that the intra-word saccade is planned along with the primary saccade, and both constitute units of motor action memorized before execution. Such a pre-programming mode of operation was seen when the word length was changed during the primary saccade. Then, the amplitude of intra-word saccades triggered after short fixation duration (< 140 ms) depended on the stimulus length given before the primary saccade. This stereotyped nature of the intra-word saccade suggests that the planning of a two-saccade sequence was 'pre-packaged' before the first saccade. This suggest the use of a non-visual motor memory (Fuster, 1994). Such a pre-programming mode of operation was also found in remembered target sequences (Zingale & Kowler, 1987; Viviani, 1990; Ditterich, Eggert, & Straube, 1998).

4.2. Updating in a retina- or head-centered reference frame

An updating mechanism posits that the target locations are represented in memory and updated after the

first saccade relative to the new eye position. It implies that the second saccade corrects the first fixation position error in order to aim for a precise target location. Such a process can be seen in our two-word conditions, where the second saccade corrects the first fixation error to aim for a precise location left of the center of the remembered second word. Does this experiment allow distinguishing between head- and retina-centered updated representations? In a head-centered updating mechanism, the memory target is held as a certain position in the orbit and the saccade has to compensate for an intervening movement to aim for a target orbital position. If the target is stored in a retina-centered representation, the saccadic system has to update this retinal representation to account for the intervening movement. In an attempt to discriminate between head- and retina-centered updated representations, Karn et al. (1997) examined whether the number of intervening saccades leads to cumulative errors in saccadic targeting to remembered targets. The increase in variable error with the additional intervening saccades is expected in a retina-centered representation because of the error associated with the updating process each time it is used to account for an intervening saccade. Alternatively, if the target is stored in a head-centered representation, intervening eye movements should have no effect on variable error. Karn et al. interpreted the observed slight increase in variable error as an evidence for a representation that relies on knowledge of eye position with respect to the head. In the present experiment, no evidence was found for an increase of the variable error due to the updating mechanism, suggesting a head-centered representation for the two-word cases.

Moreover, the present data show that, for memory-guided saccades, first fixation position errors resulting in a large deviation from the first word's center were almost fully compensated for in order to aim for the remembered second word's center. However, the presence of visual information before the second saccade triggering produced a deviation of the second saccade landing position from the second word's center that was a linear function of the distance between the first fixation position and the second target location. The farther away the first fixation position was, the greater the deviation from the second word's center. This can be accounted for by a 'center of gravity' effect whereby the oculomotor system computes the second fixation location as the 'center of gravity' of the spatial configuration between the first fixation position and the end of the second word. This is related to the launch site effect observed in text reading that produces a systematic deviation of landing sites from functional target location, the word's center (McConkie et al., 1988). Interestingly, the present data reveals that the launch site effect has less impact in the execution of memory-

guided saccades. A head-centered representation, in which the goal for the saccade is an absolute orbital position, does not predict such a launch site effect. Thus we favor the interpretation of these results as evidence supporting a head-centered representation for the remembered second word's center.

4.3. Word-centered representation

In addition to these egocentric representations, the performance for inter-word saccades indicates the use of exocentric representations. A representation in an object-centered reference frame appeared in the guidance of saccades towards a specific part of the word, that is the word's center. This leads us to propose the following assumptions: (1) an object-centered spatial representation is involved in eye movement control at the level of target selection; (2) the selection of a new target as a goal for the saccade is a prerequisite to an updating mechanism. This is in line with the saccade target object theory (McConkie & Currie, 1996; Currie, McConkie, Carlson-Radvansky, & Irwin, 2000) that gives priority to the remapping of visual information at the saccade target object in order to produce a perception of a stable world. Our data suggest that an object-centered representation is crucial for the target saccade selection process. In a word-centered representation, the endpoint is determined with reference to the selected target. When such a representation failed as found for intra-word saccades, the endpoint of saccades is determined with reference to the first fixation position.

5. Conclusion

Our present results demonstrate that readers hold internal representation of the target word in at least two different reference frames that vary with the action performed on the object: to aim for a new target word or to read it over with a second fixation. The former uses a spatial representation of a specific target location, whereas the later uses a representation of the word's intrinsic features. Evidence for multiple representations is provided by Moller and his colleagues (Moller, Hayhoe, Balard, & Albano, 1989a; Moller, Hayhoe, Balard, & Albano, 1989b; Hayhoe et al., 1992; Karn et al., 1997) and Dassonville et al. (1995) for oculomotor performance. None of these studies has provided evidence for a motor representation of the target that differs from a spatial representation. Our study reveals that these different representations are linked to motor plans that are specific of the action being performed on a word.

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