Abstract

When orienting to a newly appearing display, evidence shows that two saccadic eye movements are often prepared together. By looking the relation between the landing positions of the first and the second saccade, we examine the frame of reference used for the preparation of the second saccade aiming for a new object or exploring within the same object. We demonstrate that the action to be performed on the object affects the coding of the second saccade. A second saccade directed to a new object is coded to aim for a target position on it and is adjusted to the landing position of the first saccade, whereas a second saccade within the same object is coded as a fixed motor vector applied irrespective of the initial landing position on the object.

In our daily life, most of the motor acts we perform are complex goal-directed actions guided and controlled by action plans. Action planning will normally operate on objects. It thus supposes the selection of the appropriate objects in visual space and the encoding of their spatial properties in order to guide accurately motor actions. We discuss here the way in which spatial information about objects is used in the internal representations for the planning of saccadic eye movements.

In the case of a single saccade to a target, a retinotopic representation might seem sufficient. The image of the target is initially projected on the retina, and the motor vector of the saccade can be directly computed on the basis of the eccentricity between the actual eye position and the target retinal location. However, the saccadic system can prepare more than one single movement at a time and indeed this may be its normal mode of operation [12].

One demonstration of this ability is the double saccade paradigm in which two successively flashed peripheral targets have subsequently to be fixated in turn. This paradigm dissociates the retinal co-ordinates of the second target position from the movement required to reach it [2,11]. The system must update the spatial representation of the second target after the first saccade in order to compute the second saccade. Some authors explain the accuracy of the second saccade by assuming a representation of each target as an absolute spatial position in head co-ordinates [10,14,18,19]. Alternatively, others postulate the use of an eye-centred frame, with the representation of the second target updated after the first saccade [4,5,9]. However, one of the characteristics of all these studies using the double saccade paradigm is that the targets are small and precisely localised.

Double saccades often occur when moving the eyes to an extended target. Recent work has used a novel version of the double saccade paradigm in which orienting was required to two short words or to a single long word [1,17]. In both cases two or more saccades were produced. Consequently, the second saccade could be directed to the second word or remain within the same word. The second saccade directed...
to a new word compensated for the variability of the first saccade landing position to aim for a target location on the word, whereas the second saccade directed within the long word did not show such compensation but was coded as a fixed motor vector applied irrespective of the initial landing position on the word. Moreover, these intra-word saccades were found to be preplanned before the first saccade and based on the word length integrated at this time [16]. Whereas the object location is the main determinant of an inter-word second saccade, an intra-word second saccade is determined by the word length.

These findings imply that the perceptual information used by the saccadic system is coded in a form where word boundaries are segmented. The system appears to know whether the second saccade will be an intra-word or an inter-word saccade. Segmentation of words is one instance of more general segmentation so that the perceptual world is structured in terms of objects. Considerable interest has been generated by the finding that covert visual attention is influenced by perceptual object structuring [6,7,8,15]. The findings described above suggest that overt attention, which is saccadic eye movement planning, might be similarly sensitive to object structure.

In this study, we report an experiment to test whether the results found with isolated words would generalise to other kind of objects, thus examining the importance of the visual object structure for eye movement control. Sequences of saccadic movements were elicited either toward a single extended object or to three objects defined by the spatial grouping of 12 individual rings (Fig. 1a). Ten subjects had to perform a visual search task by determining if the target letter A or B was presented within 1 of the 12 circles. Their head was restrained and eye movements were recorded with a Fourward Technologies Dual Purkinje Generation 5.5 eye tracker. Eye position was sampled every millisecond and the resolution of the eye tracker was 10 min of arc. At the beginning of the session, the eye position on the screen was calibrated by requiring the subjects to fixate sequentially nine points arranged in a centrally presented square with an element-to-element separation of 8.13°. Calibration accuracy was checked after each experimental trial and recalibration occurred if necessary. Trials in which the initial position

![Fig. 1. (a) Example of the stimuli in three-object and one-object conditions. Twelve rings with a diameter of 1.14° were displayed on a dark grey background. The vertical spacing between the two edges was 0.18°. In the three-object condition, the horizontal spacing between each group of four rings was 0.9°. In the one-object condition, the horizontal spacing between each ring was 0.36°. On each trial, 11 black capital letters were randomly assigned to 11 rings. The 12th letter was either an A or a B and represented the target for the visual search task. This target letter appeared with equal probability on each ring over the experiment. (b) Relation between the landing position of the first and the second saccade (in degrees) for the three-object and one-object conditions. The black squares represent the position of the three objects on the screen. In the three-object condition, the initial position had to be within the contour of the first object and the final position within the contour of the second object. Fifty-one percent of the data fulfilled this requirement. In the one-object condition, the initial and final positions of the second saccade had to land within the object. Eighty percent of the data fulfilled this requirement.](image-url)
was more than 1° from the fixation cross or where saccade latencies were outside the range 75–800 ms were rejected from the subsequent analysis. Each trial began by the fixation of a cross presented 8° to the left of the screen centre for 1 s. Subjects were instructed to move the eyes and search for the target when the cross disappeared and the display appeared. 12 training trials began each session followed by two blocks each containing 144 trials.

Of interest here is the regression relationship between first and second saccade landing position which reveals how the second saccade is coded [3]. If the second saccade aims for a precise target location on the object, it should compensate for the first saccade landing position. A total compensation would give a slope of zero for the regression, i.e. second landing position is unaffected by first landing position. Alternatively, if the second saccade is coded as a fixed motor vector applied irrespective of the first saccade landing position, the slope of the linear regression is expected to be near to 1. An intermediate alternative occurs where the second saccade does not target a precise location but maintains the same direction as the initial saccade with its amplitude determined by the remaining stimulation beyond the first landing position. For example, the second saccade landing position might be directed towards the centre of gravity of this stimulation. In this case, the slope of the function would be close to 0.5.

Fig. 1b presents the relation between first and second saccade landing position in the three-object and one-object conditions. In the three-object condition, the data are selected such that the initial position had to be within the contour of the first object and the final position within the contour of the second object. These data represented 51% of all the data (one-fixation cases: 10%, second regressive saccades: 15% and within-object saccades: 24%). The coefficients of the correlation between first and second saccade landing position are significant in the three-object and one-object conditions ($r = 0.30$ and $r = 0.69$, respectively, $p < 0.05$). Clearly, the saccades directed to a new object or within the same object are coded differently. When the second saccade is directed to a new object, the slope of 0.39 indicates that the second saccade to a large extent compensates for the landing position of the first saccade. When the second saccade is directed within the same object, the slope of 1.03 demonstrates that the saccade is not directed to a second location on the object but rather is coded as a fixed motor vector applied irrespective of the initial landing position on the object.\footnote{In the great majority of cases, even when the critical letters appeared on the left part of the object, the subjects still did a second saccade coded as a fixed vector motor.}

An analysis of variance performed on the slopes from each individual’s data revealed an effect of the type of object, the slope obtained in the three-object condition (mean: 0.34, range: -0.14 to 0.63, 95% confidence interval: 0.26–0.51) being clearly different from the one obtained in the one-object condition (mean: 0.99, range: 0.60 to 1.32, 95% confidence interval: 0.96–1.12, $F(1,9) = 121.05, p < 0.0005$). One can assume that the difference in the regression slope between the three-object and one-object conditions merely results from the fact that the data set is restricted in one condition but not in the other condition. However, even when the data in the one-object case are reduced to the set of points meeting the exact same spatial criteria as the data in the three-object condition, the difference in the regression slopes is still seen (means: 0.33 and 0.81 for three-object and one-object conditions, $F(1,9) = 13.31, p < 0.05$). It is of interest to note these different regression slopes are associated with different saccade latencies, the second saccade latency being shorter for the one-object than for the three-object condition (mean of 194 and 185 ms, respectively, $F(1,9) = 4.06, p < 0.07$). However, the coding of the second saccade directed within the same object as a fixed vector cannot be explained by the short intersaccadic interval. Indeed, when we cut the data as a function of the median of the second saccade latency, a slope close to 1 was found for within-object saccades triggered after short or long latency.

Our finding shows that eye control when moving towards objects shows the same characteristics as when moving towards words [16,17]. If the second saccade is a scanning saccade within an object, it is executed as a fixed length vector. If the second saccade moves the eye between objects, it targets a specific spatial location. To the best of our knowledge, this is the first demonstration that object segmentation affects overt eye movement deployment. Several demonstrations have been made that object structure affects covert visual attention [6,7,8,15] and some of the most successful theories of eye movements during reading assume that attention is directed to successive words in text [13].

In a great majority of studies examining the sensorimotor transformation involved in the saccade planning, the task requires the aim for a precise target [10,18]. In the present study, the targeting requirements were not stated explicitly, but arose from the nature of the display, being either to aim for a new object or to explore the current object with a second saccade. The coexistence of these two different actions within the same experimental paradigm reveals that the sensorimotor transformation process operates with different coding of the saccades depending on the action performed. When the second saccade aims for a new selected object, the saccade is updated with respect to the eye position after the first saccade in order to aim for the centre of gravity of the object. Alternatively, when the second saccade explores the same object, the saccade does not aim for a specific target location on the object but rather

\footnote{The difference between the two regression slopes is still significant when we restrict the data to the same range of first landing positions between the three-object and one-object conditions (means: 0.34 and 1, respectively, $F(1,9) = 66.8, p < 0.0005$).}

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is coded as a fixed motor vector applied irrespective of the initial landing position on the object. The between object movement is computed relative to the object location, whereas the within object movement is planned relative to the size of the object. Such a result extends the previous findings during scanning of isolated words [1,16,17], and suggests that the between- and within-object distinction is a fundamental feature of the saccadic planning.

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References